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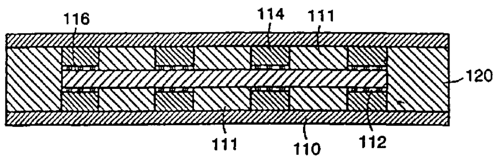
(54)【発明の名称】振動制御の方法及び装置

(57)【要約】
電子工学装置を製作するためのシステムにおける振動を制御するのに有用な、アクチュエータとセンサーを備えている振動制御システム。アクチュエータは、電極化されたシートに貼り付けられた、１つ又はそれ以上の電動アクティブ材料のプレート又は要素を備えている。



【特許請求の範囲】
【請求項１】
リソグラフィーシステムで使用するための動作制御システムにおいて、
ウェーハステージ基部と、
動作を制御するための少なくとも２つのアクチュエータと、
前記ウェーハ基部の少なくとも１つの変位のパラメータを検出して、それに応じて少なくとも２つの信号を生成する少なくとも２つのセンサーと、
前記アクチュエータ及び前記センサーと電通している少なくとも１つの回路と、を備えており、
前記センサーにより前記少なくとも１つの変位のパラメータが検出されると、前記センサーは前記回路に信号送信し、前記回路は、それに応じて前記アクチュエータを起動して前記ウェーハステージ基部を安定化することを特徴とする動作制御システム。
【請求項２】
前記アクチュエータは、ボイスコイルモーターと電動アクティブスタックアクチュエータから成るグループから選択されることを特徴とする、請求項１に記載の動作制御システム。
【請求項３】
前記センサーは、ＬＶＤＴ、加速度計、レーザー干渉計、容量変位センサーから成るグループから選択されることを特徴とする、請求項１に記載の動作制御システム。
【請求項４】
前記回路はデジタル信号プロセッサを備えていることを特徴とする、請求項１に記載の動作制御システム。
【請求項５】
前記回路は、
少なくとも１つのデジタル信号プロセッサと、
少なくとも１つのアナログ対デジタル変換器と、
少なくとも１つのデジタル対アナログ変換器と、を備えていることを特徴とする、請求項１に記載の動作制御システム。
【請求項６】
前記回路は制御技術を備えていることを特徴とする、請求項１に記載の動作制御システム。
【請求項７】
前記制御技術は、線形二次ガウス、Ｈ無限、及びミュー合成から成るグループから選択されることを特徴とする、請求項６に記載の制御技術。
【請求項８】
前記アクチュエータは、指示された入力に密接追従して前記ウェーハステージ基部を安定化させることを特徴とする、請求項１に記載の動作制御システム。
【請求項９】
リソグラフィーシステムで使用するための動作制御システムにおいて、
ウェーハステージと、
動作を制御するための少なくとも２つのアクチュエータと、
前記ウェーハ基部の少なくとも１つの変位のパラメータを検出して、それに応じて少なくとも２つの信号を生成する少なくとも２つのセンサーと、
信号コンディショナと、
シングルボード・コンピュータと、を備えており、
前記センサーにより前記少なくとも１つの変位パラメータが検出されると、前記センサーは前記信号コンディショナに信号を送り、前記信号コンディショナは信号を前記シングルボード・コンピュータに送り、前記シングルボード・コンピュータは前記アクチュエータに指示して、前記ウェーハステージが指示された位置を追跡するように指示することを特徴とする動作制御システム。

【請求項１０】
前記アクチュエータは、ボイスコイルモーターと電動アクティブスタックアクチュエータから成るグループから選択されることを特徴とする、請求項９に記載の動作制御システム。
【請求項１１】
前記センサーは、ＬＶＤＴ、加速度計、レーザー干渉計、容量変位センサーから成るグループから選択されることを特徴とする、請求項９に記載の動作制御システム。
【請求項１２】
前記ウェーハステージは、指示された位置を０．１９秒以内に追跡するように指示されることを特徴とする請求項９に記載の動作制御システム。
【発明の詳細な説明】
【技術分野】
【０００１】
本出願は、２００１年3月９日出願の米国特許出願第０９／８０３，３０２号に対する恩典を請求する。
【０００２】
電子工学設備又は構成要素を製作するためのシステムを含め、自動表面実装電子工学設備に関して存在する競争市場では、精度と速度の改良は相当な利点となる。このような設備は、例えば、半導体チップ、印刷回路板、液晶表示装置、及び薄膜デバイスなどの製作に使用されることが多く、多重ガントリ／ヘッドアッセンブリ、リニアモーター、フォトイメージングシステム、エッチングシステム、及び／又はその他多くの技術において重要な位置を占める。本発明は、作動中のそのような設備につきものの振動を低減し、それによってそのような設備の速度及び／又は精度を改善する装置及び方法に関する。
【背景技術】
【０００３】
例えば、現在のフォトリソグラフィー・ツールは非常に高度な露光精度を必要とする。これは、ツールの重要な点の弾性的変位の程度が数ナノメートルを超えない場合にのみ実現できる。リソグラフィーツールは、レチクルやウェーハステージのような多数の可動部品を含んでいるので、それら構造に作用する永続的な妨害力を受けることになる。更には、ツール構造は、床の振動や気流の乱れなど環境的妨害を受けやすい。これらの妨害は、程度を低減することはできるが、完全に排除することはできない。
【０００４】
現在、リソグラフィーツールの弾性振動を制限するために、多数の技術が採用されている。例えば、レンズアッセンブリのような基幹要素をサポートする構造体の剛性を増強する、調整されたマスダンパを使用する、可動ステージに掛ける信号を整形する、或いは、アクティブ制御空気ばねを使って床の振動を絶縁するなどである。これらの方法は、弾性振動を低減するのに効果はあるが、より進歩したフォトリソグラフィー・ツールの厳しい要件には合致しないことも多い。
【０００５】
ＳＭＴ配置設備の振動を制御するため現在行われている努力には、ガントリの端に摩擦減衰装置を配置することが含まれる。この「摩擦ブロック」は、主に、ガントリ及びヘッド軌道制御システムを安定化する働きをするが、ある種のピック・アンド・プレイス動作時には整定時間を短縮することも分かっている。しかしながら、摩擦ブロックの有効性は垂直力（又は予荷重）を正確に調整することに掛かっている。摩擦ブロックは短期間で磨耗する傾向が強く、有効性が大幅に低下し、且つ機械の残り部分を粒子によって汚染することになる。更には、摩擦ブロックは剛体の運動に抗して作動するので、設備の作動が遅れる結果となる。本発明の振動制御システムは、アクチュエータアッセンブリを備えており、摩擦ブロックに全体的に取って代わることができると同時に、整定時間を改善し、又は、代わりに、摩擦ブロックと協働して作動の精度又は速度を更に高める。
【０００６】

本発明の或る態様は、アクティブ振動低減、構造的制御、動的試験、精密な位置決め、動作感知及び制御、及びアクティブ減衰に役立つアクチュエータ要素に関する。このようなタスクには、圧電性、電歪性、又は磁歪性材料のような電動アクティブ材料が、有用である。本発明の或る実施形態では、むき出しの電動アクティブ要素を使用する。別の実施形態では、ここに説明するパッケージ化された電動アクティブ要素を使用している。

【０００７】

このように、電子構成要素を製作するためのシステムにおいて振動が制御されるやり方で、且つアクチュエータが制御対象の設備に取り付けられるやり方での改善が望ましい。

【発明の開示】

【課題を解決するための手段】

【０００８】

本発明の或る実施形態では、アクチュエータアッセンブリと、動き又は性能のパラメータを感知するためのセンサーとを備えた振動制御システムが提供されている。この振動制御システムは、１つ又は複数のガントリアッセンブリ、ヘッドアッセンブリ、及び／又は移動ステージ又は構成要素を含んでいることが多い電子工学構成要素を製作するためのシステムにおいて、振動を制御するのに特に有用である。電子工学構成要素を製作するために考えられたシステムとしては、ピック・アンド・プレースシステム、リソグラフィーシステム、及び半導体チップや印刷回路板や液晶表示装置や薄膜デバイスを製作するために使用されるシステムなどが挙げられるが、これらに限定されるわけではない。しかしながら、本発明の装置及び方法は、機械工具設備、フライス加工設備、又は自動組み立てラインで使用されるシステムなど、あらゆる種類のシステムを製作するのに有用である。また、レンズ系と、ウェーハステージと、レンズ系とウェーハステージを支持するための構造とを備えており、レンズ系が、ウェーハステージ上に最新のフォトリソグラフィーに使用されているような画像を作り出す、電子構成要素を製作するためのシステムも考えられる。

【０００９】

或る実施形態では、フォトリソグラフィー製作システムで使用されるアクティブ振動制御システムには、以下の構成要素、即ち、キーポイントでの変位の程度を測定するか、又はそのような情報が推定できる情報を提供するセンサーと、センサー入力に基づいて制御信号を計算できるデジタル又はアナログプロセッサと、構造内に弾性的変位を誘起することのできるアクチュエータと、が含まれている。

【００１０】

或る特に好適な実施形態では、フォトリソグラフィー工具と共に使用されるアクティブ振動制御システムに有用なアクチュエータは、非反応性で、バックサポートが不要で（バックサポートを要するアクチュエータは、サポート構造内に弾性的振動を励起し、これが工具に再導入されることになる）、非常に低い歪プロフィールを有する（所与の周波数又は帯域で構造的振動を制御するように設計されたアクチュエータアレイは、その帯域以外で振動を励起することはない）。

【００１１】

或る特に好適な実施形態では、本発明による振動制御システムは、構造の歪状態に直接働きかけ、実質的に歪を持たない、誘導歪アクチュエータを備えている。このようなアクチュエータは、制御される構造の弾性振動モードのみを励起し、従って制御することができ、他の全ての振動モード（各種設備のハウジング構造のモードなど）は制御されないまま残される。これは、制御システムの簡素化と強さに寄与する。

【００１２】

本発明の別の実施形態では、振動制御システムは、更に、アクチュエータアッセンブリとセンサーとに電気的に連通した回路を備えている。或る実施形態では、センサーは、動き、振動、又は性能に関する情報を回路に中継し、回路は、それに応えてアクチュエータアッセンブリに信号を送って振動を制御する。本発明が役に立つシステム内の振動は、外的妨害によるもの、又はシステム自身が作り出す本来的な妨害によるものである。

【００１３】

本発明の更に別の実施形態では、振動制御システムは、更に、製作システムに対する電気的接続部を備えている。この電気的接続部は、使用可能又は使用禁止信号、システム状態信号、又は故障・エラー状態信号の様な情報を、振動制御システムに送り、振動制御システムから受け取るために製作システムに設けられている。別の実施形態では、本発明による回路は、更に、少なくとも１つのコントローラを備えた制御システムを備えている。このような制御システムは、自動同調、ゲインスケジュール調整、外部ゲイン制御を行うことができ、又は線形フィードフォワード制御でもよいし、或いはフィードバック制御の別のソースとして働いてもよい。

【００１４】

振動制御システムが自動同調制御を有している本発明の或る実施形態では、作動前に、制御システムは１つ又は複数のテスト信号をシステムに発して応答を測定する。測定された応答を使用して工場内の内部モデルを微調整し、制御ゲインはしかるべく修正される。ループが閉じている間、制御ゲインは一定に保たれる。

【００１５】

振動制御システムがゲインスケジュール調整制御を有している本発明の或る実施形態では、コントローラは、幾つかの異なる作動点でシステムのために設計される。ピック・アンド・プレイス機の場合、これらの点はピック・アンド・プレイスヘッドの異なる位置となる。コントローラは、デジタル制御システムのメモリ内に記憶される。作動時、センサーは、リアルタイムで機械の構成を記述しているコントローラに情報を供給する。システムが各作動点を通過するのに合わせて、制御システムはその地点の随意の制御ゲインに切り替わる。この変化は、何れの地点でも時間に合わせて使用される制御ゲインは、幾つかの近隣の作動点についてメモリに記憶されている幾つかのコントローラからのゲインの線形補間である、ということである。

【００１６】

振動制御システムが外部ゲイン制御を有している本発明の或る実施形態では、制御システムは、機械の全体的性能をモニターするコンピュータシステムに接続された入力部を含んでいる。どの瞬間でも時間に合わせて実行されるコントローラは、この信号に比例するゲインを有している。監視システムは、最適性能が実現されるまでこのゲインを修正する。遅い時間変動のために性能が仕様からずれそうになると、監視システムはゲイン最適化シーケンスを繰り返す。

【００１７】

振動制御システムが、フィードバック制御（構造的振動を監視するセンサーから発せられた信号により駆動されるコントローラ）に加えて、フィードフィワード制御を有している本発明の或る実施形態では、高い調波妨害（モーターの回転など）と同位相の付加的な信号がコントローラに供給される。コントローラは、この信号のフィルタに通したものをフィードフォワードする。妨害信号に対するフィードフォワード制御の強さと位相を調整するゲインは、性能に対する妨害の影響を最小化すべく適応調整される。

【００１８】

本発明の或る実施形態では、アクチュエータアッセンブリは、歪アクチュエータ、電気有効歪アクチュエータ、圧電セラミック歪アクチュエータ、電動アクティブスタックアクチュエータ、又は少なくとも２つのアクチュエータを備えている。本発明の更に別の実施形態では、アクチュエータアッセンブリは、センサーと電通している。

【００１９】

また、本発明の或る実施形態では、センサーは、歪センサー、加速度計、レーザー変位センサー、レーザー干渉計、又は少なくとも２つのセンサーを備えている。本発明の別の実施形態では、センサーは、少なくとも２つの異なる信号を測定する少なくとも２つのセンサーを備えている。ある好適な実施形態では、センサーは、本発明が利用できるシステムの性能に直接関係する幾つかの態様を直接的に測定する。

【００２０】

本発明の或る特に好適な実施形態では、振動制御システムは、ガントリ及びヘッドの軌道

についての情報を提供する電子リンク又はケーブルを備えている。
【００２１】
本発明によるアクチュエータアッセンブリは、圧電又は電歪プレート、シェル、ファイバ、又は合成物のような１つ又は複数の歪要素と、前記要素の周囲の防御体を形成しているハウジングと、ハウジング内に取り付けられ歪要素に接続されている電気接点とを含んでおり、上記部品は全体で可撓性のカードを形成している。アッセンブリの少なくとも一方の側は、歪要素の主面に取り付けられた薄いシートを含んでおり、シートの外側を対象物に貼り付けることにより、硬い剪断が働かないカプリングが、対象物とハウジング内の歪要素との間に得られる。
【００２２】
或る好適な実施形態では、歪要素は圧電セラミックプレートであり、かなり薄く、８分の１ミリメートルより僅かに薄い程度から数ミリメートルまでの厚さで、表面積が比較的広く、幅又は長さの何れか又は両方が、厚さの数十倍又は数百倍であるのが望ましい。金属被覆処理された膜が電極接点を形成するとともに、接着剤と絶縁材料が、層割れ、亀裂発生、及び外的環境への露出を防ぐためにデバイスを気密シールしている。使用される接着剤は、Ｂステージ又はＣステージエポキシの様なエポキシ、熱可塑性材、又は圧電セラミックプレート、金属被覆膜及び絶縁材料を一体に接着するのに役立つ何らかの他の材料などである。使用できる特定の接着剤は、デバイスの意図する用途次第で異なる。或る好適な実施形態では、金属被覆膜及び絶縁材料は、両方とも丈夫なポリマー材料の可撓性回路内に設けられ、従って、密閉された要素との頑丈な機械的及び電気的カプリングを形成する。代わりに、金属被覆膜を圧電セラミックプレート上に直接配置し、絶縁材料が電気接点を有するようにしてもよい。
【００２３】
説明を目的として、以下の例では、４分の１ミリメートル厚の矩形ＰＺＴプレートを使用し、長さと幅はそれぞれ１から３センチメートルで、各要素は表面積が１から１０平方センチメートルの有効歪発生面を有する構造を説明する。ＰＺＴプレートは、堅くて頑丈なポリマー、例えば、２分の１、１、又は２ミルのポリイミドのシートの上又はシート間に搭載され、一方側又は両側が銅に覆われ、ＰＺＴプレートとの接点形成のために銅層に形成された適した導電電極パターンを有している。各種スペーサによりプレートを囲み、全体構造を構造的ポリマーと一体に接合して、プレート厚と同じ、例えば０．３０から０．５０ミリメートル程度の厚さを有する防水絶縁密閉パッケージとしている。このように密閉されると、パッケージは、曲げ、伸ばし、撓ませることができ、鋭い衝撃に曝されても、その中に入った脆いＰＺＴ要素が壊れることはない。更に、導体パターンはポリイミドシートにしっかりと取り付けられているので、ＰＺＴ要素に亀裂が入っても、電極が切断されることはなく、要素の全面積に作用が及ぶのが防止され、又は性能がひどく劣化するのが防止される。
【００２４】
薄いパッケージは、電極が付いて完成した小型の「カード」の形をした完成したモジュール単位を形成している。次いで、パッケージは、好便に一面を構造体に取り付け、密閉歪要素と構造体の間の歪を連結する。これは、例えば、パッケージに接着剤を付けるだけで、ＰＺＴプレートに対する薄くて高い剪断強度を有するカプリングを確立すると共に、全体としてシステムに対して加わる質量を最小に抑える。プレートは、エネルギーを取り付け側の構造に連結するアクチュエータであってもよいし、取り付け側の構造から連結された歪に応答するセンサーであってもよい。
【００２５】
別の実施形態では、特定の電極パターンがシート上に選択的に形成され、ＰＺＴプレートを平面内又は面をまたいで支え、ＰＺＴ要素の複数層が１枚のカード内に配置され又は重ねられ、その結果、曲げ又は剪断、更には特別な捻り動作ができ上がる。
【００２６】
本発明の更に別の態様によれば、回路要素は、振動制御システム内に又は当該システムと

共に形成され、ＰＺＴ要素が作り出す信号をろ過、分路、又は処理し、又は機械的環境を感知し、又は作動要素を駆動するために切り替え又はパワー増幅を局所的に行なうことさえする。アクチュエータパッケージは、ハーフシリンダのような事前成形されたＰＺＴ要素を用いて、パイプ、ロッド又はシャフトの周囲へ取り付けるのに適したモジュラー表面実装シェルに形成される。

【発明を実施するための最良の形態】

【００２７】

本発明の上記及びこの他の望ましい特性は、図示の実施形態の詳細な説明から理解頂けるであろう。

【００２８】

出願人は、電子工学構成要素を製作するためのシステムにおける振動を制御するのに特に有用な振動制御システムを開発した。本発明の振動制御システムは、構成要素を製作するためのシステムにおいて外的に発生するか、又はシステムに内的に発生するか、又はシステムに本来的なものであるか、の何れの振動を制御するのにも有用である。内的振動は、製作システム内で使用されるステップモーター又はＤ．Ｃ．モーターの様な各種モーター、又は液圧式又は空圧式アクチュエータにより発生する。

【００２９】

本発明による振動制御システムは、電動アクティブアクチュエータ及びセンサーを製作システムと一体化した形で備えている。制御及びパワー電子機器は別の装置で、設備に隣接して配置され、アクチュエータとセンサーに適当な連結ケーブルを介して接続されているものでもよい。代わりに、制御及びパワー電子機器は製作システムと完全に一体化されたシステムであってもよい。

【００３０】

電動アクティブアクチュエータは、様々なやり方で製作システムに、又はシステム内に固定される。図１７、１９及び２０に示すように、例えば、アクチュエータは、ボルト４１４をアクチュエータに押し付けて、又はアクチュエータに貫通させて、所定の位置に固定することができる。代わりに、アクチュエータは、摩擦、張力、又は付勢嵌合により固定してもよい。或る実施形態では、図１８に示すように、アクチュエータをプレート４１２に貼り付け、プレート４１２を製作システムの構成要素にボルト４１４、４１４’、４１４１”及び４１４”’を用いてボルト止めする。別の実施形態では、アクチュエータをプレートに貼り付け、プレートを第２のプレートにボルト止めし、第２のプレートを製作システムの構成要素にボルト止めする。別の実施形態では、アクチュエータアッセンブリは、振動制御システム内に取り外し可能に固定され、又は製作システムの構成要素に取り外し可能に固定される。

【００３１】

図２１は、製作システムに使用される本発明の実施形態を示している。この実施形態では、製作システムは、ウェーハステージ４００と、レチクルステージ４０２と、Ｘ＆Ｙミラー付きレーザー干渉計４０４、４０４’、４０４”及び４０４’”と、支持構造４０６とを備えている。支持構造４０６は、レンズアッセンブリ４１０を支持している。干渉計４０４、４０４’、４０４”及び４０４’”は、ウェーハステージ４００上、レチクルステージ４０２、及びレンズアッセンブリ４１０上に配置されている。支持構造４０６の上には、例えば電動アクティブ要素を備えている２つのアクチュエータ４０８、４０８’が搭載されている。各アクチュエータ４０８、４０８’は、回路と電通している。干渉計４０４、４０４’、４０４”及び４０４”’からの信号は、ＳＢＣアナログＩ／Ｏチャネルと増幅器を通してアクチュエータ４０８、４０８’に中継され、アクチュエータ４０８と４０８’は、これに応答して製作システム内の振動を制御する。製作システム内の振動を制御することにより、ウェーハステージ上の半導体内の金属被覆トレースの配置と絶対寸法の精度が改善される。代わりに又は追加的に、製作システムのスループットは、精度を落とすことなく上げることができる。

【００３２】

本発明では、電動アクティブアクチュエータッセンブリが有用である。図１Ａは、先行技術による表面実装圧電アクチュエータアッセンブリ１０の処理及び全体配置を図式で示している。構造体要素又は機械要素、板、翼形又は他の相互作用用的シート、又はそのデバイス又は一部、である構造２０は、導電性及び構造的ポリマー１４、１６の何らかの組み合わせによって構造２０に貼り付けられたスマート材料のシート１２を有している。その全体又は一部が構造的ポリマー１６によって形成される絶縁体１８は、スマート材料を密閉保護すると共に、導電性リード又は表面電極が、導電性ポリマーにより形成され又は取り付けられる。外部制御システム３０は、配線３２ａ、３２ｂに沿ってスマート材料に駆動信号を供給し、歪ゲージ３５のような表面実装計器から測定信号を受けとり、それから適当な駆動信号を引き出す。様々な形態の制御を行うことができる。例えば、歪ゲージは、自然共振の励起を感知するために配置され、制御システム３０は、センサー出力に応じて構造の剛性が上がるようにＰＺＴ要素を単純に作動させるので、共振周波数が変わる。代わりに、センサーが感知した振動を、発生している動的状態をゼロにする処理済位相遅延駆動信号としてフィードバックしてもよいし、又はアクチュエータを動作制御するため駆動してもよい。よく解読された機械的システムでは、コントローラは、実験的条件、即ち空気力学的状態又は事象を認識し、望ましい変化を実現するために各アクチュエータ１２を駆動する信号のゲインと位相を指定する特別な制御則を選択するようにプログラムされている。

【００３３】

このような用途全てにおいて、むき出しのＰＺＴプレートをその制御回路と加工物に取り付けるのが要求される主な作業であるが、組み立て段階の多くは失敗することもあり、或いは、定量的制御を行いたい場合は、製作工程において作り出される特定の厚さと機械的剛性に相応しい有効な作動モードのための制御パラメータを確立するために、デバイス組み立て後にデバイスの示量的モデル化が必要になることもある。プレートに貼り付ける場合に電動アクティブ要素をパッケージ化する利点は、製作システムのプレート、構造体又は何れの部分からも電気的絶縁又は容量的分離が実現できることである。

【００３４】

図１Ｂは、本発明の或る実施形態で有用なアクチュエータアッセンブリを示している。図示のように、それは５分エポキシ１３のような高速硬化接着剤で構造体２０に単純に取り付けただけの、或いは別の構成では一点又は線状に取り付けられた、モジュラーパック、即ちカード４０である。感知と制御の動作は、こうして、より容易に設置可能で且つ均一にモデル化されたアクチュエータ構造から恩恵を受ける。具体的には、モジュラーパック４０は、カード、即ち硬いが屈曲可能なプレートの形をしており、望ましくはパッドの形をした１つ又は複数の電気コネクタを縁部（図示せず）に配置して、多重ピンソケットに差し込み、単純化された制御システム５０に接続できるようになっている。図２Ｃに関連して後に更に詳しく説明するが、モジュールパッケージ４０は、内蔵型の平坦な又は背の低い回路要素でもよく、加重又は分路レジスタ、インピーダンス整合器、フィルタ、及び信号調整前置増幅器のような信号処理要素を含んでおり、更に、直接デジタル制御下で作動させるための切換トランジスタ及び他の要素も含んでいるので、必要な外部電気接続は、マイクロプロセッサ又は論理コントローラ並びに電源装置だけになる。

【００３５】

特にパワーの低い制御状況に用いられる更に別の実施形態では、図１Ｃに示すようなモジュールパッケージ６０は、バッテリ又はパワーセルのような自身の電力源を含み、オンボードドライバと分流器を作動させるためにマイクロプロセッサチップ又はプログラム可能な論理アレイのようなコントローラを含んでおり、外部回路接続なしで感知及び制御動作の完全なセットが有効に働くようにしている。

【００３６】

本発明は、厳密には圧電ポリマーに、そして、焼結金属ジルコン酸塩、ニオブ酸塩結晶のような材料又は硬いが極めて脆いこともある同様の圧電セラミック材料に関する。本発明は電歪性材料にも関する。特許請求の範囲にも使用しているように、要素の材料が電気機

械的特性を有している圧電及び電歪要素の両方を、電動アクティブ要素と称する。高い剛性は、要素の表面を横切って、歪みを、通常は金属又は硬質の構造ポリマー製の外部構造体又は加工物に効果的に伝達するのに欠かせないので、本発明は、アクチュエータ態様において、軟質ポリマー圧電材料を一般的には考慮していない。「硬い（剛性が高い）」と「軟かい」という用語は相対的であるが、ここでは、アクチュエータに用いられる場合の硬さは、概ね金属、硬化エポキシ、ハイテク複合物、又はその他の硬質材料などの硬さであり、ヤング係数が０．１×１０^{6}より大きい、望ましくは０．２×１０^{6}より大きい材料であると理解頂きたい。アクチュエータではなくセンサーを構成する場合には、本発明は、ポリビニリデン・ジフルオライド（ＰＶＤＦ）膜の様な低剛性圧電材料、及び低硬化温度結合又は接着材料の代用物の使用を考慮している。しかしながら、上記の第一級圧電材料では、基本的な構成上の難題が発生し、それについて以下、説明する。

【００３７】

一般的に、本発明は、アクチュエータの新しい形態及びそのようなアクチュエータを作る方法を含んでおり、ここでいう「アクチュエータ」とは、電力が供給されると力や動き等を対象物又は構造体に連結する完全且つ機械的に有用な装置を意味するものと理解頂きたい。広義において、アクチュエータを作ることには、原料の電動アクティブ要素を「パッケージ化」して機械的に有用にする段階を含んでいる。一例として、原料の電動アクティブ圧電材料、即ち「要素」は、各種半加工材料塊形態で一般に市販されており、基本形状がシート、リング、ワッシャ、シリンダ、プレートなどの圧電原材料、並びにスタックのようなより複雑又は複合的形態、又は材料塊をレバーなどの機械的要素と共に含んだハイブリッド形態の圧電原材料が挙げられる。これら材料又は原料要素は、１つ又はそれ以上の表面に金属被膜を施して電気接点として働くようになっていてもよいし、金属被覆されていなくてもよい。以下の説明では、圧電材料を一例として論じているが、これら全ての形態の原料を「要素」、「材料」又は「電動アクティブ要素」と呼ぶ。上記のように、本発明は、これら方法により作られ、歪、振動、位置、又は他の物理特性を、作動させるのではなく感知するためのトランスジューサとして作動する構造体又は装置を更に含んでいるので、以下の記述では「アクチュエータ」という用語は感知用トランスジューサを含んでいる。

【００３８】

本発明の実施形態では、これら硬い電気作動式材料を、厚さが数ミリメートル未満、一例的には５分の１から４分の１ミリメートルの薄いシート、即ち円板、環、板、及び円筒又はシェルの形態で採用している。好都合に、このように薄い寸法にすることによって、全体的に電位差が比較的低いプレートの厚さ寸法に匹敵する距離に亘って高い電界強度を実現できるので、１０から５０ボルト又はそれより小さい駆動電圧でフルスケールの圧電作動性を得ることができる。このような薄い寸法によって、対象物の構造的又は物理的応答特性を大幅に変更することなく、要素を対象物に取り付けることができる。しかしながら、先行技術においては、このように薄い要素は脆く、取扱い、組み立て、又は硬化時の異常な応力によって破壊されることがある。数センチメートルからの落下の衝撃によってさえ圧電プレートは壊れるので、破壊に至らないようにするには極端に小さい曲げたわみしか許容されない。

【００３９】

本発明によれば、薄くて電気的に作動する要素が、硬い絶縁材料の層で封入され、少なくとも層の内１つは、その表面にパターン化された導体を有し要素自体より薄い丈夫な膜である。パッケージは、圧電要素、絶縁層、及び各種スペーサ又は構造的充填材料から組立てられ、全体として電極、（複数の）圧電要素、及び封入膜又は層は、むき出しの作動要素よりも厚さが実質的に厚くない密封カードを形成する。以下に説明するように、要素が幾つかの層に配置される場合、パッケージの厚さは、積層された作動要素の厚さの合計よりも目に付くほど厚くはない。

【００４０】

図２Ａは、本発明の基本的実施形態１００を示している。ポリイミド材料のような絶縁性

の高い材料の薄膜１１０は、少なくとも一方の側が、通常は銅被覆により金属被覆され、仕上げられたアクチュエータパッケージと同一の広さ、又はそれより僅かに大きい矩形を形成している。複数層の回路板の製作に使用できる適した材料は、Ｆｌｅｘ－Ｉ－Ｍｉｄ３０００接着剤不使用回路材料として、アリゾナ州チャンドラーのロジャース社より配布されており、ロール状の銅箔上に形成されたポリイミド膜で構成されている。広範囲な大きさのものが商業的に入手可能であり、金属箔は、厚さが１８から７０ミクロンで、厚さ１３から５０ミクロンのポリイミド膜で一体にコートされている。他の厚さで製作することもできる。この商業的材料では、箔とポリマー膜が接着剤なしで直に貼り合わされているので、金属層は従来のマスキングとエッチングによりパターン形成することができ、以下に更に詳しく説明する方法によって、残留接着剤がアッセンブリを弱体化したり層割れを発生させることなく、複数のパターン形成層を多重層板に作り上げることができる。ロール状の銅箔は高い面内引っ張り強さを提供すると共に、ポリイミド膜は強くて丈夫で欠陥のない電気的絶縁バリヤを提供する。

【００４１】

以下に説明した構成では、膜は電極を覆う絶縁体だけを構成しているのではなく、デバイスの外表面も構成している。従って、高い誘電強度、高い剪断強度、耐水性、及び他の表面に対する結合能力が要求される。好適な製作工程で使用される温度硬化の観点から高い耐熱性が必要であるが、他にも用途環境によって耐熱性が必要とされる場合がある。一般的には、ポリアミド／イミドが有用であると分かっているが、ポリエステル又は同様の特性を持つ熱可塑性プラスチックなど他の材料を使用することもできる。

【００４２】

本構造では、箔層は従来のマスキング及びエッチング技術（例えば、フォトレジストマスキング及びパターニング、次いで塩化第２鉄エッチング）によりパターン形成され、圧電プレート要素の表面と接触するための電極が形成される。代わりに、より延性があり薄い導電層を使用してもよい。例えば、薄い導電層をポリマー膜上に印刷してもよいし、銀の導電性インクを使って圧電要素に直に印刷してもよい。図２Ａでは、電極１１１は、矩形体内部の１つ又は複数のサブ領域に亘って広がり、デバイスの縁に延びている補強パッド又はランド部１１１ａ、１１１ｂに繋がっている。電極は、要素の全長及び全幅に亘って広範に巡る経路に沿って圧電要素に接触するためパターン状に配置され、電極又は圧電要素に幾つかの亀裂又は局所的な破壊が起きても要素が接続された状態に確実に維持されるようにしている。フレーム部材１２０は、シート１１０の周囲に配置され、少なくとも１つの圧電プレート要素１１２が、電極１１１が接触するように中央領域に設置されている。フレーム部材は、縁結合として働くので、薄い積層は縁部まで広がらず、更に、以下に説明するホットプレスアッセンブリ工程で厚さスペーサとして、及び積層パッケージ組立の初期段階で挿入される圧電プレートの位置を決める位置マーカーとしても働く。

【００４３】

図２Ａは、実際にプレート１１２を覆って広がりスペーサ１２０及びシート１１０と共にアッセンブリを密閉する別の半透明の表面層１１６（図２Ｂ）を含め、デバイスを一体に固定するデバイスの層構造を示していない点においては、幾分概略的な図である。同様の層１１４が圧電要素の下に配置され、適した切込みを付けて電極１１０が要素に接触できるようになっている。層１１４、１１６は、硬化性のエポキシシート材料で形成するのが望ましく、硬化後の厚さは金属電極層の厚さに等しく、各側でこれと接触する材料と一体に結合する接着層として働く。硬化すると、このエポキシは、デバイスの構造体を構成し、アッセンブリの剛性を高め、圧電要素の表面の実質的な部分に亘って全体的に広がり、要素を強化してクラックの成長を止め、寿命を延ばす。更に、この層のエポキシは、実際には顕微鏡的に薄く広がっているが、かなり不連続な膜であり、電極上の厚さは約０．００２５ｍｍで、電極を圧電プレートにしっかりと結合してはいるが、十分な数のボイドとピンホールを備えているので、電極と圧電要素の間の直接的な電気接触が、相当の且つ分散された接触領域全体に亘って生じる。

【００４４】

図２Ｂは、縮尺合わせをしていないが、図２Ａの実施形態の断面図である。大まかな割合で言えば、圧電プレート１１２は厚さが０．２から０．２５ミリメートル、絶縁膜１１０はもっと薄くてプレートの１０分の１から５分の１の厚さ、そして導電性銅電極層１１１は典型的には１０から５０ミクロンであるが、後者の範囲は厳密に限界が定められたものではなく、電気的に作動可能且つ製作に好都合で、歪伝達の効率を損なうか層割れ問題を生じさせるほどには厚くない有効範囲を表している。構造エポキシ１１４は、各層の電極１１１の間の空間を埋め、厚さは電極とほぼ同じなので、アッセンブリ全体で中実のブロックを形成する。スペーサ１２０は、どちらかというと非架橋性のポリマーのような弾性係数が低い比較的圧縮可能な材料で形成され、後に述べるように圧力硬化エポキシと共に使用されるときは、厚さが概ね圧電プレートまたは要素の積層と同じとなって、膜１１０の表面層と底面層の間の他の構成要素を囲んで縁結合を形成するのが望ましい。

【００４５】

製造の好適な方法には、層１１６が硬化する際にパッケージ全体に圧力をかける段階が含まれている。スペーサ１２０は、圧電プレートと、以下に図３から図５に関連して説明する回路要素を整列させるよう働き、硬化段階での組み立て中に僅かに圧縮されるフレームを形成し、その間にフレームは変形して応力又はでこぼこを残すことなく縁部をシールする。圧縮によりボイド部分がなくなり、高密度でクラックの無い中実媒体が形成されると共に、硬化熱は高水準の架橋を生じさせるので、結果的に強度と剛性が高まる。

【００４６】

図２Ａ、図２Ｂの実施形態に関わる組み立て工程は以下の通りである。それぞれに合計の厚さが０．０２５から０．０５０ミリメートルの銅被覆ポリイミド膜の１つ又は複数の部片を、最終的なアクチュエータパッケージ寸法よりも僅かに大きいサイズに切断する。膜の銅側はマスクされパターン形成され、圧電要素を導電性のリード及び所望のランド部又はアクセス端子と一体に接触させるための所望形状の電極を形成する。干し草用フォーク型の電極パターンを示しており、ここでは３つの尖叉が圧電要素の一方の面の中央と両側に接するように配置されているが、他の実施形態では、Ｈ型又は櫛型が使用されている。パターン化は、回路板又は半導体処理技術では馴染みのように、マスキング、エッチング及びその後の洗浄処理により行なわれる。マスキングは、フォトレジストパターン化、スクリーニング、テープマスキング、又は他の適した処理により行われる。従来の印刷回路板のようなポリイミド膜の各電極片は、回路要素又はアクチュエータシートの位置決めをするが、以下では、単純に「可撓性回路」と呼ぶことにする。しかしながら、本発明の方法と装置は、「可撓性回路」ではなくて、電極型の圧電要素、絶縁体、及び電気接点を使うことも想定している。

【００４７】

次に、厚さが電極箔層とほぼ同じか又は僅かに厚い未硬化のシートエポキシ材料を切断し、随意的に、組み立て時の電気的接触を高めることができるように電極パターンと整合する貫通開口を設けて、各可撓性回路上に配置し、可撓性回路に接着して電極形成部分の間とその周囲に平坦化層を形成する。次に、可撓性回路に取り付けられたエポキシ層から裏当てが除去され、事前に裁断されたスペーサ１２０が可撓性回路の角部と縁部に配置される。スペーサは、電極面上方に伸びるフレームの輪郭を描き、次の組み立て段階で圧電要素を嵌合する１つ又は複数の窪みを画定する。次いで、単数又は複数の圧電要素が、スペーサにより画定された窪みに配置され、第２の電極膜１１１、１１２が、それぞれの平坦化／結合層１１４と共に要素上の定位置に置かれ、圧電要素の頂部の電極接点が形成される。幾つかの曲げアクチュエータ構造の場合のように、デバイスが数層の圧電要素を有する場合、電極膜と圧電プレートが１枚増える毎に上記組み立て段階を繰り返すが、中間シートの上下両側でアクチュエータ要素と接触することになる中間電極層を形成する場合には、両面が被覆されパターン化されたポリイミド膜を使用できる点に留意されたい。

【００４８】

一旦、全ての要素が配置されると、パターン付けされた可撓性回路、圧電シート、スペーサ、及び硬化性のパターン付けされたエポキシ層の完全なサンドイッチアッセンブリが、

加熱プラテン間のプレス機内に配置され、温度と圧力を上げて、アッセンブリは剛性がありクラックの無いアクチュエータカードへと硬化される。図示の実施形態では、温度３５０°Ｆ、圧力５０－１００ｐｓｉで３０分間の硬化サイクルが使用されている。エポキシは、硬化温度が圧電要素の分極防止温度より低く、それでも高水準の剛性を達成できるように選択される。

【００４９】

上記構造は、１枚の圧電プレートを電極形成された２枚の膜の間に挟み、プレートが薄膜を通してアクチュエータカードの表面に剪断歪を効率的に伝えるようにした、単純なアクチュエータカードを示している。剪断弾性係数を層厚の二乗で割って求める伝達効率の尺度は、ここではガンマ（Γ）で表しているが、これは、エポキシ１１４、ロール状箔電極１１１、及びポリイミド膜１１０の弾性係数と厚さに依存する。エポキシと銅電極層が１．４ミル厚で、エポキシの弾性係数が０．５×１０^{6}である代表的な実施形態では、ガンマは凡そ９×１０^{10}ポンド／インチ^{4}となる。０．８ミル箔のより薄いエポキシ層と膜を使用すれば、実質的にΓは高くなる。一般的に、電極／エポキシ層のガンマは５×１０^{10}ポンド／インチ^{4}よりも大きく、一方、膜のガンマは２×１０^{10}ポンド／インチ^{4}よりも大きい。

【００５０】

なお、厚さ１０ミルのＰＺＴアクチュエータプレートを使用して、ＰＺＴプレート２枚を重ね３枚の可撓性回路電極付き膜層（真ん中は、両方のプレートに接触させるため両面被覆）付としたカードでは、合計厚さが２８ミルとなり、プレートだけの場合より４０％しか厚くならない。質量でいえば、アクチュエータ要素の重量がアッセンブリ全体の重量の９０％を占める。一般的には、他の構成では、プレートはパッケージ厚さの５０％から７０％を占め、質量の７０％から９０％を占める。この様に、アクチュエータ自体は、理論的性能に近いモデルを実現する。この構造は、単シートの積層又はアレイと同じく（上記）ベンダーを実装する場合の高い汎用性も提供する。

【００５１】

本発明に従って作られたアクチュエータの有用な別の性能指標として、アクチュエータ歪ε対自由圧電要素歪Λの比率が高いことがあるが、これは上記の２層の実施形態では凡そ（０．８）であり、一般的には（０．５）より大きい。同様に、パッケージ対自由要素曲率比Ｋは、上記構造では凡そ０．８５－０．９０で、一般には０．７より大きい。

【００５２】

こうして、全体的には、圧電要素を可撓性回路に埋め込んで構造化することによるパッケージ化は、重量及び電気機械的動作特性の低下が５０％未満で１０％程度と小さいと同時に、その硬度及び他の重要な点に関する機械的作動範囲は十分に強化されている。例えば、基本要素にシートパッケージ化構造を加えることにより、得られるＫは下がるが、実用上、可撓性カード構造は圧電ベンダー構造となり、亀裂故障や他の機械的故障モードを発生することなく、大型プレート構造を製作し高い曲率で繰り返し作動させることができるので、全体として遙かに大きな変位が実現される。幾つかの図面では、このような強化された物理特性を実現できる各種構造を示している。

【００５３】

先ず、可撓性回路間に埋め込まれた電動アクティブ要素の構造は、予想可能な応答特性を備えた低質量統合型機械構造を提供するだけでなく、回路要素をアクチュエータカード内に又はカード上に組み込めるようにする。図２Ｃは、この型式の或るデバイス７０の上面図であり、領域７１、７３はそれぞれボード電動アクティブシートを保有し、中央領域７２は、バッテリ７５、平面パワー増幅器又は増幅器セット７７、マイクロプロセッサ７９、及び複数の歪ゲージ７８を含む回路又はパワー要素を保有している。他の回路要素８２ａ、８２ｂは、周辺部周りの回路導体８１の経路に沿う他の場所に配置されている。他の実施形態でのように、スペーサ１２０は、デバイスのレイアウトとシール縁を画定し、一方、電極１１１は、電動アクティブ要素をここでは内蔵型である処理又は制御回路に取り付ける。回路要素８２ａ、８２ｂは、デバイスがセンサーとして使用される場合には加重

用レジスタを備え、或いは、受動減衰制御を実行する場合には分路レジスタを備える。代わりに、それらは、キャパシタ、増幅器などのような、ろ過、増幅、インピーダンス整合、又は記憶装置要素としてもよい。どの場合でも、これら要素も電動アクティブプレート８４から離して配置される。構成要素は集合的に歪を感知し、感知された状態に応じて各種作動パターンを実行し、又は他の感知又制御タスクを行なう。

【００５４】

これより本発明のアクチュエータ態様に戻るが、図３は、大きさが約１．２５ｘ９．００ｘ０．０３０インチで、各４枚のプレートからなる圧電プレート２層で組立てられたアクチュエータパッケージ２００の上面図を示している。端タブ２１０ａを備えた矩形ポリイミドシート２１０には、相互に接続され、且つタブにつながっている１本のランナー２１１ａに接続されているＨ状の薄い銅線の格子の形をした電極２１１が配置されており、こうして圧電プレートを保持する４つの矩形領域それぞれに直に低インピーダンス接続部を提供している。

【００５５】

Ｈ型のスペーサ要素２２０ａ、２２０ｂ、又はＬ型の２２０Ｃは、角部を定め、圧電プレート２１６を位置決めするための矩形空間の輪郭を定めている。この実施形態では、後に詳しく説明するが、複数の隙間２３０が、隣接するＨ型又はＬ型スペーサの間に現われている。以下の説明から明らかなように、組み立て中に、アッセンブリ位置を定め圧電要素を受け入れる窪みを形成するために、粘着性の結合エポキシ層１１４上に容易に配置することができるので、これら小さい個別のスペーサ要素（Ｉ型、Ｔ型、Ｏ型のスペーサも好都合である）を使用することが促進される。しかしながら、スペーサ構造は、個別要素のこのような集合体に限定されるわけではなく、打ち抜きシート又はモールド成形シートとして形成された１つ又は数個のフレーム片として設け、全てを又は１つ又はそれ以上を、縁部又は回路要素の動作を保持するための窪みを配置し、及び／又はシールするように使ってもよい。

【００５６】

図５は、シートと電極と圧電プレートの３層それぞれの上面図を示しており、図５Ａは膜、導体、及びスペーサ／圧電層の概略的な積層順を示している。図示のように、スペーサ２２０と圧電プレート２１６は、電極層各対の間で単一の層を構成している。

【００５７】

図４Ａ及び４Ｂ（縮尺は合っていない）は、図３の“Ａ”と“Ｂ”で示す位置の垂直断面に沿う組立て済みアクチュエータの層構造を示している。図４Ａにより明瞭に示すように、エポキシシート２１４のパターン化された結合層は、各電極層２１１と同面であり、電極間の空間を満たしており、一方でスペーサ２２０ｃは、圧電プレート２１６と同面であり、実質的にプレートと同じ厚さであるか又はそれより僅かに厚くなっている。図示上は、圧電プレート２１６は、商業的には５から２０ミルの厚さで入手可能なＰＺＴ－５Ａセラミックプレートであり、電極２１１と接触するために各面を覆っている連続導電層２１６ａを有している。スペーサ２２０は、軟化温度が約２５０℃の幾分圧縮可能なプラスチックで形成されている。これにより、硬化温度における高い順応性が生まれるので、スペーサ材料は、組み立て工程中に僅かなボイド２１４ａ（図４Ａ）を充填することができる。図４Ｂに示すように、スペーサ間の隙間２３０（設けられている場合）は、結果的に開口部２１４ｂとなり、これにより硬化性結合層２１４から余分なエポキシを抜き、硬化工程時にはエポキシを充填する。同図に示すように、ある一定量のエポキシが電極２１１と圧電プレート２１６の間の膜２１５のパッチ内に流れ込む。電極２１１が大きく且つ連続して広がっているため、エポキシのこのパッチ状の漏れが、圧電要素との電気的接触を損なうことはなく、それが提供する追加の構造的連結により電極の層割れが防止される。

【００５８】

なお、図示の電極の配置では、それぞれ垂直に積層された対の圧電プレートは、互いに反対に作動し曲げを発生させるが、より多くの別々の電極を設けて異なる対のプレートを異なるように作動させてもよい。一般的に言えば、上記のように、本発明は、感知、制御、

及びパワー又は減衰要素全てを同一カード上に取り付けて、多くの別個の要素を異なるやり方で作動させる極めて複雑なシステムを考慮している。これに関して、カード自身の可撓性によって、カードを実際のタスクに適合させる際の柔軟性がさらに高まる。概括すると、厚さ３ミルのエポキシ帯片の可撓性に匹敵する追従的な可撓性を有しているので、損傷を受けずに曲げ、重ね、又は振動することができる。圧電要素が封入されていないその中心線ＣＬ（図３）の領域で鋭く曲がり、又は湾曲して、取り付け面又は角部に順応する。当該要素は、極性を付与されて面内又は面を横切る寸法を変え、従って、アクチュエータは、上記制御動作の何れかを行なうために、或いは、屈曲、剪断又は圧縮波の様な特定の波形又は特定の型式の音響エネルギー隣接する面に発射するために、効果的なやり方で隣接する面に歪を伝えるために取り付けられる。

【００５９】
図６は、別のアクチュエータ実施形態３００を示している。概略的に図示したこの実施形態では、エポキシ結合層、膜、及びスペーサ要素は示しておらず、作動機構を担う電極及び圧電シートしか示していない。電極の第１セット３４０と第２セット３４２は、両方とも同一層内に設けられ、それぞれ２つの櫛が互いに噛み合った櫛の形をしており、電気的動作の場は、一方の櫛の歯と他方の櫛の隣接する歯との間に設けられる。図６では、平行な一対の櫛３４０ａ、３４２ａが圧電シートを挟んで設けられ、櫛電極３４０は３４０ａにつながれ、櫛電極３４２は３４２ａにつながれ、等電位線“ｅ”が圧電シートを通って延び、異なる櫛の各対の歯の間に面内電位勾配ができるように、電界が設定される。図示の実施形態では、圧電セラミックプレートは金属被覆されていないので、直接的な電気接点が各櫛とプレートの間に作られる。プレートは、最初に櫛をまたいで高電圧を掛けて、面内方向に沿う方向に毎インチ１－２千ボルトを超える電界強度を作り出すことにより、面内で極化される。これにより、その後に２つの櫛電極にまたがる電位差がかかると面内（剪断）動作が発生するように、圧電構造が配向される。こうして、互いに噛み合った電極の直接接触により、圧電要素に、作動方向に概ね平行な電界が形成される。

【００６０】
剪断動作の他に、本発明の方法及び装置を使えば、指向性の動作と減衰を働かせることができる。例えば、図７に示すように、このようなアクチュエータ３００を２つ使って交差させると、ねじり動作を作り出せる。

【００６１】
上記実施形態を論じる際、電極／ポリイミド層を介して隣接する構造体に歪エネルギーを直接伝えることは、特出した新規性に富む利点として認識されてきた。このような動作は動作タスクに有用であり、又、翼型形状制御作動、及びノイズ又は振動打ち消し又は制御として多方面に有用である。図８Ａ及び図８Ｂは、アクチュエータの平坦（図８Ａ）及び半円筒形（図８Ｂ）実施形態６０の代表的な図を示しており、これらは平坦又は僅かに湾曲した表面及びシャフトそれぞれに対して用いられる。

【００６２】
しかしながら、これらアクチュエータの電気機械材料が歪エネルギー変換により作動するのに対し、本発明の用途は、アクチュエータ面を介する歪カプリングを超えて広がり、アクチュエータにより作用する動き、トルク又は力を全体として利用する多数の特別な機械的構造を含んでいる。これら実施形態それぞれにおいて、基本的な帯状またはシェル状にシールされたアクチュエータは、頑丈で弾力がある機械要素として使用され、長さに沿って１つ又はそれ以上の点でピン留め又は接続されている。図９に示すように、電気的に作動させると、帯片は、単独で或いは他の要素と共に、自己動作レバー、フラップ、リーフスプリング、スタック、又はベローズとして機能する。図９（ａ）から図９（ｑ）の図では、要素Ａ、Ａ’、Ａ”．．．は、上記図中に示すような帯片即ちシートアクチュエータであり、小さな三角形は、例えば構造体に対する固定取り付け点又は接続点に対応する固定位置又はピン留め位置を示している。矢印は、動き又は動作の方向、或いはこのような動作に関する接点を示し、一方Ｌはアクチュエータに取り付けられたレバー、Ｓはスタック要素又はアクチュエータを示している。

【００６３】
スタック、ベンダー、又はピン留めベンダーとしての図９（ａ）から図９（ｃ）の構成は、多くの従来型アクチュエータに置き換えることができる。例えば、カンチレバービームは、針を支えて高度に制御された単軸変位を提供して、ペンプロッタの高度に線形で大きな変位位置決め機構を構成することができる。特に興味深い機械的特性及び作動特性は、多重要素構成９（ｄ）以下から期待でき、それは或るシート範囲を有し機械的に頑丈なアクチュエータを利用している。このように、図９（ｄ）及び図９（ｅ）に示すように、ピン対ピンベローズ構成は、カメラの焦点合わせのような用途の場合の単純な面接触移動による広範且つ精密な単軸Ｚ移動位置決めにとって有用であり、又は流体に対する全面軸受の動きを利用することによる蠕動型ポンプの実施に有用である。図３に関連して指摘したように、可撓性回路はコンプライアンスが高いので、ヒンジ付き又は折り畳み型の縁部は、図３の中心線のような位置に沿って単に折り曲げるだけで作ることができ、少数の大型多重要素アクチュエータユニットで密閉ベローズアッセンブリを作ることができる。可撓性回路構造なので、アクチュエータ要素の帯片又はチェッカーボードは、隣接する要素の対と対の間に折り畳み線を付けて配置することができ、この折り畳み線は、硬化処理段階の間に、輪郭付けられた（例えば、ワッフルアイロン）プレスプラテンを使って薄く刻印することができる。この様な構造を使えば、全体に継ぎ目のないベローズ、又は他の折り畳み型アクチュエータを、１つの可撓性回路アッセンブリから作ることができる。
【００６４】
上記のように、圧電要素は、剛性の高いセラミック要素である必要はなく、可撓性回路をセンサーとしてのみ使用する場合、セラミック要素、又はＰＶＤＦのような軟らかい材料の何れも使用できる。ポリマーの場合には、要素を連結するのに、硬い硬化性エポキシ結合層ではなく、薄くてしなやかな低温接着剤を使用する。
【００６５】
本発明の或る実施例を下に例示する。
【実施例１】
【００６６】
本例において、振動制御システムは、ガントリのアクティブ制御システムの機能的要件の或るパラメータを求めるために設計された。定義された機能的要件には以下のものが含まれる（が、それらに限定されるわけではない）。
・精度
・整定時間
・アクチュエータ及びセンサーの質量、大きさ、及び位置
・パワー
・ピーク歪
・寿命
・温度範囲
・湿気及び溶剤への露出
・費用
・現行のガントリ制御システムとのインタフェース
【００６７】
作動中のガントリの構造的応答に関するデータを収集するために、ガントリには圧電歪センサーと加速度計のアレイを装備した。圧電アクチュエータの配置と寸法決めには正確な歪モード形状情報が必要で、それはこのデータから得て有限要素モデル（ＦＥＭ）と比較した。プロジェクトのこの局面で得られた１片の重要な情報は、力学上の異なるヘッド位置の影響を包含するものであった。アクチュエータ設計と全ての制御ソフトウェア設計の両者は、振動制御が適用される時期、即ちヘッドがガントリに沿って移動している間、及び／又はヘッドがガントリ上の任意の位置に停止した後、によって左右された。
【００６８】
摩擦ブロックを定位置に設けた場合とそうでない場合の両方についてデータを捕捉し、摩

擦ブロックを電動アクティブ振動制御システムに完全に置き換えた場合について、少なくとも可能性の分析的評価ができるようにした。

【００６９】

上記で得たデータを有限要素モデル化情報と併用して、システムレベルの設計を行なった。この設計には、アクチュエータ配置、センサーの型式、及び制御アルゴリズムの型式を含むシステムアーキテクチャを選択することが含まれた。上記のように、ガントリ力学に大きな影響を有する移動ヘッドにより、電動アクティブ振動制御システムの有効性は、動作制御システム内で使用可能な軌道情報を作成することによって改善された。この情報は、動作コントローラの回路の適切な位置に取り付けた単純なクリップリードで、動作制御システムに中継してもよい。例えば、容易にアクセスできることが多いモーター電流のプロットの様な情報を、振動制御システムに提供するようにしてもよい。

【００７０】

システムアーキテクチャを選択した後、振動制御の制御アルゴリズムを設計するため、及びその性能をシミュレートするために、システムの分析的「入力／出力」モデルを開発した。本システム設計は、コンプライアンスを確保するために機能的要件と比較された。この分析は、制御システムの各種構成要素、特にアナログセンサー信号調整電子機器、デジタル信号プロセッサ（ＤＳＰ）ベースの制御装置、及び電動アクティブアクチュエータに必要な電圧と電流を提供するために使用されるパワー増幅器、に関する仕様を定義するのに供された。

【００７１】

次いで、各種電子機器構成要素を始めとする、電動アクティブ振動制御システムの各構成要素を設計した。電動アクティブアクチュエータ自体は、本願に明らかにした方法を使って製作した。各アクチュエータは標準的な品質制御法を使ってテストした。システム設計業務で考案した仕様に従って、全ての電子機器を製作し機能性とコンプライアンスについてテストした。

【００７２】

設計の重要な態様には、アクチュエータとセンサーをガントリと一体化することが包含されていた。例えば、所与のガントリについて、ガントリに沿うヘッドの動きと干渉が起こらないようにするため、０．５ｍｍのアクチュエータ厚さが決められる。次いで、ガントリ上のアクチュエータとセンサーを電子設備に接続するのに使用されるケーブルの型式を決定した。

【００７３】

この特定の例では、自動化されたＳＭＴ電子機器コレクト・アンド・プレース設備のガントリには、アクチュエータ、センサー、電子機器を装備し、プレート要素つきのＦＥＭを使って分析した。基本的なコンセプトを、図１０のブロック図に示すが、これには、ガントリに貼り付けた電動アクティブ歪アクチュエータ及びセンサーと共に、振動低減を行うために必要なパワー、信号、及びデジタル制御電子機器が含まれている。本研究の目的に限り、ヘッドはガントリの端部に固定されるものとした。アクチュエータの設置は真空貼り付け手順を使って行なった。

【００７４】

次いで「オープンループ」テストを行なった。オープンループテストは、信号をアクチュエータに注入してガントリの応答を測定し、この研究で先に行なった分析的モデル化を実験的に確認することを含んでいる。このテストは、ガントリとヘッドを静止させた場合と、ある「標準的な」軌道に沿って移動させた場合について行なった。ガントリ及びヘッド動作コントローラから振動制御システムに送られた（複数の）信号も、上記テスト中に測定した。電動アクティブアクチュエータは、振動の第１自然モードで最大歪エネルギーを有するガントリの表面積の１０％以上に亘って分散配置した。振動の最初の３モードの励起時における、アクチュエータ分散の有効性は、設計ソフトウェアを使ってモデル化した。全ての歪エネルギーの８０－８４％はプレート要素内にあり、プレートエネルギーの６２－７５％は伸び歪であるので、表面に貼った電動アクティブ制御装置によって補足する

ことができる。従って、モード内の歪みエネルギーの少なくとも５２％が利用可能である。このエネルギーの幾らかは、移動ヘッドのフレーム／サポート内にある。図１３に示すように、伸び歪エネルギーを、所与量の電動アクティブ要素の性能を最大化するためにソートした。

【００７５】

構造モデルに減衰機能を加えた。ハンマーによる衝撃後のヘッドの加速度対時間をプロットしたところ、摩擦ブロックを定位置に配置した場合の第１モードで臨界減衰凡そ５％であることが示された。

【００７６】

標準的な線形二次調整器（ＬＱＲ）方式を用いてフィードバック制御を設計し、圧電作動制御電圧がアクチュエータ装置の限界を超えることのないようにした。閉フィードバックループ内の作動電圧は、ガントリの動きに伴う入力妨害力に比例する。ここで、ガントリは、ｙ方向（ガントリ軸に対し横向き）に、最大速度３ｍ／ｓに至るまで、一定の２５ｍ／ｓ^{2}で加速するものと仮定した。１０ｋｇの質量に対応付けられたダランベール慣性力をヘッドの重心にかけた。この質量は、５ｋｇのヘッド質量に有効ガントリ質量５ｋｇを加えたものであった。

【００７７】

次いで、振動を制御したシステムの周波数及びタイムドメイン応答をシミュレートした後、減衰及び整定時間の改善を求めた。周波数応答は図１１にシミュレートしているが、ピック・アンド・プレースヘッドの下側の点でｙ方向に測定した。単位入力に対する動的応答の低減が、本図から明らかである。図１１並びに表Ｉに示すように、モード１閉ループ減衰は約１２％、モード２閉ループ減衰は約１１％、モード３閉ループ減衰は約１０％であった。同一点同一方向での時間応答を図１２にシミュレートしている。このシミュレーションは、電動アクティブ制御によって整定時間が劇的に短縮することを示している。この様に、非常に少ない付加質量で非常に効果的な制御を実現することができる。

【００７８】

表Ｉ：ガントリの構造力学パラメータ

モード	詳細	周波数（Ｈｚ）	固有の減衰比（対臨界％）	圧電制御有りの場合の減衰比（％）
１	ガントリ軸周りのねじり	４６	５	１２
２	ｘｙ（走査）面内の曲げ	９３	５	１１
３	曲げ／ねじり連結	１３６	５	１０

【００７９】

ＦＥＭからガントリ／ヘッドの構造力学特性を表Ｉに示す。ここで設計された代表的なアクチュエータ分散は、厚さが０．５ｍｍで、面積が３３０ｃｍ^2、質量は１００ｇ未満であった。これも表Ｉに示す閉ループモデル減衰は、分析に含まれる全３モードの振動に関して、摩擦ブロック付のガントリに固有と仮定された５％値の少なくとも２倍である。この様に、振動振幅及び整定時間は著しく低減した。

【００８０】

図１４及び図１５に示すように、振動制御システムは、周波数応答及びゲイン制御に変化を誘発した。この研究では、減衰は１桁以上増えた。この増加は、数１０倍の配置精度増に相当する。

【００８１】

開ループテストに引き続いて、データを分析し、最終的な制御アルゴリズム設計を実行した。必要に応じ、アクチュエータとセンサーハードウェアは、機能的要件を伴うコンプライアンスを確保するよう変更してもよい。次いで、最終的な電動アクティブ振動制御システムの「閉ループ」テストを行なうことになる。閉ループテストは、一般的に、アクチュ

エータが少なくとも部分的にはセンサーで作られた信号によって駆動されている時に行う。
【００８２】
この研究は、ガントリの効果的且つ能動的な電動アクティブ振動制御が可能であることを実証した。
【実施例２】
【００８３】
本発明による振動制御システムをリソグラフィー機に使用した。図１６は、レーザー測定学システムにより記録されたエラー信号のパワースペクトル密度を示しているが、図示のように、振動制御システムの使用によって、７５から１２５Ｈｚの帯域ではシステム応答に３倍の低下が見られた。振動制御システムを使用したピークの低下は、従来の方式を使用して５０Ｈｚと２２５Ｈｚでのピークを下げた後、システムの画像ボケを２～３倍抑えると期待できるはずである。代わりに、ある事例では、振動制御システムは、５０Ｈｚ又は２２５Ｈｚ又は他の周波数でピークを下げるために使用できる。画像ボケを抑えることにより、製作システムは、より微細なトレース寸法及び造形サイズを作ることができるようになり、造形配置の精度も改善される。
【００８４】
本発明の実施形態及び例についての上記説明は、本発明を適用する構造の範囲を実証するために提示したものである。当業者には理解頂けるように、本発明の精神及び範囲を逸脱することなく、上に述べた本発明について多くの修正及び変更を加えることができる。
【００８５】
ここに論じた本発明の追加的態様は、６自由度のリソグラフィー工具のウェーハステージを能動的に安定化する（その動作を制御する）ことに関している。図２２は、ウェーハステージ基部５０１とウェーハステージ５００の一例的な簡略化された２次元物理モデルを示している。このコンセプトは、３次元が関係する実際のシステムに対して容易に一般化される。
【００８６】
ステージと基部の質量はほぼ同じで、それぞれ約２００ｋｇである。ウェーハステージ基部は、長さ約１ｍｘ幅約１ｍｘ厚さ約０．１５ｍである。ウェーハステージは、長さ約１．２５ｍｘ幅約０．５ｍｘ厚さ約０．５ｍである。アクチュエータ（モーター）入力は符合u_iで表され、ｉは特定のボイスコールモーターを表す。線形圧電セラミックモーターを含む代わりのアクチュエータも考えられる。センサー出力はy_iで表され、ｉはボイスコイル入力と関連するレーザー変位測定値を表す。本例では、代わりの出力センサー（線形可変変位トランスジューサ（ＬＶＤＴ）、加速計を含む）及びセンサー位置（ほぼ同配置、十分に同配置）も考えられる。システムに対する妨害（d_iにより表される）には、オンボード妨害（モーター、ファン、フリーバランス・アームを含む）とオフボード妨害（地面振動、気流、熱変動を含む）が含まれる。
【００８７】
ウェーハステージ５００は、空気軸受から成る空圧システム５０２によりウェーハステージ基部上に支持されている。ウェーハステージ５００をウェーハ基部ステージ５０１に対してほぼ摩擦なしに移動できるようにするために、空気軸受が設けられている。ウェーハステージ基部５０１は、エアマウント５０３、５０４の空圧システムによって地面上に支持されている。エアマウントの物理的特性は、ばね（ｋ１）とダッシュポット（ｃ１）により表される。空気軸受の物理特性は、ばね（ｋ２）とダッシュポット（ｃ２）により表される。空圧システム５０３及び５０４は、ウェーハステージ５００とウェーハステージ５０１の地面に対する重量を相殺する。空圧システム５０３及び５０４は、ウェーハステージ基部５０１の沈下と傾きに関する低周波数（概ね数ヘルツ）制御を行う。加えて、基部ステージ５０１の高周波数制御が、ボイスコイルモーターＵ１、Ｕ２により行われる。通常、マイクロプロセッサシステム５１０を使用して、出力を感知し、マイクロプロセッサシステム５１０により実行される制御アルゴリズムの関数として入力を指示（操作）す

る。システム５１０は、リソグラフィーシステム要件に基づいて、ウェーハステージ基部５０１に対してウェーハステージ５００を移動し又は位置決めしようとする。例えば、リソグラフィーシステムでは、ウェーハ上の画像を露光する間、ウェーハステージ５００の一定の走査動作を行う必要がある。代わりに、リソグラフィーシステムは、ウェーハステージを別の位置に配置し直すため、ウェーハステージ５００の急激な加速を指示するかもしれない。ウェーハステージ５００は、速度、精度、及び／又は整定時間の要件に合致するようにこれらの移動を行なうことが要求されることになる。整定時間とは、絶対位置に対し或る許容ばらつき内で所与の位置を実現するのに要する時間をいう。（２ｇまでもの）非常に高加速度で上記所定の動作をすることにより、基部に伝達される大きな反力が発生する。更に、上記動作は、基部ステージシステムの重力の複合中心の位置を高速で変化させる。現在では、基部安定化制御は、６つの独立した単入力単出力（ＳＩＳＯ）コントローラを実装することを通してマイクロプロセッサ５１０によって実現される。通常、ＳＩＳＯコントローラは、特定の用途で各自由度毎に１つ使用される。典型的な３次元システムは、各独立制御式システム構成要素又はステージ毎に、６自由度を持つことができる。ＳＩＳＯコントローラは、基部に対するステージ位置の変動に影響されやすい。これは、個々のコントローラには付加的な出力情報が与えられないからである。或る実施形態では、ここに説明する発明は、多重入力多重出力コントローラ（ＭＩＭＯ）を使用して、基部に対するステージ位置の変動があっても、ＳＩＳＯ実装のものよりも良好な性能を実現する。ＭＩＭＯ実装のものでは、制御は、２つ以上のセンサー（出力）とアクチュエータ（入力）の出入力を知って実行される。更に、ＭＩＭＯ制御アーキテクチャを使えば、線形二次ガウス（ＬＱＧ）、Ｈ無限、及びミュー合成を含む現代の制御技術を実行することができるが、これらに限定されるわけではない。上記技術は、ＳＩＳＯアーキテクチャとは効率よく組み合わせることができない。

【００８８】

図２３は、ＭＩＭＯコントローラが、如何に巧くロールモメントに対する指示された入力（ステージピッチ妨害）に追従することができるか（ＡＣＸロールモーメントコマンドにより示す）を、ＳＩＳＯ制御装置の典型的な性能（名目上のロールモーメントコマンドにより表される）と比較して示している。このように、妨害力に対し非常に素早く反応することができ、妨害力をシステムから排除する。これは、ステージの速度、精度、又はスループットの或る種の組み合わせを改善する。

【００８９】

リソグラフィーシステムにおけるステージ制御用途の別の実施形態では、システムが指示された位置を正確に追跡するための整定時間を短縮することが望まれていた。図２４は、その実施形態を説明するブロック図である。この実施形態では、３つの加速度計６００、６０１、６０２をフィードバック制御用のセンサーとして使用している。加速度計６００及び６０１は、ｘ軸方向の加速度を測定する加速度計を表している。加速度計６０２はｙ軸方向の加速度を測定する単一の加速度計を表している。概ね加速度に比例するこれらの測定値は、信号コンディショナ６０６に送られ、信号コンディショナ６０６は信号をバッファして、ステージの加速度に概ね比例した信号をシングルボード・コンピュータ６０７に送る。代表的なシングルボード・コンピュータは、カリフォルニア州シミバレーに事務所を置くＩｎｎｏｖａｔｉｖｅ　Ｉｎｔｅｇｒａｔｉｏｎ社により供給されているモデルＳＢＣ６７である。このプロセッサは、高性能自立型デジタル信号プロセッサ・シングルボード・コンピュータであり、アナログ入出力能力を特徴としている。電圧信号６１２ａ、ｂ、ｃは、アナログ入力に入力される。これらアナログ入力は、次いで、デジタル信号に変換され、それに対してプロセッサは制御アルゴリズムを提供してフィルターを掛ける。このアルゴリズムは、デジタル信号のセットを作成し、それが次いでアナログ出力信号６１３ａ、ｂ、ｃ、ｄに変換される。これら出力信号は、次に４つのモーター６０８、６０９、６１０、６１１それぞれに適用される。モーター６０８と６０９は、ステージのｘ軸方向の位置を制御するｘ軸モーターである。モーター６１０と６１１は、ステージのｙ軸方向の位置を制御するｙ軸モーターである。Ｘ軸干渉計６０３とＹ軸干渉計６０４を使

用して、ステージの基部に対するステージのｘ及びｙ方向の位置を測定する（簡潔性を期して図示を省略している）。
【００９０】
フィルタ（フィードバック制御アルゴリズム）は、標準的な線形二次調整器方式を使用して設計し、モーター制御信号がモーター又はモーター増幅器限界を超えないことを保証することができる。閉フィードバックループにおけるモーター制御信号は、ステージの加速度に関連付けられた加速度計６００、６０１、６０２の信号に比例している。制御設計は、先ず、マサチューセッツ州、ケンブリッジに事務所を置く、Ａｃｔｉｖｅ Ｃｏｎｔｒｏｌ Ｅｘｐｅｒｔｓ社から市販されているＳｍａｒｔ ＩＤ[TM]システム識別ソフトウェアパッケージを使って、伝達関数データから状態対空間プラントモデルを作成することにより行った。フィルタ（又はコントローラ）は、Ｆａｎｓｏｎ及びＴｈｅ Ｃｏｎｔｒｏｌ Ｈａｎｄｂｏｏｋ，Ｗｉｌｌｉａｍ Ｓ．Ｌｅｖｉｎｅ，Ｅｄｉｔｏｒ，ＣＲＣ Ｐｒｅｓｓ，１９９６年に論じられている技術のコンピュータシミュレーション及び応用を使って設計した。
【００９１】
図２５及び２６は、この実施形態に適用されたＭＩＭＯ制御の実験的及び分析的結果を表している。ＭＩＭＯの結果を、代わりに複数のＳＩＳＯループを利用した場合の結果と比較している。図２６は、０．１５ｓと０．３０ｓの間の期間を拡大したときの結果を示している。本図は、ＭＩＭＯ制御が、約０．１９ｓで整定範囲内（概ねグラフのｙ軸上の１００）に落ち着くが、ＳＩＳＯ（現行のコントローラ）は、この性能に達するのに、約０．２６ｓも要することを示している。これは、整定時間が約３０％改善されていることを示している。
【図面の簡単な説明】
【００９２】
【図１Ａ】典型的な先行技術によるアクチュエータのシステム図である。
【図１Ｂ】本発明による２つのシステムの対応図の１つである。
【図１Ｃ】本発明による２つのシステムの対応図の１つである。
【図２Ａ】本発明による基本的なアクチュエータ又はセンサーカードの上面図である。
【図２Ｂ】本発明による基本的なアクチュエータ又はセンサーカードの断面図である。
【図２Ｃ】回路要素を備えたアクチュエータ又はセンサーを示している。
【図３】別のカードを示している。
【図４Ａ】図３のカードの断面図である。
【図４Ｂ】図３のカードの断面図である。
【図５】図３のカードの層構造の詳細を示した図である。
【図５Ａ】図３のカードの層構造の詳細を示した図である。
【図６】面内動作用のアクチュエータパッケージ櫛電極を示している。
【図７】図６のカードを使用したねじりアクチュエータパッケージを示している。
【図８Ａ】表面上に表面実装アクチュエータとして取り付けられたアクチュエータを示している。
【図８Ｂ】ロッド上に表面実装アクチュエータとして取り付けられたアクチュエータを示している。
【図９】機械要素として取り付けられたアクチュエータを示している。
【図１０】ガントリ用の電動アクティブ振動制御システムの実施例のブロック図である。
【図１１】電動アクティブ振動制御がある場合とない場合につき、ガントリの先端のコレクト・アンド・プレイスヘッドの周波数応答のシミュレーションを示した図である。
【図１２】電動アクティブ制御がある場合とない場合につき、コレクト・アンド・プレイスヘッドの時間応答のシミュレーションを示した図である。
【図１３】伸び歪エネルギー集中を示した図である。
【図１４】本発明による振動制御システムを有するピック・アンド・プレイス機の周波数応答に関する閉ループテストの結果を示した図である。

【図１５】本発明による振動制御システムを有するピック・アンド・プレイス機のゲイン制御に関する閉ループテストの結果を示した図である。
【図１６】リソグラフィー機のレーザー測定システムにより記録されるエラー信号のパワースペクトル密度を示す図である。
【図１７】製作システムで使用される、本発明の異なる実施例を示した図である。
【図１８】製作システムで使用される、本発明の異なる実施例を示した図である。
【図１９】製作システムで使用される、本発明の異なる実施例を示した図である。
【図２０】製作システムで使用される、本発明の異なる実施例を示した図である。
【図２１】製作システムで使用される、本発明の或る実施例を示した図である。
【図２２】ウェーハステージとウェーハステージ基部の単純化した２次元物理モデルを示す図である。
【図２３】コントローラの結果を示した図である。
【図２４】ステージ制御のブロック図である。
【図２５】実験と分析の結果を示した図である。
【図２６】実験と分析の結果を示した図である。

【図１Ａ】

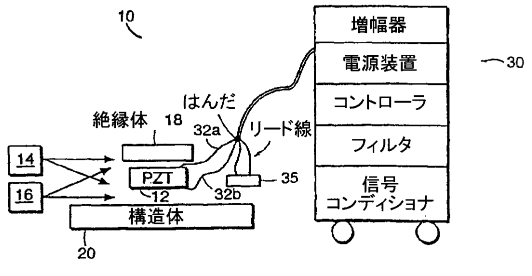


FIG. 1A
(先行技術)

【図１Ｂ】

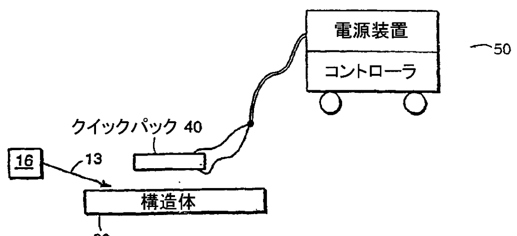


FIG. 1B

【図１Ｃ】

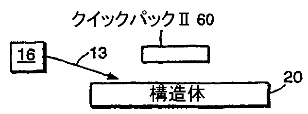
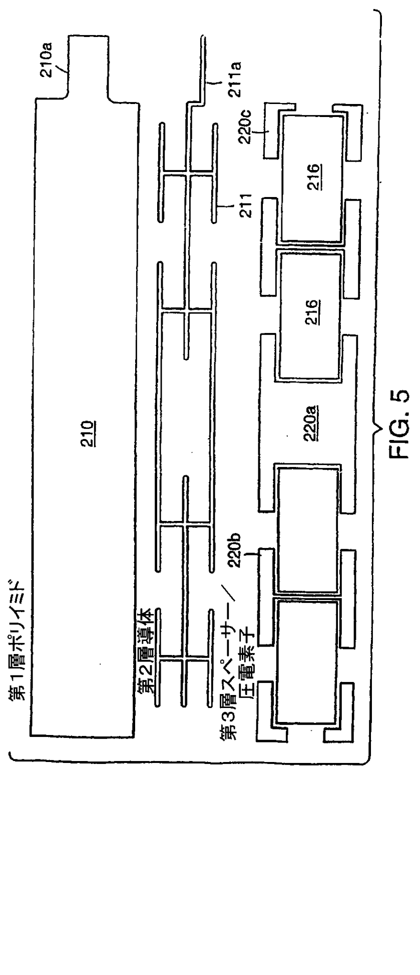


FIG. 1C

【図５】



【図９Ｉ】

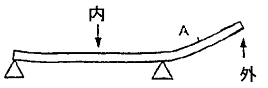


FIG. 9I

【図９Ｊ】

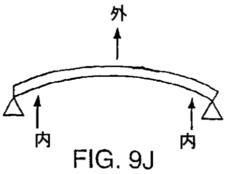


FIG. 9J

【図９Ｋ】

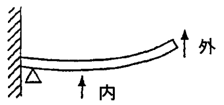


FIG. 9K

【図９Ｌ】

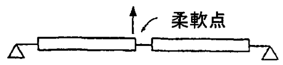


FIG. 9L

【図１０】

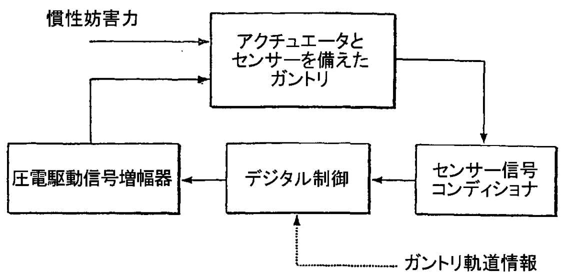


FIG. 10

【図１１】

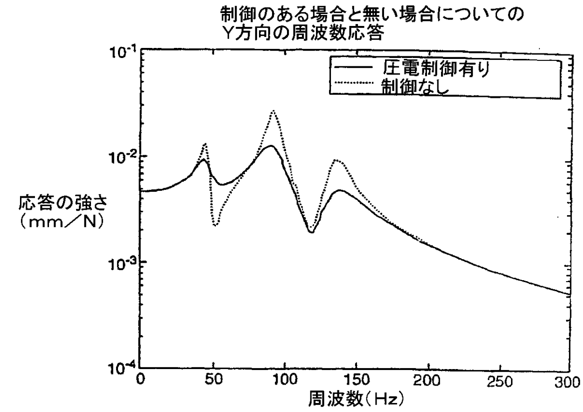


FIG. 11

【図１２】

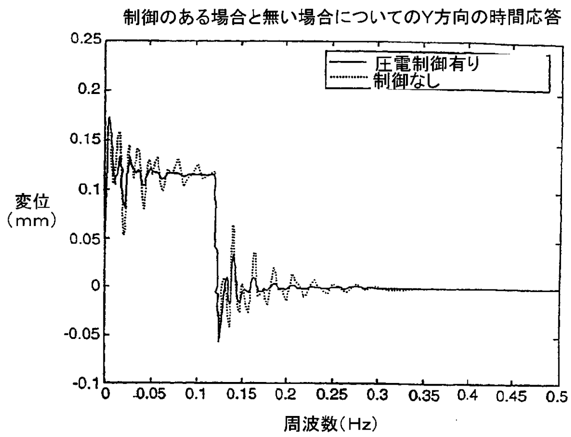


FIG. 12

【図１３】

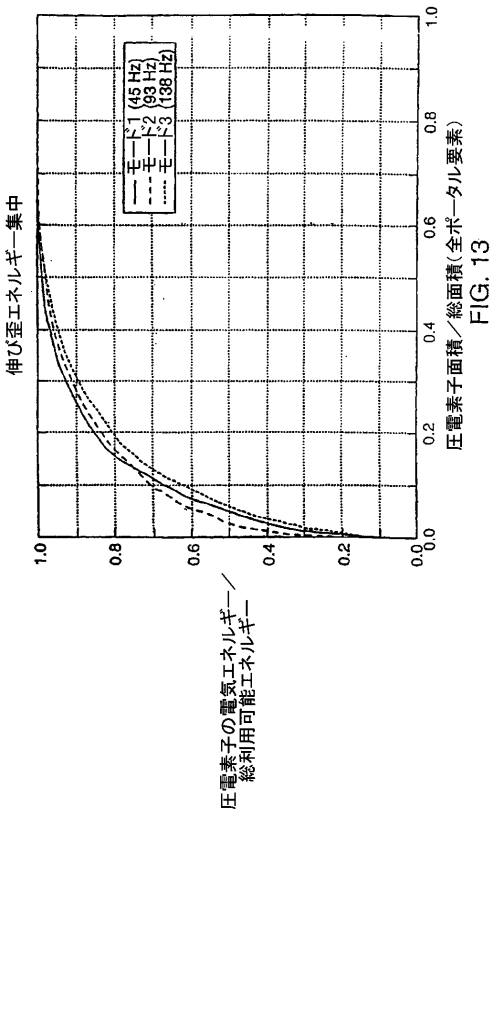


FIG. 13

【図１４】

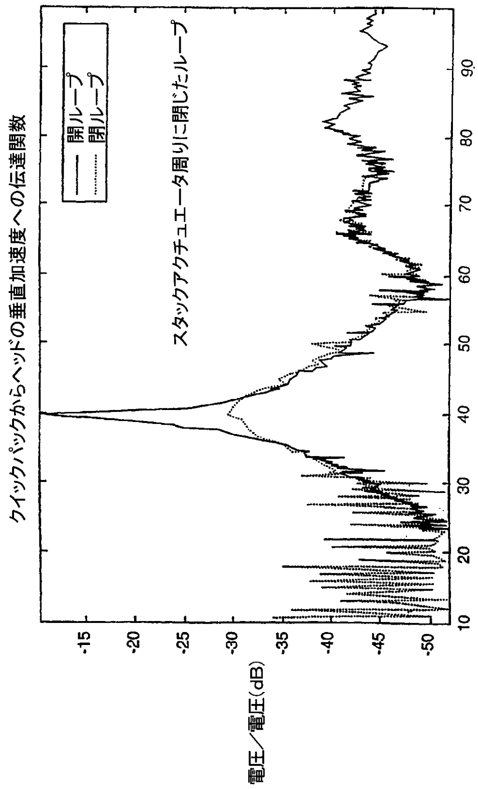


FIG. 14

【図１５】

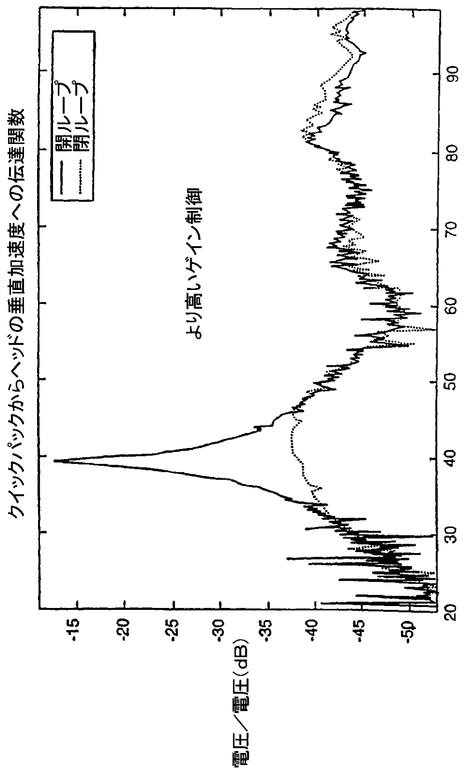


FIG. 15

【図１６】

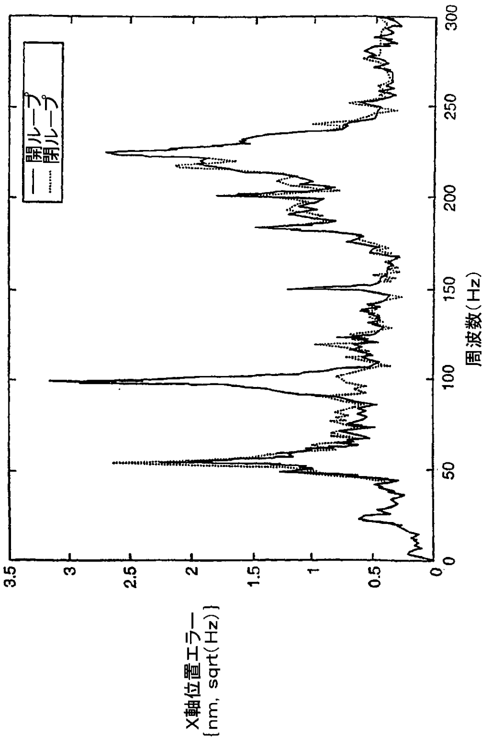


FIG. 16

【図２１】

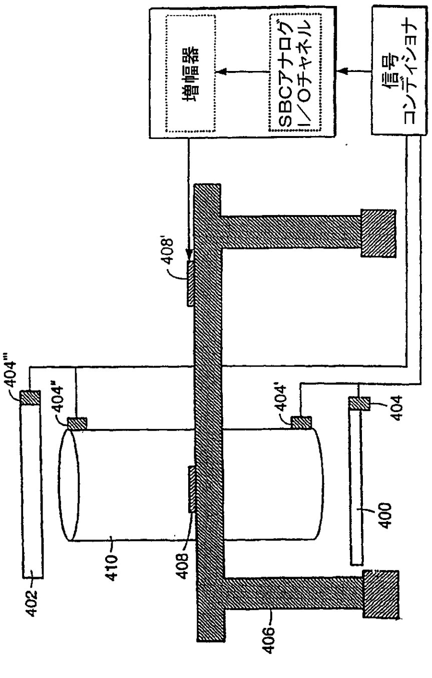


FIG. 21

【図２２】

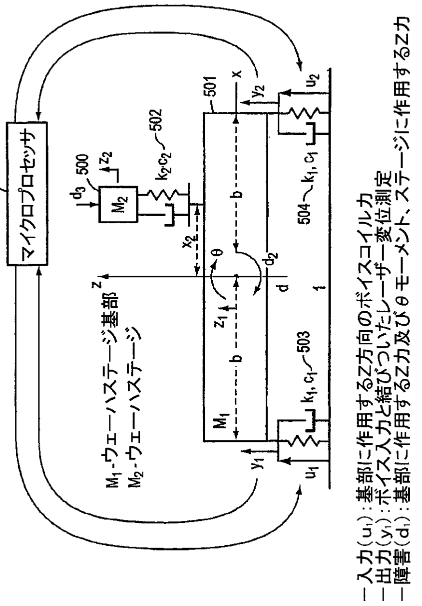


FIG. 22

【図２３】

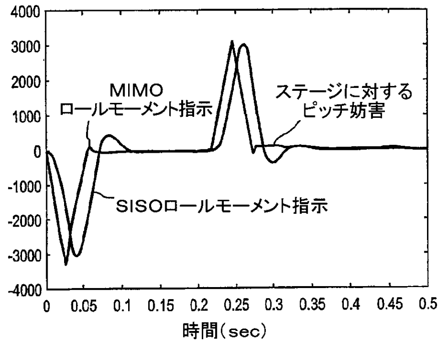


FIG. 23

【図２４】

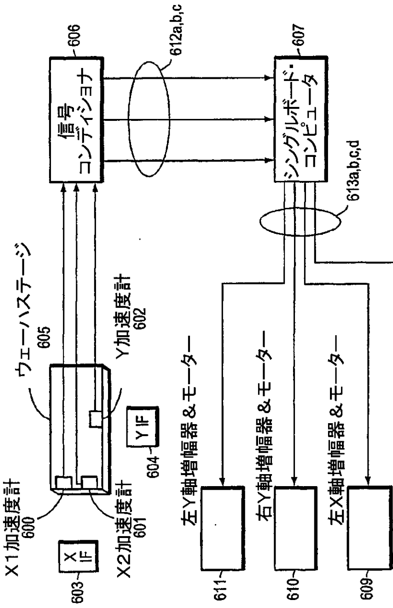


FIG. 24

【図２５】

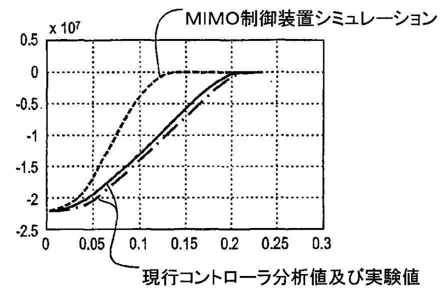


FIG. 25

【図２６】

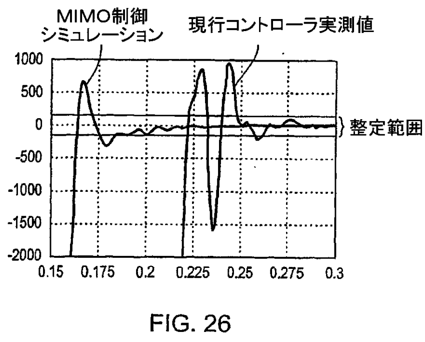


FIG. 26

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(54) Title: METHOD AND DEVICE FOR VIBRATION CONTROL

(57) Abstract: A vibration control system comprising an actuator, and a sensor useful for controlling vibrations in systems for fabricating electronics equipment. The actuator may comprise one or more plates or elements of electroactive material bonded to an electroded sheet.

METHOD AND DEVICE FOR VIBRATION CONTROL

Related Applications

This application claims the benefit of U.S. Application No. 09/803,302, filed March 9, 2001.

Background of the Invention

In the competitive marketplace which exists for automated surface-mount (SMT) electronics equipment, including systems for fabricating electronics equipment or components, improvements in accuracy and speed are a significant advantage. Such equipment is often used in fabricating, for example, semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices, and may feature multiple gantry/head assemblies, linear motors, photoimaging systems, etching systems, and/or a number of other technologies. The present invention relates to devices and methods for reducing vibration inherent in such equipment during operation thereby to improve the speed and/or accuracy of such equipment.

For example, modern photolithography tools require extremely high exposure accuracy. This can only be achieved if the levels of elastic displacement at crucial points in the tool do not exceed several nano-meters. Since lithography tools contain numerous moving parts such as the reticle and wafer stages, they are subject to persistent disturbing forces acting on their structure. Moreover, the tool structure is subject to environmental disturbances such as floor vibrations and air turbulence. While the level of these disturbances can be reduced, they cannot be eliminated in their entirety.

There are a number of existing techniques employed to limit the elastic vibration of lithography tools. For example, the stiffness of the structure that supports key elements such as the lens assembly may be increased, tuned mass dampers may be used, the signals applied to the moving stages may be shaped, or the floor vibrations may be isolated using actively controlled air springs. While effective in reducing elastic vibration, these methods often do not meet the stringent requirements of more advanced photolithography tools.

Current efforts to control vibration on SMT placement equipment include placing frictional damping device at the end of the gantry. This "friction block" serves mainly to stabilize the gantry and head trajectory control system, but it also has been shown to reduce the settling time during certain pick and place operations. However, the effectiveness of the friction block depends on precise tuning of the normal force (or pre-load). The friction block tends to wear out quickly, greatly reducing its effectiveness and contaminating the rest of the machine with particles. Moreover, the friction block works against rigid body movement, resulting in slower operation of the equipment. The vibration control system of the present invention, which comprises an actuator assembly, serves to replace the friction block entirely while improving settling time, or, alternatively, to operate in conjunction with the friction block, providing additional accuracy or speed of operation.

One aspect of the present invention relates to actuator elements useful for active vibration reduction, structural control, dynamic testing, precision positioning, motion sensing and control, and active damping. Electroactive materials, such as piezoelectric, electrostrictive or magnetostrictive materials, are useful in such tasks. In one embodiment of the invention, bare electroactive elements are used. In another embodiment, packaged electroactive elements, as described herein, are used.

Thus, improvements are desirable in the manner in which vibration is controlled in systems for fabricating electronic components, as well as the manner in which an actuator is attached to the equipment to be controlled.

Summary of the Invention

In one embodiment of the invention, a vibration control system is provided comprising an actuator assembly, and a sensor for sensing a parameter of movement or performance. The vibration control system is particularly useful for controlling vibration in systems for fabricating electronics components, which often include one or more gantry assemblies, head assemblies, and/or moving stages or components. Contemplated systems for fabricating electronics components include, but are not limited to, pick and place systems, lithography systems, and those used to fabricate semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices. However, the devices and methods of the invention would be useful in fabricating systems of any sort, such as machine tool equipment, milling equipment, or systems used in an automated assembly line. Also contemplated are systems for fabricating electronic components wherein the systems comprise a lens system, a wafer stage, and a structure for supporting the lens system and wafer stage where the lens system creates an image on the wafer stage such as would be used in modern photolithography.

In one embodiment, an active vibration control system for use with a photolithography fabricating system includes the following components: a sensor that measures the displacement levels at the key points, or provides information from which such information can be estimated; a digital or analog processor that can compute a control signal based on the sensors input, and an actuator that can induce elastic displacement in the structure.

In a particularly preferred embodiment, an actuator useful in an active vibration control system used in conjunction with photolithography tools is non-reactive and does not require back support (actuators that require back support may excite elastic vibrations in the support structure, which may be re-introduced unto the tool), and has a very low distortion profile (an actuator array designed to control structural vibration at a given frequency or band must not excite any vibration outside that band).

In a particularly preferred embodiment, a vibration control system in accordance with the invention comprises an induced-strain actuator that acts directly on the strain state of the structure, and has virtually no distortion. Such an actuator can excite, and therefore control, only the elastic vibration modes of the controlled structure, leaving all other vibration modes (such as the modes of various equipment housing structures, etc.) uncontrolled. This contributes to the control system simplicity and robustness.

In another preferred embodiment of the invention, the vibration control system further comprises a circuit in electrical communication with the actuator assembly and the sensor. In one embodiment, the sensor relays information about movement, vibration or performance to the circuit, which, in response, signals the actuator assembly to control vibration. The vibration in the systems in which the present invention are useful may be due to external disturbance or due to the inherent disturbances generated by the system itself.

In yet another preferred embodiment of the invention, the vibration control system further comprises an electrical connection to the fabricating system. The electrical connection may provide for the fabricating system to send to, or receive from the vibration control system information such as abling or disabling signals, system status signals, or fault/error status signals. In another embodiment, a circuit according to the invention further comprises a control system comprising at least one controller. Such a control system may permit auto-tuning, gain scheduling, external gain control, or it may be a linear feed forward control, or may serve as another source of feedback control.

In an embodiment of the invention wherein the vibration control system has an auto-tuning control, prior to operation, the control system injects one or more test signals into the system and measures the response. The measured response is used to refine an internal model of the plant, and the control gains are modified accordingly. Control gains are kept constant while the loop is closed.

In an embodiment of the invention wherein the vibration control system has a gain scheduling control, the controllers are designed for the system at several different operating points. In the case of a pick and place machine, these points would be different positions of the pick and place head. The controllers are stored in memory in the digital control system. During operation, sensors feed information to the controller describing the configuration of the machine in real time. As the system moves through each operating point, the control system switches to the optimal control gains for that point. A variant of this is that the control gains used at any point in time are a linear interpolation of the gains from several controllers stored in memory for several nearby operating points.

In an embodiment of the invention wherein the vibration control system has an external gain control, the control system includes an input which connects to the computer system which monitors the overall performance of the machine. The controller implemented at any instant in time has a gain which is proportional to this signal. The monitoring system modifies this gain until optimal performance is achieved. If performance begins to move out of specification due to slow time variation, the monitoring system would repeat the gain optimization sequence.

In an embodiment of the invention wherein the vibration control system has a feed forward control, in addition to the feedback control (controller driven by signals originating from sensors which monitor the structural vibration), an additional signal which is in phase with a harmonic disturbance (such as motor rotation) provided to the controller. The controller feeds forward a filtered version of this signal. The gains which adjust the magnitude and phase of the feed forward control relative to the disturbance signal are adjusted adaptively to minimize the influence of the disturbance on the performance.

In certain embodiments of the invention, the actuator assembly may comprise a strain actuator, an electroactive strain actuator, a piezoceramic strain actuator, an electroactive stack actuator, or at least two actuators. In yet another embodiment of the invention, the actuator assembly is in electrical communication with the sensor.

Also in certain embodiments of the invention, the sensor may comprise a strain sensor, an accelerometer, laser displacement sensor, laser interferometer, or at least two sensors. In another embodiment of the invention, the sensor may comprise at least two sensors measuring at least two different signals. In a preferred embodiment, the sensor directly measures some aspect directly related to performance of the systems in which the present invention is useful.

In a particularly preferred embodiment of the invention, the vibration control system comprises an electronic link or cable providing information about the trajectory of a gantry and head.

An actuator assembly according to the present invention may include one or more strain elements, such as a piezoelectric or electrostrictive plate, shell, fiber or composite; a housing forming a protective body about the element; and electrical contacts mounted in the housing and connecting to the strain element; these parts together forming a flexible card. At least one side of the assembly includes a thin sheet which is attached to a major face of the strain element, and by bonding the outside of the sheet to an object a stiff shear-free coupling is obtained between the object and the strain element in the housing.

In a preferred embodiment, the strain elements are piezoceramic plates, which are quite thin, preferably between slightly under an eighth of a millimeter to several millimeters thick, and which have a relatively large surface area, with one or both of their width and length dimensions being tens or hundreds of times greater than the thickness dimension. A metallized film makes electrode contact, while a bonding agent and insulating material hermetically seal the device against delamination, cracking and environmental exposure. The bonding agent used may be an epoxy, such as B-stage or C-stage epoxy, a thermoplastic, or any other material useful in bonding together the piezoceramic plate, metallized film and insulating material. The specific bonding agent used will depend on the intended application of the device. In a preferred embodiment, the metallized film and insulating material are both provided in a flexible circuit of tough polymer material, which thus provides robust mechanical and electrical coupling to the enclosed elements. Alternatively, the metallized film may be located directly on the piezoceramic plate, and the insulating material may have electrical contacts.

By way of illustration, an example below describes a construction utilizing rectangular PZT plates a quarter millimeter thick, with length and width dimensions each of one to three centimeters, each element thus having an active strain-generating face one to ten square centimeters in area. The PZT plates are mounted on or between sheets of a stiff strong polymer, e.g., one half, one or two mil polyimide, which is copper clad on one or both sides and has a suitable conductive electrode pattern formed in the copper layer for contacting the PZT plates. Various spacers surround the plates, and the entire structure is bonded together with a structural polymer into a waterproof, insulated closed package, having a thickness about the same as the plate thickness, e.g., .30 to .50 millimeters. So enclosed, the package may bend, extend and flex, and undergo sharp impacts, without fracturing the fragile PZT elements which are contained within. Further, because the conductor pattern is firmly attached to the polyimide sheet, even cracking of the PZT element does not sever the electrodes, or prevent actuation over the full area of the element, or otherwise significantly degrade its performance.

The thin package forms a complete modular unit, in the form of a small "card", complete with electrodes. The package may then conveniently be attached by bonding one face to a structure so that it couples strain between the enclosed strain element and the structure. This may be done for example, by simply attaching the package with an adhesive to establish a thin, high shear strength, coupling with the PZT plates, while adding minimal mass to the system as a whole. The plates may be actuators, which couple energy into the attached structure, or sensors which respond to strain coupled from the attached structure.

In different embodiments, particular electrode patterns are selectively formed on the sheet to either pole the PZT plates in-plane or cross-plane, and multiple layers of PZT elements may be arranged or stacked in a single card to result in bending or shear, and even specialized torsional actuation.

In accordance with a further aspect of the invention, circuit elements are formed in, or with, the vibration control system to filter, shunt, or process the signal produced by the PZT elements, to sense the mechanical environment, or even to locally perform switching or power amplification for driving the actuation elements. The actuator package may be formed with pre-shaped PZT elements, such as half-cylinders, into modular surface-mount shells suitable for attaching about a pipe, rod or shaft.

Brief Description of the Drawings

These and other desirable properties of the invention will be understood from the detailed description of illustrative embodiments, wherein:

FIGURE 1A is a system illustration of a typical prior art actuator;

FIGURE 1B and 1C are corresponding illustrations of two systems in accordance with the present invention;

FIGURES 2A and 2B show top and cross-sectional views, respectively, of a basic actuator or sensor card in accordance with the present invention; FIGURE 2C illustrates an actuator or sensor card with circuit elements;

FIGURE 3 illustrates another card;

FIGURES 4A and 4B show sections through the card of FIGURE 3;

FIGURES 5 and 5A show details of the layer structure of the card of FIGURE 3;

FIGURE 6 shows an actuator package comb electrodes for in-plane actuation;

FIGURE 7 illustrates a torsional actuator package using the cards of FIGURE 6;

FIGURES 8A and 8B show actuators mounted as surface mount actuators on a surface or rod, respectively;

FIGURE 9 shows actuators mounted as mechanical elements;

FIGURE 10 shows a block diagram of an embodiment of an electroactive vibration control system for a gantry;

FIGURE 11 shows a simulated frequency response on a collect and place head at the tip of a gantry, without and with electroactive vibration control;

FIGURE 12 shows the simulated time response of a collect and place head without and with electroactive control;

FIGURE 13 shows extensional strain energy concentration;

FIGURE 14 shows the results of a closed loop test on the frequency response of a pick and place machine having a vibration control system in accordance with the invention;

FIGURE 15 shows the results of a closed loop test on the gain control of a pick and place machine having a vibration control system in accordance with the invention;

FIGURE 16 shows the power spectral density of error signals recorded by a laser metrology system in a lithography machine;

FIGURES 17-20 show different embodiments of the invention as used with a fabricating system;

FIGURE 21 shows an embodiment of the invention as used with a fabricating system;

FIGURE 22 shows a simplified two-dimensional physics model of a wafer stage and wafer stage base;

FIGURE 23 shows controller results;

FIGURE 24 shows a block diagram for stage control;

FIGURE 25 shows experimental and analytical results;

FIGURE 26 shows experimental and analytical results.

Detailed Description of the Invention

Applicants have developed a vibration control system particularly useful for controlling vibration in a system for fabricating electronics components. The vibration control system of the invention is useful for controlling vibration that is either externally produced in the system for fabricating components, or is internal to or inherent in the system. Internal vibration may be caused by various motors, such as step or D.C. motors, or hydraulic or pneumatic actuators used in a fabricating system.

A vibration control system according to the invention may comprise electroactive actuators and sensors, integrated with the fabricating system. The control and power electronics may be separate units, located adjacent to the equipment and connected to the actuators and sensors through appropriate linking cabling. Alternatively, the control and power electronics may be a fully integrated system with the fabricating system.

The electroactive actuator may be secured to or within the fabricating system in various ways. As shown in Figures 17, 19, and 20, for example, the actuator may be fixed into place by a bolt 414 either pushing against or going through the actuator. Alternatively, the actuator may be secured by friction, tension, or otherwise force fit. In one embodiment, as shown in Figure 18, the actuator is bonded to a plate 412, which, in turn, is bolted to a component of a the fabricating system with bolts 414, 414', 414", and 414'". In another embodiment, the actuator is bonded to a plate, which is bolted to a second plate, and the second plate is then bolted to a component of the fabricating component. In another embodiment, the actuator assembly is detachably secured within the vibration control system, or detachably secured to a component of a fabricating system.

Figure 21 shows an embodiment of the invention as used in a fabricating system. In this embodiment, the fabricating system comprises a wafer stage 400, a reticle stage 402, laser interferometers 404, 404', 404", and 404'" with X&Y mirrors, and a support structure 406. The support structure 406 supports a lens assembly 410. The interferometers 404, 404', 404", and 404'" are located on the wafer stage 400, the reticle stage 402, and on the lens assembly 410. Mounted on the support structure 406 are two actuators 408 and 408' comprising, for example, an electroactive element. Each of the actuators 408 and 408' are in electrical communication with a circuit. Signals from the interferometers 404, 404', 404", and 404'" are relayed through an SBC analog I/O channel and amplifiers to the actuators 408 and 408', which, in response, controls vibration within the fabricating system. By controlling the vibration within the fabricating system, the accuracy of the placement and absolute size of the metallized traces in the semiconductor on a wafer stage may be improved. Alternatively or in addition, the through-put of the fabrication system may be increased without decreasing accuracy.

Useful in this invention are electroactive actuator assemblies. Figure 1A illustrates in schema the process and overall arrangement of a prior art surface mounted piezoelectric actuator assembly 10. A structure 20, which may be a structural or machine element, a plate, airfoil or other interactive sheet, or a device or part thereof has a sheet 12 of smart material bonded thereto by some combination of conductive and structural polymers, 14, 16. An insulator 18, which may be formed entirely or in part of the structural polymer 16, encloses and protects the smart material, while conductive leads or surface electrodes are formed or attached by the conductive polymer. An external control system 30 provides drive signals along lines 32a, 32b to the smart material, and may receive measurement signals from surface-mounted instrumentation such as a strain gauge 35, from which it derives appropriate drive signals. Various forms of control are possible. For example, the strain gauge may be positioned to sense the excitation of a natural resonance, and the control system 30 may simply actuate the PZT element in response to a sensor output, so as to stiffen the structure, and thereby shift its resonant frequency. Alternatively, a vibration sensed by the sensor may be fed back as a processed phase-delayed driving signal to null out an evolving dynamic state, or the actuator may be driven for motion control. In better-understood mechanical systems, the controller may be programmed to recognize empirical conditions, i.e., aerodynamic states or events, and to select special control laws that specify the gain and phase of a driving signal for each actuator 12 to achieve a desired change.

For all such applications, major work is required to attach the bare PZT plate to its control circuitry and to the workpiece, and many of the assembly steps are subject to failure or, when quantitative control is desired, may require extensive modeling of the device after it has been assembled, in order to establish control parameters for a useful mode of operation that are appropriate for the specific thicknesses and mechanical stiffnesses achieved in the fabrication process. A benefit of packaging an electroactive element when bonding to the plate is that electrical isolation or capacitive decoupling from the plate, structure or any part of the fabrication system may be achieved.

FIGURE 1B shows an actuator assembly useful in one embodiment of the present invention. As shown, it is a modular pack or card 40 that simply attaches to a structure 20 with a quick setting adhesive, such as a five-minute epoxy 13, or in other configurations attaches at a point or line. The operations of sensing and control thus benefit from a more readily installable and uniformly modeled actuator structure. In particular, the modular pack 40 has the form of a card, a stiff but bendable plate, with one or more electrical connectors preferably in the form of pads located at its edge (not shown) to plug into a multi-pin socket so that it may connect to a simplified control system 50. As discussed in greater detail below with respect to FIGURE 2C, the modular package 40 may also incorporate planar or low-profile circuit elements, which may include signal processing elements, such as weighting or shunting resistors, impedance matchers, filters and signal conditioning preamplifiers, and may further include switching transistors and other elements to operate under direct digital control, so that the only external electrical connections necessary are those of a microprocessor or logic controller, and a power supply.

In a further embodiment particularly applicable to some low power control situations, a modular package 60 as shown in Figure 1C may include its own power source, such as a battery or power cell, and may include a controller, such as a microprocessor chip or programmable logic array, to operate on-board drivers and shunts, thus effecting a complete set of sensing and control operations without any external circuit connections.

The present invention specifically pertains to piezoelectric polymers, and to materials such as sintered metal zirconate, niobate crystal or similar piezoceramic materials that are stiff, yet happen to be quite brittle. It also pertains to electrostrictive materials. As used in the claims below, both piezoelectric and electrostrictive elements, in which the material of the elements has an electromechanical property, will be referred to as electroactive elements. High stiffness is essential for efficiently transferring strain across the surface of the element to an outside structure or workpiece, typically made of metal or a hard structural polymer, and the invention in its actuator aspect does not generally contemplate soft polymer piezoelectric materials. While the terms "stiff" and "soft" are relative, it will be understood that in this context, the stiffness, as applied to an actuator, is approximately that of a metal, cured epoxy, high-tech composite, or other stiff material, with a Young's modulus greater than $.1 \times 10^6$, and preferably greater than $.2 \times 10^6$. When constructing sensors, instead of actuators, the invention also contemplates the use of low-stiffness piezoelectric materials, such as polyvinylidene difluoride (PVDF) film and the substitution of lower cure temperature bonding or adhesive materials. The principal construction challenges, however, arise with the first class of piezo material noted above, and these will now be described.

In general, the invention includes novel forms of actuators and methods of making such actuators, where "actuator" is understood to mean a complete and mechanically useful device which, when powered, couples force, motion or the like to an object or structure. In its broad form, the making of an actuator involves "packaging" a raw electroactive element to make it mechanically useful. By way of example, raw electroactive piezoelectric materials or "elements" are commonly available in a variety of semi-processed bulk material forms, including raw piezoelectric material in basic shapes, such as sheets, rings, washers, cylinders and plates, as well as more complex or composite forms, such as stacks, or hybrid forms that include a bulk material with a mechanical element, such as a lever. These materials or raw elements may have metal coated on one or more surfaces to act as electrical contacts, or may be non-metallized. In the discussion below, piezoelectric materials shall be discussed by way of example, and all these forms of raw materials shall be referred to as "elements", "materials", or "electroactive elements". As noted above, the invention further includes structures or devices made by these methods and operating as transducers to sense, rather than actuate, a strain, vibration, position or other physical characteristic, so that where applicable below, the term "actuator" may include sensing transducers.

Embodiments of the invention employ these stiff electrically-actuated materials in thin sheets - discs, annuli, plates and cylinders or shells - that are below several millimeters in thickness, and illustratively about one fifth to one quarter millimeter thick. Advantageously, this thin dimension allows the achievement of high electric field strengths across a distance comparable to the thickness dimension of the plate at a relatively low overall potential difference, so that full scale piezoelectric actuation may be obtained with driving voltages of ten to fifty volts, or less. Such a thin dimension also allows the element to be attached to an object without greatly changing the structural or physical response characteristics of the object. However, in the prior art, such thin elements are fragile, and may break due to irregular stresses when handled, assembled or cured. The impact from falling even a few centimeters may fracture a piezoceramic plate, and only extremely small bending deflections are tolerated before breaking.

In accordance with the present invention, the thin electrically actuated element is encased by layers of stiff insulating material, at least one of which is a tough film which has patterned conductors on one of its surfaces, and is thinner than the element itself. A package is assembled from the piezo elements, insulating layers, and various spacers or structural fill material, such that altogether the electrodes, piezo element(s), and enclosing films or layers form a sealed card of a thickness not substantially greater than that of the bare actuating element. Where elements are placed in several layers, as will be described below, the package thickness is not appreciably greater than the sum of the thicknesses of the stacked actuating elements.

FIGURE 2A illustrates a basic embodiment 100 of the invention. A thin film 110 of a highly insulating material, such as a polyimide material, is metallized, typically copper clad, on at least one side, and forms a rectangle which is coextensive with or slightly larger than the finished actuator package. A suitable material available for use in fabricating multilayer circuit boards is distributed by the Rogers Corporation of Chandler, Arizona as their Flex-I-Mid 3000 adhesiveless circuit material, and consists of a polyimide film formed on a rolled copper foil. A range of sizes are available commercially, with the metal foils being of 18 to 70 micrometer thickness, integrally coated with a polyimide film of 13 to 50 micrometer thickness. Other thicknesses may be fabricated. In this commercial material, the foil and polymer film are directly attached without adhesives, so the metal layer may be patterned by conventional masking and etching, and multiple patterned layers may be built up into a multilayer board in a manner described more fully below, without residual adhesive weakening the assembly or causing delamination. The rolled copper foil provides high in-plane tensile strength, while the polyimide film presents a strong, tough and defect-free electrically insulating barrier.

In constructions described below, the film constitutes not only an insulator over the electrodes, but also an outer surface of the device. It is therefore required to have high dielectric strength, high shear strength, water resistance and an ability to bond to other surfaces. High thermal resistance is necessary in view of the temperature cure used in the preferred fabrication process, and is also required for some application environments. In general, polyamide/imides have been found useful, but other materials, such as polyesters or thermoplastics with similar properties, may also be used.

In the present constructions, the foil layer is patterned by conventional masking and etch techniques (for example, photoresist masking and patterning, followed by a ferric chloride etch), to form electrodes for contacting the surface of piezo plate elements. Alternatively, a more ductile, thin conductive layer may be used. For example, a thin conductive layer may be printed on the polymer film or directly on the piezoelectric element using silver conductive ink. In FIGURE 2A, electrodes 111 extend over one or more sub-regions of the interior of the rectangle, and lead to reinforced pads or lands 111a, 111b extending at the edge of the device. The electrodes are arranged in a pattern to contact a piezoelectric element along a broadly-turning path, which crosses the full length and width of the element, and thus assures that the element remains connected despite the occurrence of a few cracks or local breaks in the electrode or the piezo element. Frame members 120 are positioned about the perimeter of sheet 110, and at least one piezoelectric plate element 112 is situated in the central region so that it is contacted by the electrodes 111. The frame members serve as edge binding, so that the thin laminations do not extend to the edge, and they also function as thickness spacers for the hot-press assembly operation described further below, and as position-markers which define the location of piezo plates that are inserted during the initial stages of assembling the laminated package.

FIGURE 2A is a somewhat schematic view, inasmuch as it does not show the layer structure of the device which secures it together, including a further semi-transparent top layer 116 (FIGURE 2B), which in practice extends over the plate 112 and together with the spacers 120 and sheet 110 closes the assembly. A similar layer 114 is placed under the piezo element, with suitable cut-outs to allow the electrodes 111 to contact the element. Layers 114, 116 are preferably formed of a curable epoxy sheet material, which has a cured thickness equal to the thickness of the metal electrode layer, and which acts as an adhesive layer to join together the material contacting it on each side. When cured, this epoxy constitutes the structural body of the device, and stiffens the assembly, extending entirely over a substantial portion of the surface of the piezo element to strengthen the element and arrest crack growth, thereby enhancing its longevity. Furthermore, epoxy from this layer actually spreads in a microscopically thin but highly discontinuous film, about .0025 mm thick, over the electrodes, bonding them firmly to the piezo plate, but with a sufficient number of voids and pinholes so that direct electrical contact between the electrodes and piezo elements still occurs over a substantial and distributed contact area.

FIGURE 2B shows a cross-sectional view, not drawn to scale, of the embodiment of FIGURE 2A. By way of rough proportions, taking the piezoelectric plate 112 as .2 - .25 millimeters in thickness, the insulating film 110 is much thinner, no more than one-tenth to one-fifth the plate thickness, and the conductive copper electrode layer 111 may have a thickness typically of ten to fifty microns, although the latter range is not a set of strict limits, but represents a useful range of electrode thicknesses that are electrically serviceable, convenient to manufacture and not so thick as to either impair the efficiency of strain transfer or introduce delamination problems. The structural epoxy 114 fills the spaces between electrodes 111 in each layer, and has approximately the same thickness as those electrodes, so that the entire assembly forms a solid block. The spacers 120 are formed of a relatively compressible material, having a low modulus of elasticity, such as a relatively uncrosslinked polymer, and, when used with a pressure-cured epoxy as described below, are preferably of a thickness roughly equivalent to the piezoceramic plate or stack of elements, so that they form an edge binding about the other components between the top and bottom layers of film 110.

A preferred method of manufacture involves applying pressure to the entire package as the layer 116 cures. The spacers 120 serve to align the piezoceramic plates and any circuit elements, as described below with reference to FIGURES 3-5, and they form a frame that is compressed slightly during assembly in the cure step, at which time it may deform to seal the edges without leaving any stress or irregularities. Compression eliminates voids and provides a dense and crack-free solid medium, while the curing heat effects a high degree of cross-linking, resulting in high strength and stiffness.

An assembly process for the embodiment of FIGURES 2A, 2B is as follows. One or more pieces of copper clad polyimide film, each approximately .025 to .050 millimeters thick in total, are cut to a size slightly larger than the ultimate actuator package dimensions. The copper side of the film is masked and patterned to form the desired shape of electrodes for contacting a piezo element together with conductive leads and any desired lands or access terminals. A pitchfork electrode pattern is shown, having three tines which are positioned to contact the center and both sides of one face of a piezo element, but in other embodiments an H- or a comb-shape is used. The patterning may be done by masking, etching and then cleaning, as is familiar from circuit board or semiconductor processing technology. The masking is effected by photoresist patterning, screening, tape masking, or other suitable process. Each of these electroded pieces of polyimide film, like a classical printed circuit board, defines the positions of circuit elements or actuator sheets, and will be referred to below simply as a "flex circuit." However, methods and devices of the invention also contemplate using an electroded piezo element, an insulator, and electrical contacts, rather than a "flex circuit".

Next, uncured sheet epoxy material having approximately the same thickness or slightly thicker than the electrode foil layer is cut, optionally with through-apertures matching the electrode pattern to allow enhanced electrical contact when assembled, and is placed over each flex circuit, so it adheres to the flex circuit and forms a planarizing layer between and around the electroded portions. The backing is then removed from the epoxy layers attached to the flex circuits, and pre-cut spacers 120 are placed in position at corner and edges of the flex circuit. The spacers outline a frame which extends above the plane of the electrodes, and defines one or more recesses into which the piezo elements are to be fitted in subsequent assembly steps. The piezo element or elements are then placed in the recesses defined by the spacers, and a second electroded film 111, 112 with its own planarizing/bonding layer 114 is placed over the element in a position to form electrode contacts for the top of the piezo element. If the device is to have several layers of piezo elements, as would be the case for some bending actuator constructions, these assembly steps are repeated for each additional electroded film and piezoelectric plate, bearing in mind that a polyimide film which is clad and patterned on both sides may be used when forming an intermediate electrode layer that is to contact actuator elements both above and below the intermediate sheet.

Once all elements are in place, the completed sandwich assembly of patterned flex circuits, piezo sheets, spacers and curable patterned epoxy layers is placed in a press between heated platens, and is cured at an elevated temperature and pressure to harden the assembly into a stiff, crack-free actuator card. In a representative embodiment, a cure cycle of thirty minutes at 350°F and 50-100 psi pressure is used. The epoxy is selected to have a curing temperature below the depoling temperature of the piezo elements, yet achieve a high degree of stiffness.

The above construction illustrates a simple actuator card having a single piezo plate sandwiched between two electroded films, so that the plate transfers shear strain efficiently through a thin film to the surface of the actuator card. The measure of transfer efficiency, given by the shear modulus divided by layer thickness squared, and referred to as gamma (Γ), depends on the moduli and thickness of the epoxy 114, the rolled foil electrodes 111, and the polyimide film 110. In a representative embodiment in which the epoxy and copper electrode layers are 1.4 mils thick and the epoxy has a modulus of $.5x10^6$, a gamma of approximately $9x10^{10}$ pounds/inch^4 is achieved. Using a thinner epoxy layer and film with .8 mil foil, substantially higher Γ is achieved. In general, the gamma of the electrode/epoxy layer is greater than $5x10^{10}$ pounds/inch^4, while that of the film is greater than $2x10^{10}$ pounds/inch^4.

It should be noted that using PZT actuator plates ten mils thick, a card having two PZT plates stacked over each other with three flex circuit electroded film layers (the middle one being double clad to contact both plates) has a total thickness of 28 mils, only forty percent greater than the plates alone. In terms of mass loading, the weight of the actuator elements represents 90% of the total weight of this assembly. Generally, the plates occupy fifty to seventy percent of the package thickness, and constitute seventy to ninety percent of its mass, in other constructions. Thus, the actuator itself allows near-theoretical performance modeling. This construction offers a high degree of versatility as well, for implementing benders (as just described) as well as stacks or arrays of single sheets.

Another useful performance index of the actuator constructed in accordance with the present invention is the high ratio of actuator strain ε to the free piezo element strain Λ, which is approximately (.8) for the two layer embodiment described herein, and in general is greater than (.5). Similarly, the ratio of package to free element curvatures, K, is approximately .85 - .90 for the described constructions, and in general is greater than .7.

Thus, overall, the packaging involved in constructing a piezo element embedded in a flex circuit impairs its weight and electromechanical operating characteristics by well under 50%, and as little as 10%, while profoundly enhancing its hardiness and mechanical operating range in other important respects. For example, while the addition of sheet packaging structure to the base element would appear to decrease attainable K, in practical use the flex card construction results in piezo bender constructions wherein much greater total deflection may be achieved, since large plate structures may be fabricated and high curvature may be repeatedly actuated, without crack failure or other mechanical failure modes arising. Several Figures will illustrate the variety of constructions to which such enhanced physical characteristics are brought.

First, the structure of an electroactive element embedded between flex circuits not only provides a low mass unified mechanical structure with predictable response characteristics, but also allows the incorporation of circuit elements into or onto the actuator card. FIGURE 2C shows a top view of one device 70 of this type, wherein regions 71, 73 each contain broad electroactive sheets, while a central region 72 contains circuit or power elements, including a battery 75, a planar power amplification or set of amplifiers 77, a microprocessor 79, and a plurality of strain gauges 78. Other circuit elements 82a, 82b may be located elsewhere along the path of circuit conductors 81 about the periphery. As with the other embodiments, spacers 120 define layout and seal edges of the device, while electrodes 111 attach the electroactive elements to the processing or control circuitry which is now built-in. The circuit elements 82a, 82b may comprise weighting resistors if the device is operated as a sensor, or shunting resistors to implement passive damping control. Alternatively, they may be filtering, amplifying, impedance matching or storage elements, such as capacitors, amplifiers or the like. In any case, these elements also are located away from electroactive plates 84. The components collectively may sense strain and implement various patterns of actuation in response to sensed conditions, or perform other sensing or control tasks.

Returning now to the actuator aspect of the invention, FIGURE 3 shows a top view of an actuator package 200 having dimensions of about 1.25 x 9.00 x .030 inches and assembled with two layers of piezoelectric plates of four plates each. A rectangular polyimide sheet 210 with an end tab 210a carries an electrode 211 in the form of a lattice of H-shaped thin copper lines interconnected to each other and to a single runner 211a that leads out to the tab, thus providing a low impedance connection directly to each of four rectangular regions which hold the piezo plates.

Spacer elements 220a, 220b of H-shape, or 220c of L-shape mark off corners and delineate the rectangular spaces for location of the piezo plates 216. In this embodiment, a plurality of gaps 230, discussed further below, appear between adjacent the H- or L- spacers. As will be apparent from the description below, the use of these small discrete spacer elements (I-, T- or O-shaped spacers may also be convenient) is enhanced because they may be readily placed on the tacky bonding epoxy layer 114 during assembly to mark out assembly positions and form a receiving recess for the piezo elements. However, the spacer structure is not limited to such a collection of discrete elements, but may be a single or couple of frame pieces, formed as a punched-out sheet or molded frame, to provide all, or one or more, orienting and/or sealing edges, or recesses for holding actuation of circuit components.

FIGURE 5 illustrates a top view of each of the three sheet, electrode and piezo plate layers separately, while FIGURE 5A illustrates the general layering sequence of the film, conductor, and spacer/piezo layers. As shown, the spacers 220 and piezo plates 216 constitute a single layer between each pair of electrode layers.

FIGURES 4A and 4B (not drawn to scale) illustrate the layer structure of the assembled actuator along the vertical sections at the positions indicated by "A" and "B" in FIGURE 3. As more clearly shown in FIGURE 4A, a patterned bonding layer of epoxy sheet 214 is coplanar with each electrode layer 211 and fills the space between electrodes, while the spacer 220c is coplanar with the piezo plate 216 and substantially the same thickness as the plate or slightly thicker. Illustratively, the piezo plate 216 is a PZT-5A ceramic plate, available commercially in a five to twenty mil thickness, and has a continuous conductive layer 216a covering each face for contacting the electrodes 211. The spacers 220 are formed of somewhat compressible plastic with a softening temperature of about 250°C. This allows a fair degree of conformability at the cure temperature so the spacer material may fill slight voids 214a (FIGURE 4A) during the assembly process. As shown in FIGURE 4B, the gaps 230 (when provided) between spacers result in openings 214b which vent excess epoxy from the curable bonding layers 214, and fill with epoxy during the cure process. As illustrated in that FIGURE, a certain amount of epoxy also bleeds over into patches of film 215 between the electrodes 211 and the piezo plate 216. Because of the large and continuous extent of electrode 211, this patchy leakage of epoxy does not impair the electrical contact with the piezo elements, and the additional structural connection it provides helps prevent electrode delamination.

It will be appreciated that with the illustrated arrangements of electrodes, each vertically stacked pair of piezo plates may be actuated in opposition to each other to induce bending, or more numerous separate electrodes may be provided to allow different pairs of plates to be actuated in different ways. In general, as noted above, the invention contemplates even quite complex systems involving many separate elements actuated in different ways, with sensing, control, and power or damping elements all mounted on the same card. In this regard, great flexibility in adapting the card to practical tasks is further provided by its flexibility. In general, it has a supple flexibility comparable to that of an epoxy strip thirty mils thick, so that it may be bent, struck or vibrated without damage. It may also be sharply bent or curved in the region of its center line CL (FIGURE 3) where no piezo elements are encased, to conform to an attaching surface or corner. The elements may be poled to change dimension in-plane or cross-plane, and the actuators may therefore be attached to transmit strain to an adjacent surface in a manner effective to perform any of the above-described control actions, or to launch particular waveforms or types of acoustic energy, such as flexural, shear or compressional waves into an adjacent surface.

FIGURE 6 shows another actuator embodiment 300. In this embodiment, illustrated schematically, the epoxy bonding layer, film and spacer elements are not shown, but only electrode and piezo sheets are illustrated to convey the operative mechanisms. A first set of electrodes 340 and second set 342 are both provided in the same layer, each having the shape of a comb with the two combs interdigitated so that an electrical actuation field is set up between the tooth of one comb and an adjacent tooth of the other comb. In FIGURE 6, a parallel pair of combs 340a, 342a is provided on the other side of the piezo sheet, with comb electrode 340 tied to 340a, and comb electrode 342 tied to 342a, so as to set up an electric field with equipotential lines "e" extending through the piezo sheet, and in-plane potential gradient between each pair of teeth from different combs. In the embodiment shown, the piezoceramic plates are not metallized, so direct electrical contact is made between each comb and the plate. The plates are poled in-plane, by initially applying a high voltage across the combs to create a field strength above one two thousand volts per inch directed along the in-plane direction. This orients the piezo structure so that subsequent application of a potential difference across the two-comb electrodes results in in-plane (shear) actuation. Thus, the direct contact of interdigital electrodes provides to the piezo element an electrical field which is generally parallel to the actuation direction.

In addition to shear actuation, directional actuation and damping may be effected using methods or devices of the invention. For example, as shown in FIGURE 7, two such actuators 300 may be crossed to provide torsional actuation.

In discussing the embodiments above, the direct transfer of strain energy through the electrode/polyimide layer to any adjoining structure has been identified as a distinct and novel advantage. Such operation may be useful for actuation tasks or diverse as airfoil shape control actuation and noise or vibration cancellation or control. FIGURES 8A and 8B illustrates typical installations of flat (FIGURE 8A) and hemicylindrical (FIGURE 8B) embodiments 60 of the actuator, applied to a flat or slightly curved surface, and a shaft, respectively.

However, while the electromechanical materials of these actuators operate by strain energy conversion, applications of the present invention extend beyond strain-coupling through the actuator surface, and include numerous specialized mechanical constructions in which the motion, torque or force applied by the actuator as a whole is utilized. In each of these embodiments, the basic strip- or shell-shaped sealed actuator is employed as a robust, springy mechanical element, pinned or connected at one or more points along its length. As shown in FIGURE 9, when electrically actuated, the strip then functions, alone or with other elements, as a self-moving lever, flap, leaf spring, stack or bellows. In the diagrams of FIGURES 9(a) - 9(q), the elements A, A', A" . . . are strip or sheet actuators such as shown in the above FIGURES, while small triangles indicate fixed or pinned positions which correspond, for example, to rigid mounting points or points of connection to a structure. Arrows indicate a direction of movement or actuation or the contact point for such actuation, while L indicates a lever attached to the actuator and S indicates a stack element or actuator.

The configurations of FIGURES 9(a)-9(c) as stacks, benders, or pinned benders may replace many conventional actuators. For example, a cantilevered beam may carry a stylus to provide highly controlled single-axis displacement to constitute a highly linear, large displacement positioning mechanism of a pen plotter. Especially interesting mechanical properties and actuation characteristics are expected from multi-element configurations 9(d) et seq., which capitalize on the actuators having a sheet extent and being mechanically robust. Thus, as shown in FIGURES 9(d) and (e), a pin-pin bellows configuration may be useful for extended and precise one-axis Z-movement positioning, by simple face-contacting movement, for applications such as camera focusing; or may be useful for implementing a peristalsis-type pump by utilizing the movement of the entire face bearing against a fluid. As noted in connection with FIGURE 3, the flex circuit is highly compliant, so hinged or folded edges may be implemented by simply folding along positions such as the centerline in FIGURE 3, allowing a closed bellows assembly to be made with small number of large, multi-element actuator units. The flex circuit construction allows strips or checkerboards of actuator elements to be laid out with fold lines between each adjacent pair of elements, and the fold lines may be impressed with a thin profile by using a contoured (e.g. waffle-iron) press platen during the cure stage. With such a construction, an entire seamless bellows or other folded actuator may be made from a single flex circuit assembly.

As noted above, the piezo element need not be a stiff ceramic element, and if the flex circuit is to be used only as a sensor, then either a ceramic element, or a soft material such as PVDF may be employed. In the case of the polymer, a thinner more pliant low temperature adhesive is used for coupling the element, rather than a hard curable epoxy bonding layer.

Certain embodiments of the invention are exemplified below.

EXAMPLE 1

In this example, a vibration control system was designed to determine certain parameters of functional requirements of a gantry active control system. The functional requirements defined included (but were not limited to) the following:

- Accuracy
- Settling time
- Mass, size and location of the actuators and sensors
- Power
- Peak strains
- Lifetime
- Temperature range
- Exposure to humidity and solvents
- Cost
- Interfaces with existing gantry control system

In order to gather data on the structural response of a gantry during operation, the gantry was equipped with an array of piezoelectric strain sensors and accelerometers. Placement and sizing of the piezoelectric actuators required accurate strain mode shape information, which were obtained from this data, and were compared to the Finite Element Model ("FEM"). One important piece of information obtained in this phase of the project involved the effect of different head positions on the dynamics. Both the actuator design and any control software design depended on when the vibration control was applied, i.e., while the head was moving along the gantry, and/or after it had stopped at an arbitrary position on the gantry.

Data was acquired both with and without a friction block in place, to allow at least analytical evaluation of the potential for complete replacement of the friction block by the electroactive vibration control system.

Using the data acquired above, along with finite element modeling information, the system-level design was performed. This design involved selecting a system architecture, including actuator placement, type of sensor, and the type of control algorithm. As discussed above, with the moving head having a significant effect on the gantry dynamics, the electroactive vibration control system's effectiveness was improved by making the trajectory information available in the motion control system. This information may be relayed to the motion control system with a simple clip lead attached to the proper point in the motion controller's circuitry. For example, information such as the plots of motor current, which is often easily accessible, may be provided to the vibration control system.

After selecting the system architecture, an analytical "input/output" model of the system was developed, to design the control algorithm for vibration control, and to simulate its performance. The system design was compared to the functional requirements, to ensure compliance. This analysis served to define the specifications on the various components of the control system, especially the analog sensor signal conditioning electronics, the digital signal processor (DSP) based control unit, and the power amplifier used to provide the necessary voltage and current to the electroactive actuators.

Each of the components of the electroactive vibration control system were then designed, including the various electronic components. The electroactive actuators themselves were fabricated using methods disclosed herein. Each actuator was tested using standard quality control methods. All electronics were fabricated and tested for functionality and for compliance with the specifications devised in the system design task.

An important aspect of the design involved the integration of the actuators and sensors with the gantry. For example, for a given gantry, a 0.5 mm actuator thickness may be determined to not likely interfere with motion of the head along the gantry. The types of cable used to connect the actuators and sensor on the gantry to the electronic equipment were then determined.

In this particular example, the gantry of an automated SMT electronics collect and place equipment was equipped with actuators, sensors and electronics, and analyzed using an FEM with plate elements. The basic concept, shown in block diagram in Figure 10, includes electroactive strain actuators and sensors bonded to the gantry, along with the necessary power, signal, and digital control electronics to achieve vibration reduction. For the purposes of this study, the head was assumed to be fixed at the end of the gantry. The installation of actuators was done using a vacuum-bonding procedure.

"Open loop" testing was then performed. Open loop testing involves injecting signals into the actuators and measuring the response of the gantry to confirm experimentally the analytical modeling done earlier in this study. This testing was performed with the gantry and head stationary, as well as moving along some "standard" trajectories. The signal(s) to be passed from the gantry and head motion controller to the vibration control system were measured as well during these tests. The electoactive actuators were distributed over 10% of the surface area of the gantry having the maximum strain energy in the first natural mode of vibration. The effectiveness of the actuator distribution at exciting the first three modes of vibration was modeled using design software. Between 80-84% of all strain energy is in the plate elements; and between 62-75% of the plates' energy is extensional strain, and therefore available for capture by electroactive control devices bonded to the surface. Thus, at least 52% of the strain energy in a mode is available. Some of this energy is in the frame/support for the moving head. As shown in FIGURE 13, the extensional strain energy was sorted to maximize performance for a given amount of electroactive element.

Damping was added to the structural model. Plots of acceleration versus time at the head, after impact by a hammer, showed roughly 5% of critical damping in the first mode with the friction block in place.

Feedback control was designed using the standard Linear Quadratic Regulator (LQR) approach, ensuring that piezoelectric actuation control voltages did not exceed the actuator device limits. Actuation voltages in the closed feedback loop are proportional to the input disturbance forces associated with the motion of the gantry. Here, the gantry was assumed to accelerate in the y-direction (transverse to the gantry axis) at a constant 25 m/s^2 until maximum velocity of 3 m/s was reached. The D'Alembert inertial force associated with a 10 kg mass was applied at the center of gravity of the head. This mass included the 5 kg head mass, plus 5 kg of effective gantry mass.

The improvements in damping and settling time were then determined after simulating the vibration-controlled system's frequency and time domain responses. Frequency responses are simulated in Figure 11, measured at a point on the underside of the pick and place head, in the y-direction. The reduction in dynamic response to a unit input force is evident in this figure. As shown in FIGURE 11, as well as Table I, mode 1 closed loop damping was about 12%, mode 2 closed loop damping was about 11%, and mode 3 closed loop damping was about 10%. Time responses at the same point, in the same direction, are simulated in Figure 12. This simulation shows a dramatic reduction in settling time with the electroactive control. Thus, very effective control can be achieved with very little additional mass.

Table I: Gantry structural dynamic parameters.

Mode	Description	Frequency (Hz)	Inherent Damping Ratio (% of critical)	Damping Ratio with Piezo Control (%)
1	Twisting about gantry axis	46	5	12
2	Bending in xy (scanning) plane	93	5	11
3	Coupled bend/twist	136	5	10

The gantry/head structural dynamic properties, from FEM, are shown in Table I. The representative actuator distribution designed here was 0.5 mm thick, with an area of 330 cm^2, and a mass of less than 100g. The closed loop modal damping, also shown in Table I, was at least twice the assumed 5% value inherent to the gantry with the friction block, for all three modes of vibration included in the analysis. Thus, the vibration amplitude and settling time were significantly reduced.

As shown in Figures 14 and 15, the vibration control system induced changes in the frequency response and gain control. In this study, the damping was increased by over one order of magnitude. This increase corresponds to an increase in placement accuracy of a factor of ten.

Following the open loop tests, the data was analyzed and the final control algorithm design was performed. If necessary, the actuator and sensor hardware may be modified to ensure compliance with the functional requirements. Then, "closed loop" testing of the final electroactive vibration control system may be performed. Closed loop testing is generally when actuators are driven at least in part by signals generated by sensors.

This study demonstrated that effective active electroactive vibration control of the gantry is possible.

EXAMPLE 2

A vibration control system in accordance with the invention was used in a lithography machine. As shown in Figure 16, which shows the power spectral density of error signals recorded by a laser metrology system, use of the vibration control system resulted in a three-fold reduction in system response in the band from 75 to 125 Hz. The reduction in the peak using the vibration control system would be expected to reduce the system image blur by a factor of two-three after conventional methods are used to reduce peaks at 50 Hz and 225 Hz. Alternatively, in some cases, the vibration control system might be used to reduce the peaks at 50 Hz or 225 Hz or at other levels. Reducing the image blur allows the fabrication system to produce finer trace dimensions and feature sizes and improves the accuracy of the feature placement

The foregoing description of embodiments and examples of the present invention are presented to demonstrate the range of constructions to which the invention applies. Those skilled in the art will appreciate that many other modifications and variations of the invention as set forth herein above may be made without departing from the spirit and scope thereof.

An additional aspect of the invention discussed herein relates to actively stabilizing (controlling the motion of) wafer stages in lithography tools in six degrees of freedom. Figure 22,, illustrates an exemplary simplified two-dimensional physics model of a wafer stage base 501 and a wafer stage 500. This concept is readily generalizable to a real system in which three-dimensions are of concern.

The masses of the stage and the base are relatively similar and each weigh approximately 200 kg. The wafer stage base measures approximately 1m in length x 1 m in width x 0.15 m in thickness. The wafer stage measures approximately 1.25 m in length x 0.5 m in width x 0.5 m in thickness. Actuator (motor) inputs are represented by the symbol u_i, where i represents a specific voice coil motor. Alternative actuators are contemplated which include linear piezoceramic motors. Sensor outputs are represented by y_i, where i represents a laser displacement measurement that is collocated with the voice coil input. Alternative output sensors (including linear variable displacement transducers (LVDT's), accelerometers) and sensor locations (nearly co-located, sufficiently colocated) are contemplated for this example. Disturbances (represented by d_i) to the system include on-board (including motors, fans, and articulating arms) and off-board disturbances (including ground vibrations, air currents, thermal fluctuations).

The wafer stage 500 is supported on the wafer stage base by a pneumatic system 502 comprised of airbearings. This airbearing is provided to allow the wafer stage 500 to move nearly frictionless with respect to the wafer base stage 501. The wafer stage base 501 is supported on the ground by a pneumatic system of airmounts 503 and 504. The physical properties of the airmounts are represented by a spring (k1) and a dashpot (c1). The physical properties of the airbearing are represented by a spring (k2) and a dashpot (c2). The pneumatic system 503 and 504 offsets the weight of the wafer stage 500 and the wafer stage base 501 with respect to the ground. The pneumatic system 503 and 504 provides a low-frequency (approximately several Hertz) control of the plunge and tilt of the wafer stage base 501. Additional high frequency control of the base stage 501 is provided by the voice coil motors u1, u2. A microprocessor system 510 is typically used to sense the outputs and command (actuate) the inputs as a function of the control algorithm implemented by the microprocessor system 510. The system 510 attempts to move or position the wafer stage 500 relative to the wafer stage base 501 based upon the lithography system requirements. For example the lithography system may require a constant scanning motion of the wafer stage 500 to be performed during exposure of an image on a wafer. Alternatively, the lithography system may command a rapid acceleration of the wafer stage 500 to re-locate the wafer stage to an alternative position. The wafer stage 500 would be required to make these movements to meet requirements of speed, accuracy, and/or settling time. Settling time refers to the time required to achieve a given position within some allowable variation of the absolute position. These prescribed motions with very high accelerations (up to 2g), create significant reaction forces that are transmitted to the base. In addition, these motions cause the compound center of gravity of the base stage system to rapidly change position. Currently base stabilization control is accomplished by the microprocessor system 510 through the implementation of six independent single-input, single-output (SISO) controller. Typically a SISO controller is used for each degree of freedom in the specific application. Typical three-dimensional systems could possess six degrees of freedom for each independently controlled system component or stage. SISO controllers are generally susceptible to variations in the location of the stage relative to the base. This is because the individual controller is not provided with additional output information. In one embodiment, the invention described herein, uses a multi-input, multi-output controller (MIMO) to achieve better performance than a SISO implementation even with variations of the location of the stage relative to the base. In a MIMO implementation the control is accomplished with knowledge of the output and input of more than one sensor (output) and actuator (input). Additionally, MIMO control architecture allows for the implementation of modern control techniques, including but not limited to, linear quadratic Gaussian (LQG), H-infinity, and mu synthesis. These techniques cannot be efficiently combined with SISO architecture.

Figure 23 illustrates how well a MIMO controller can follow (indicated by ACX roll moment command) a commanded input (stage pitch disturbance) to the roll moment compared with typical performance of a SISO controller (indicated by Nominal roll moment command). The MIMO controller tracks very closely to the disturbance. Thus, it is capable of reacting very quickly to a disturbance force and reject it from the system. This improves some combination of the speed, accuracy, or throughput of the stage.

In another embodiment of a stage control application in a lithography system, it was desired to decrease the settling time for a system to accurately track a commanded position. Figure 24 illustrates the block diagram that describes the embodiment. In this embodiment, three accelerometers 600, 601, 602 are used as the sensor for feedback control. Accelerometers 600 and 601 represent accelerometers that measure x-axis acceleration. Accelerometer 602 represents a single accelerometer that measures y-axis acceleration. These measurements which are generally proportional to the acceleration are sent to a signal conditioner 606 that buffers the signals and then sends the signals which are generally proportional to the acceleration of the stage to a single board computer 607. A representative single board computer is Model SBC67 supplied by Innovative Integration Inc. with offices in Simi Valley, CA. This processor is a high performance stand-alone digital signal processor single board computer featuring analog input and output capability. The voltage signals 612 a,b,c are fed into analog inputs. These analog inputs are then converted to digital signals that the processor then applies a control algorithm or filter to. The algorithm creates a set of digital signals which are then converted to analog output signals 613 a,b,c,d. These output signals are then applied to each of the four motors 608, 609, 610, 611. Motors 608 and 609 are x-axis motors that control the position of the stage in the x-axis. Motors 610 and 611 are y-axis motors that control the position of the stage in the y-axis. X-axis interferometer 603 and Y-axis interferometer 604 are used to measure the x and y position of the stage relative to the base of the stage (which is not depicted here for simplification).

The filter (feedback control algorithm) may be designed using the standard Linear Quadratic Regulator approach, ensuring that the motor control signals do not exceed the motor or motor amplifier limits. Motor control signals in the closed feedback loop are proportional to the accelerometer 600,601,602 signals associated with acceleration of the stage. Control design was accomplished by first creating a state-space plant model from transfer function data using the Smart ID™ system identification software package commercially available from Active Control Experts, Inc. with offices in Cambridge, Massachusetts. The filter (or controller) was then designed through computer simulation and application of techniques discussed in Fanson and *The Control Handbook, William S. Levine, Editor, CRC Press, 1996.*

Figure 25 and 26 represent experimental and analytical results of the MIMO control applied in this embodiment. The MIMO results are compared with results in which multiple SISO loops are instead utilized. Figure 26 illustrates the results when zoomed in between the 0.15s and 0.30s time period. This figure illustrates that the MIMO control settles to within the settle range (approximately 100 on the y-axis of the graph) by approximately 0.19 s while the SISO (existing controller) only achieves this performance at approximately 0.26 s. This represents an improvement in settling time of approximately 30%.

What is claimed is:

CLAIMS

1. An motion control system for use with a lithography system, said motion control system comprising:

a wafer stage base;

at least two actuators for controlling motion;

at least two sensors for detecting at least one parameter of displacement of said wafer base and producing at least two signals in response thereto; and

at least one circuit in electrical communication with said actuators and said sensors;

wherein, upon the detection of said at least one parameter of displacement by said sensors, said sensors signal said circuit, which, in response, activates said actuators to stabilize the wafer stage base.

2. The motion control system of claim 1, said actuators are selected from the group consisting of a voice coil motor and electroactive stack actuator.

3. The motion control system of claim 1, said sensors selected from the group consisting of LVDT, accelerometer, laser interferometer, capacitive displacement sensor.

4. The motion control system of claim 1, said circuit comprising a digital signal processor.

5. The motion control system of claim 1, said circuit comprising:

at least one digital signal processor,

at least one analog to digital converter, and

at least one digital to analog converter.

6. The motion control system of claim 1, said circuit comprising a control technique.

7. The control technique of claim 6, said control technique selected from the group of linear quadratic gaussian, H-infinity, and mu-synthesis.

8. The motion control system of claim 1, wherein said actuators stabilize said wafer stage base to closely follow a commanded input.

9. An motion control system for use with a lithography system, said motion control system comprising:

a wafer stage;

at least two actuators for controlling motion;

at least two sensors for detecting at least one parameter of displacement of said wafer base and producing at least two signals in response thereto;

a signal conditioner; and

a single board computer

wherein, upon the detection of said at least one parameter of displacement by said sensors, said sensors feed a signal to said signal conditioner, said signal conditioner feeds a signal to said single board computer, and said single board computer commands said actuators to command said wafer stage to track a commanded position.

10. The motion control system of claim 9, wherein said actuators are selected from the group consisting of voice coil motor and electroactive stack actuator.

11. The motion control system of claim 9, wherein said sensors are selected from the group consisting of LVDT, accelerometer, laser interferometer, capacitive displacement sensor.

12. The motion control system of claim 9, wherein said wafer stage is commanded to track a commanded position within 0.19 seconds.

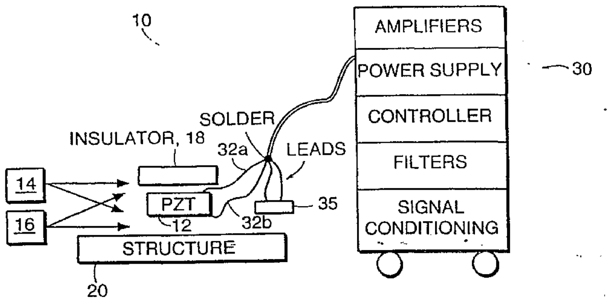


FIG. 1A
(PRIOR ART)

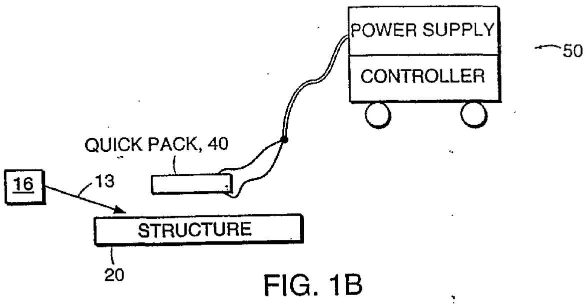


FIG. 1B

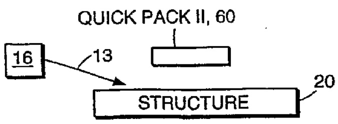


FIG. 1C

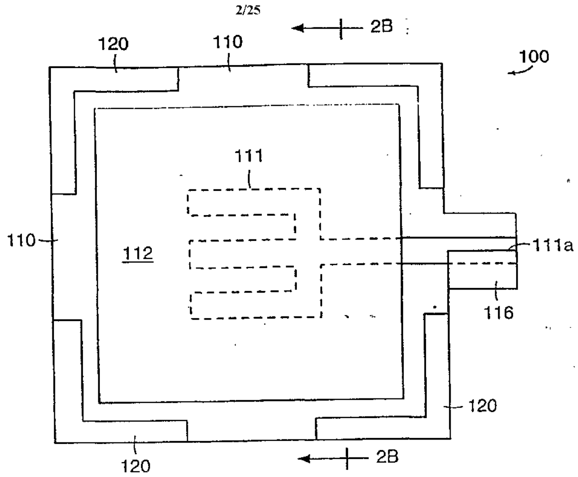

2B
120
110
100
111
110
112
111a
116
120
120
2B

FIG. 2A

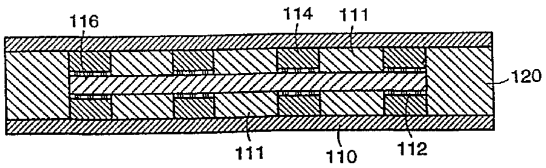

116
114
111
120
111
110
112

FIG. 2B

WO 02/073318 PCT/US02/06974

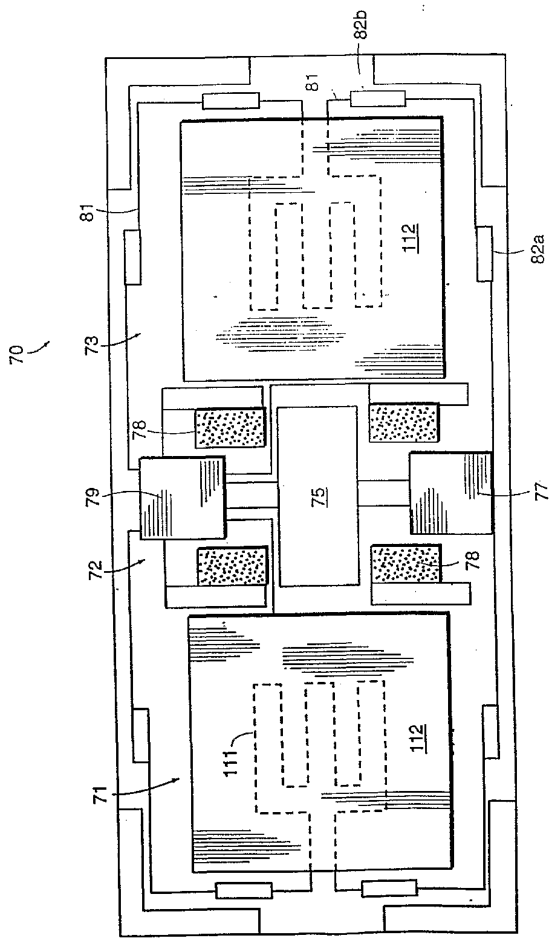


FIG. 2C

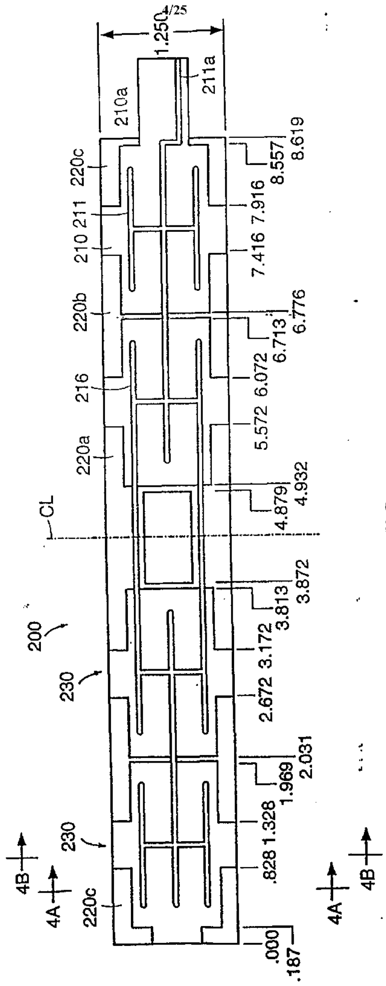

1.250
210a
211a
220c
210 211
220b
216
220a
CL
200
230
230
220c
4A
4B
8.619
8.557
7.916
7.416
6.776
6.713
6.072
5.572
4.932
4.879
3.872
3.813
3.172
2.672
2.031
1.969
1.328
.828
.000
.187

FIG. 3

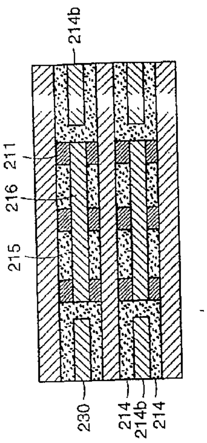

214b
211
216
215
230
214
214b
214

FIG. 4B

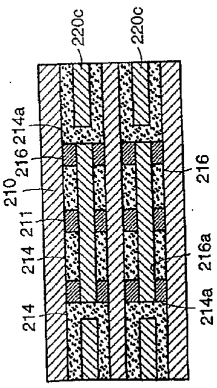

220c
220c
214a
216
210
211
214
214
216
216a
214a

FIG. 4A

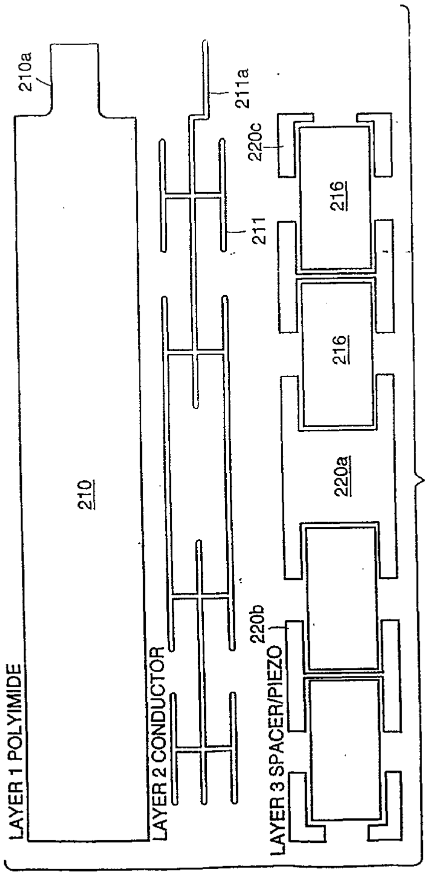

LAYER 1 POLYIMIDE
210
210a
LAYER 2 CONDUCTOR
211
211a
LAYER 3 SPACER/PIEZO
216
216
220a
220b
220c

FIG. 5

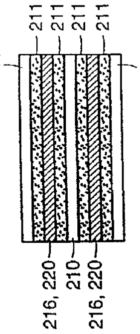

210
211
211
211
211
210
216, 220
210
216, 220

FIG. 5A

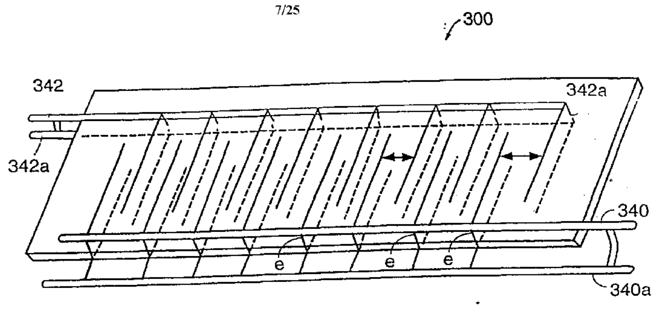


FIG. 6

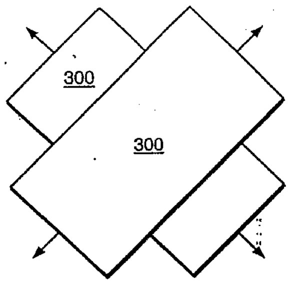


FIG. 7

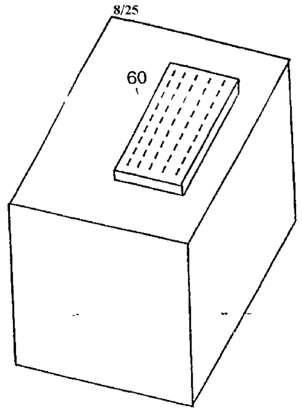


FIG. 8A

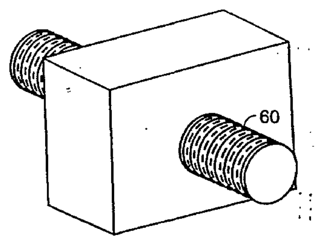


FIG. 8B

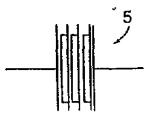


FIG. 9A

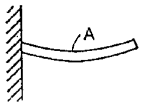


FIG. 9B

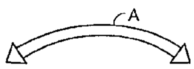


FIG. 9C

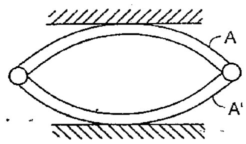


FIG. 9D

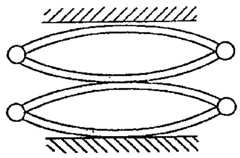


FIG. 9E

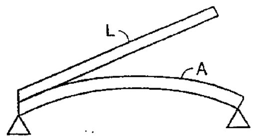


FIG. 9F

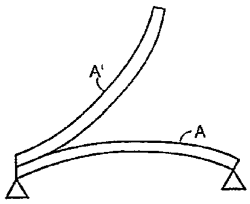


FIG. 9G

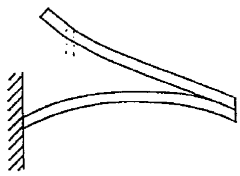


FIG. 9H

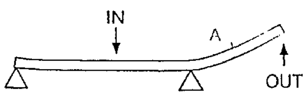


FIG. 9I

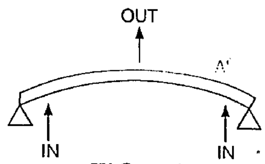


FIG. 9J

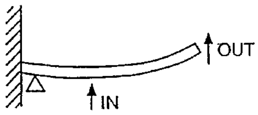


FIG. 9K

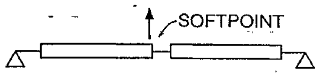


FIG. 9L

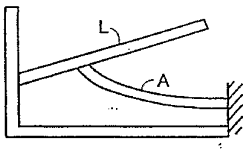


FIG. 9M

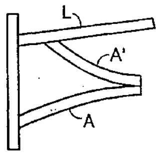


FIG. 9N

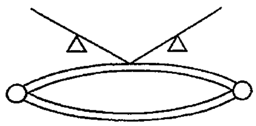


FIG. 9O

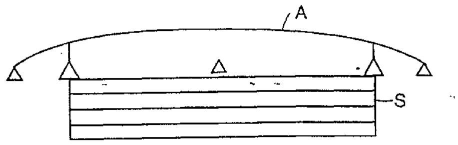


FIG. 9P

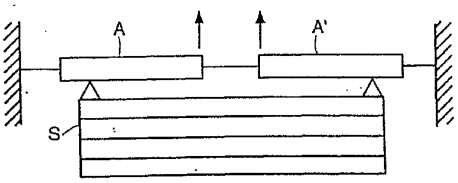


FIG. 9Q

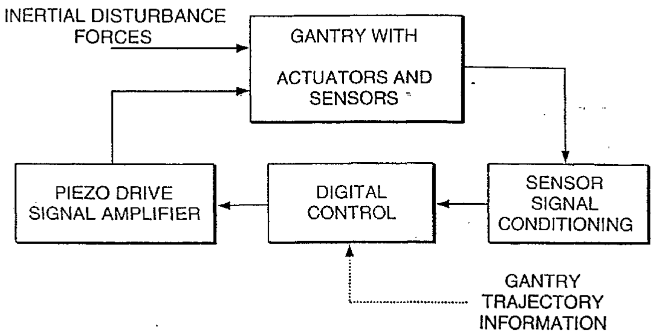

INERTIAL DISTURBANCE FORCES
GANTRY WITH
ACTUATORS AND SENSORS
PIEZO DRIVE SIGNAL AMPLIFIER
DIGITAL CONTROL
SENSOR SIGNAL CONDITIONING
GANTRY TRAJECTORY INFORMATION

FIG. 10

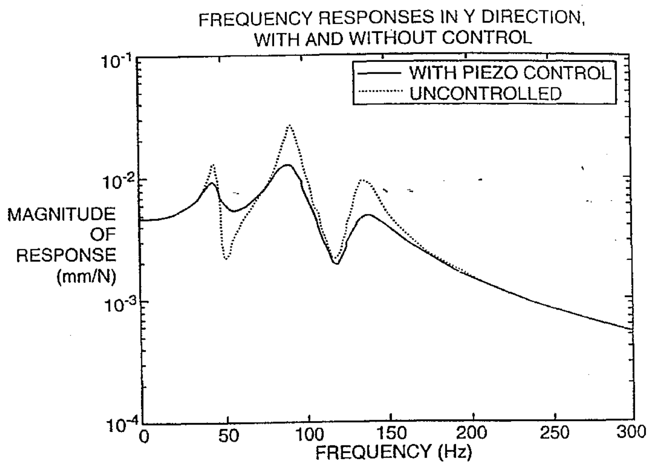

FREQUENCY RESPONSES IN Y DIRECTION,
WITH AND WITHOUT CONTROL
WITH PIEZO CONTROL
UNCONTROLLED
MAGNITUDE OF RESPONSE (mm/N)
10-1
10-2
10-3
10-4
0
50
100
150
200
250
300
FREQUENCY (Hz)

FIG. 11

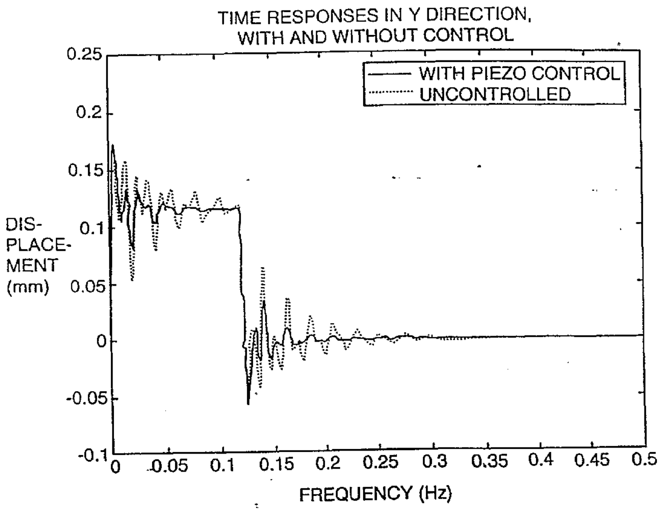

TIME RESPONSES IN Y DIRECTION, WITH AND WITHOUT CONTROL
WITH PIEZO CONTROL
UNCONTROLLED
DIS-PLACE-MENT (mm)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
FREQUENCY (Hz)

FIG. 12

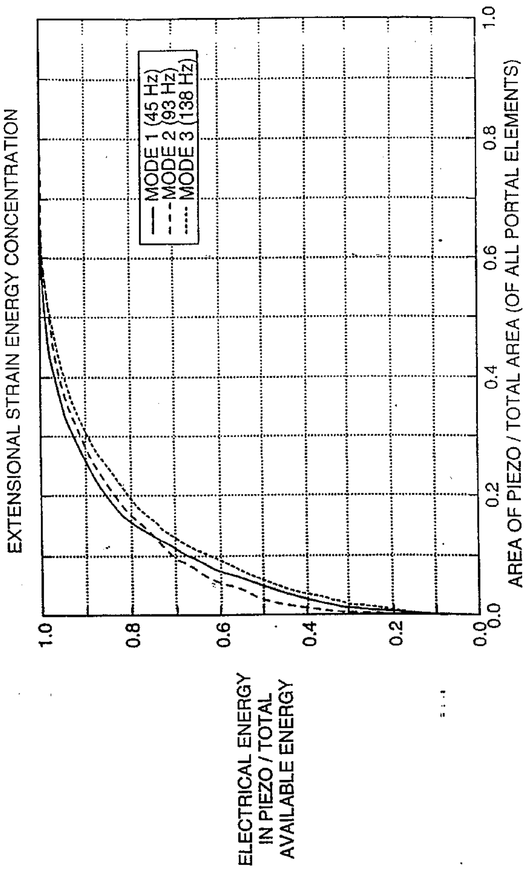

EXTENSIONAL STRAIN ENERGY CONCENTRATION
MODE 1 (45 Hz)
MODE 2 (93 Hz)
MODE 3 (138 Hz)
ELECTRICAL ENERGY
IN PIEZO / TOTAL
AVAILABLE ENERGY
1.0
0.8
0.6
0.4
0.2
0.0
AREA OF PIEZO / TOTAL AREA (OF ALL PORTAL ELEMENTS)

FIG. 13

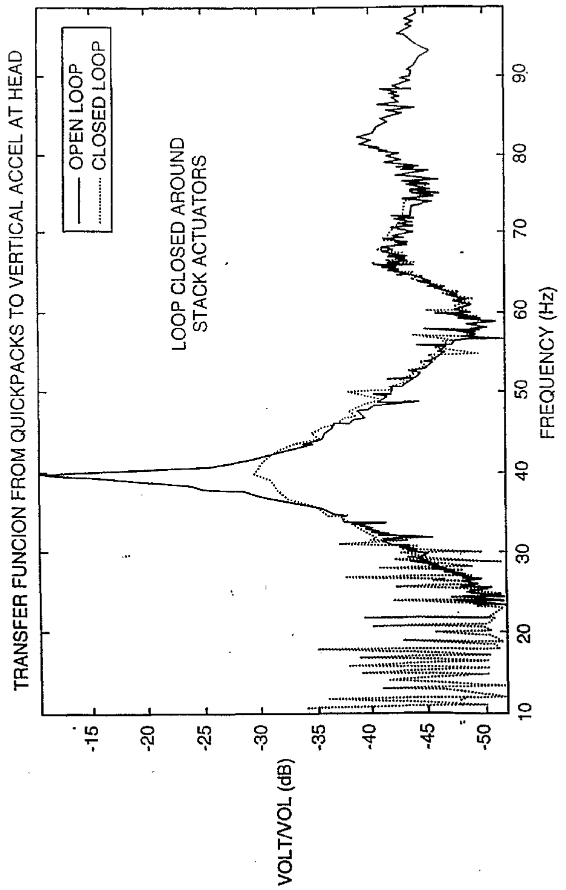

TRANSFER FUNCION FROM QUICKPACKS TO VERTICAL ACCEL AT HEAD
OPEN LOOP
CLOSED LOOP
LOOP CLOSED AROUND STACK ACTUATORS
VOLT/VOL (dB)
FREQUENCY (Hz)
-15
-20
-25
-30
-35
-40
-45
-50
10
20
30
40
50
60
70
80
90

FIG. 14

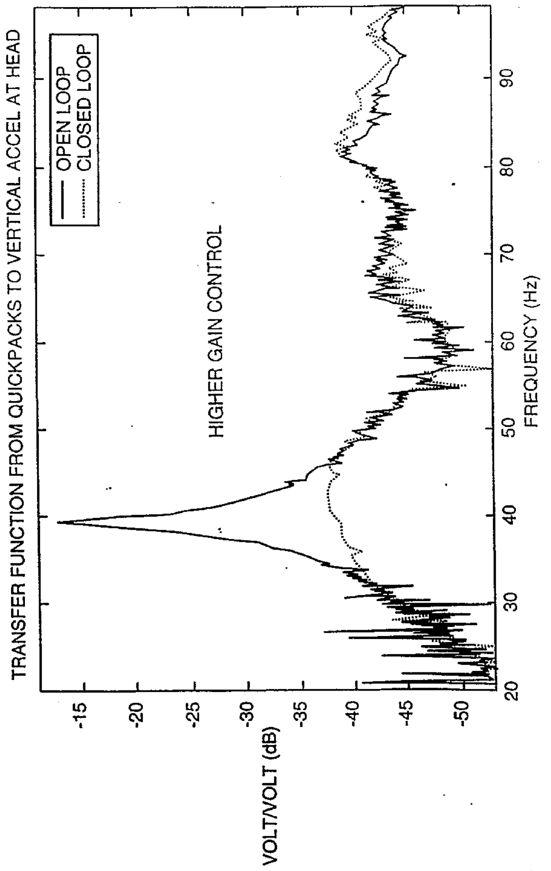

TRANSFER FUNCTION FROM QUICKPACKS TO VERTICAL ACCEL AT HEAD
OPEN LOOP
CLOSED LOOP
HIGHER GAIN CONTROL
VOLT/VOLT (dB)
-15
-20
-25
-30
-35
-40
-45
-50
20
30
40
50
60
70
80
90
FREQUENCY (Hz)

FIG. 15

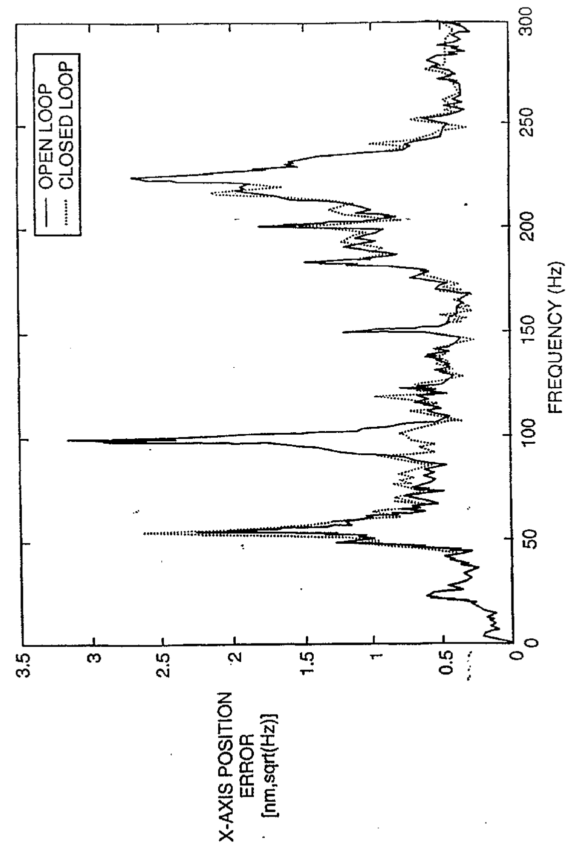

OPEN LOOP
CLOSED LOOP
X-AXIS POSITION
ERROR
[nm,sqrt(Hz)]
FREQUENCY (Hz)
0
0.5
1
1.5
2
2.5
3
3.5
0
50
100
150
200
250
300

FIG. 16

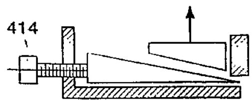


FIG. 17

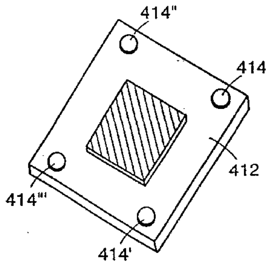


FIG. 18

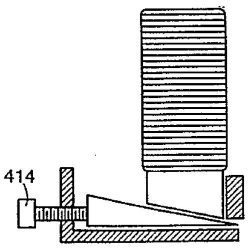


FIG. 19

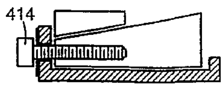


FIG. 20

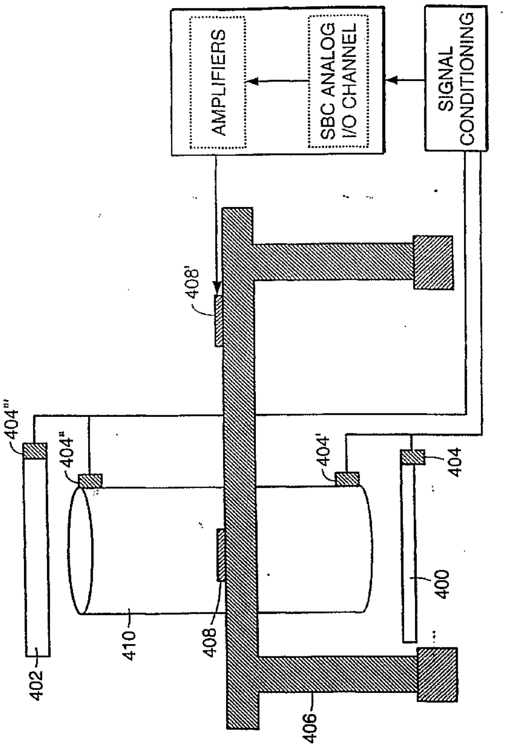
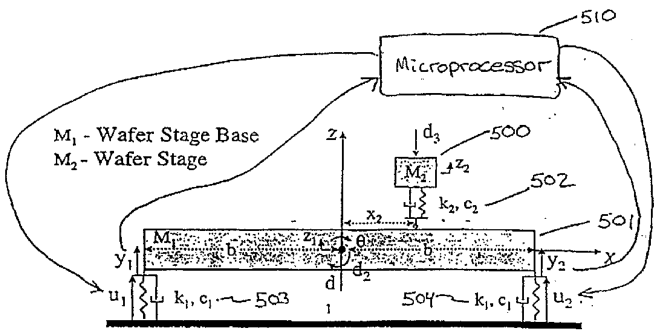

AMPLIFIERS
SBC ANALOG I/O CHANNEL
SIGNAL CONDITIONING
408'
404'''
404''
404'
404
410
408
402
400
406

FIG. 21



- Inputs (u_i): Voice Coil forces on base in Z
- Outputs (y_i): Laser displacement measurements collocated with voice coil inputs
- Disturbances (d_i): Z-force and θ moment on base, Z force on stage

FIG. 22

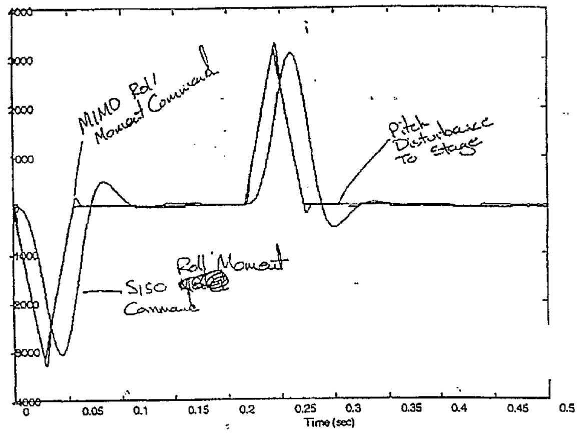

MIMO Roll Moment Command
Pitch Disturbance To Stage
SISO Roll Moment Command
Time (sec)

FIG. 23

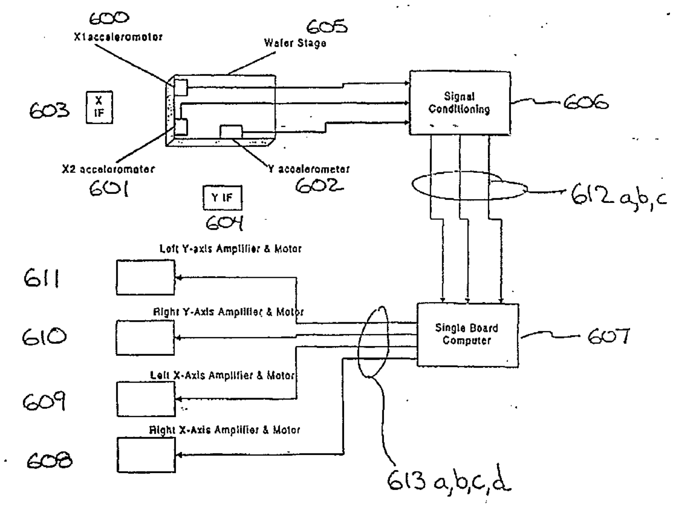

600
X1 accelerometer
605
Wafer Stage
603
X
IF
Signal
Conditioning
606
X2 accelerometer
601
Y accelerometer
602
612 a,b,c
Y IF
604
Left Y-axis Amplifier & Motor
611
Right Y-Axis Amplifier & Motor
610
Single Board
Computer
607
Left X-Axis Amplifier & Motor
609
Right X-Axis Amplifier & Motor
608
613 a,b,c,d

FIG. 24

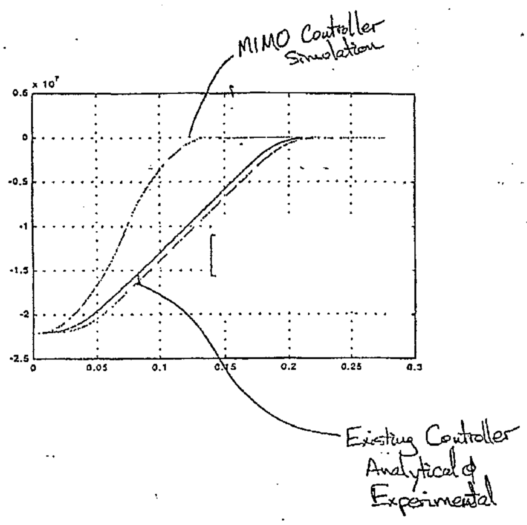

MIMO Controller Simulation
x 10^7
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
0.05
0.1
0.15
0.2
0.25
0.3
Existing Controller Analytical & Experimental

FIG. 25

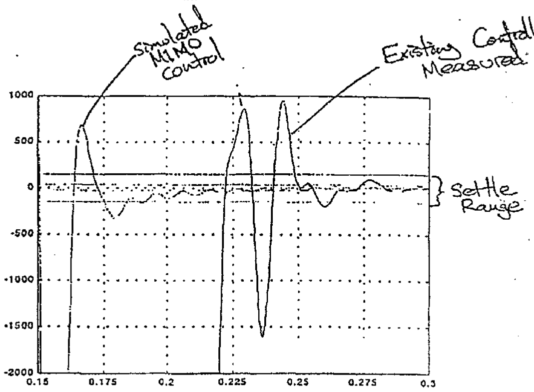

Simulated MIMO control
Existing Controller Measured
Settle Range
1000
500
0
-500
-1000
-1500
-2000
0.15
0.175
0.2
0.225
0.25
0.275
0.3

FIG. 26

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(54) Title: METHOD AND DEVICE FOR VIBRATION CONTROL

(57) Abstract: A vibration control system comprising an actuator, and a sensor useful for controlling vibrations in systems for fabricating electronics equipment. The actuator may comprise one or more plates or elements of electroactive material bonded to an electroded sheet.

METHOD AND DEVICE FOR VIBRATION CONTROL

Related Applications

This application claims the benefit of U.S. Application No. 09/803,302, filed March 9, 2001.

Background of the Invention

In the competitive marketplace which exists for automated surface-mount (SMT) electronics equipment, including systems for fabricating electronics equipment or components, improvements in accuracy and speed are a significant advantage. Such equipment is often used in fabricating, for example, semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices, and may feature multiple gantry/head assemblies, linear motors, photoimaging systems, etching systems, and/or a number of other technologies. The present invention relates to devices and methods for reducing vibration inherent in such equipment during operation thereby to improve the speed and/or accuracy of such equipment.

For example, modern photolithography tools require extremely high exposure accuracy. This can only be achieved if the levels of elastic displacement at crucial points in the tool do not exceed several nano-meters. Since lithography tools contain numerous moving parts such as the reticle and wafer stages, they are subject to persistent disturbing forces acting on their structure. Moreover, the tool structure is subject to environmental disturbances such as floor vibrations and air turbulence. While the level of these disturbances can be reduced, they cannot be eliminated in their entirety.

There are a number of existing techniques employed to limit the elastic vibration of lithography tools. For example, the stiffness of the structure that supports key elements such as the lens assembly may be increased, tuned mass dampers may be used, the signals applied to the moving stages may be shaped, or the floor vibrations may be isolated using actively controlled air springs. While effective in reducing elastic vibration, these methods often do not meet the stringent requirements of more advanced photolithography tools.

Current efforts to control vibration on SMT placement equipment include placing frictional damping device at the end of the gantry. This "friction block" serves mainly to stabilize the gantry and head trajectory control system, but it also has been shown to reduce the settling time during certain pick and place operations. However, the effectiveness of the friction block depends on precise tuning of the normal force (or pre-load). The friction block tends to wear out quickly, greatly reducing its effectiveness and contaminating the rest of the machine with particles. Moreover, the friction block works against rigid body movement, resulting in slower operation of the equipment. The vibration control system of the present invention, which comprises an actuator assembly, serves to replace the friction block entirely while improving settling time, or, alternatively, to operate in conjunction with the friction block, providing additional accuracy or speed of operation.

One aspect of the present invention relates to actuator elements useful for active vibration reduction, structural control, dynamic testing, precision positioning, motion sensing and control, and active damping. Electroactive materials, such as piezoelectric, electrostrictive or magnetostrictive materials, are useful in such tasks. In one embodiment of the invention, bare electroactive elements are used. In another embodiment, packaged electroactive elements, as described herein, are used.

Thus, improvements are desirable in the manner in which vibration is controlled in systems for fabricating electronic components, as well as the manner in which an actuator is attached to the equipment to be controlled.

Summary of the Invention

In one embodiment of the invention, a vibration control system is provided comprising an actuator assembly, and a sensor for sensing a parameter of movement or performance. The vibration control system is particularly useful for controlling vibration in systems for fabricating electronics components, which often include one or more gantry assemblies, head assemblies, and/or moving stages or components. Contemplated systems for fabricating electronics components include, but are not limited to, pick and place systems, lithography systems, and those used to fabricate semiconductor chips, printed circuit boards, liquid crystal displays, and thin film devices. However, the devices and methods of the invention would be useful in fabricating systems of any sort, such as machine tool equipment, milling equipment, or systems used in an automated assembly line. Also contemplated are systems for fabricating electronic components wherein the systems comprise a lens system, a wafer stage, and a structure for supporting the lens system and wafer stage where the lens system creates an image on the wafer stage such as would be used in modern photolithography.

In one embodiment, an active vibration control system for use with a photolithography fabricating system includes the following components: a sensor that measures the displacement levels at the key points, or provides information from which such information can be estimated; a digital or analog processor that can compute a control signal based on the sensors input, and an actuator that can induce elastic displacement in the structure.

In a particularly preferred embodiment, an actuator useful in an active vibration control system used in conjunction with photolithography tools is non-reactive and does not require back support (actuators that require back support may excite elastic vibrations in the support structure, which may be re-introduced unto the tool), and has a very low distortion profile (an actuator array designed to control structural vibration at a given frequency or band must not excite any vibration outside that band).

In a particularly preferred embodiment, a vibration control system in accordance with the invention comprises an induced-strain actuator that acts directly on the strain state of the structure, and has virtually no distortion. Such an actuator can excite, and therefore control, only the elastic vibration modes of the controlled structure, leaving all other vibration modes (such as the modes of various equipment housing structures, etc.) uncontrolled. This contributes to the control system simplicity and robustness.

In another preferred embodiment of the invention, the vibration control system further comprises a circuit in electrical communication with the actuator assembly and the sensor. In one embodiment, the sensor relays information about movement, vibration or performance to the circuit, which, in response, signals the actuator assembly to control vibration. The vibration in the systems in which the present invention are useful may be due to external disturbance or due to the inherent disturbances generated by the system itself.

In yet another preferred embodiment of the invention, the vibration control system further comprises an electrical connection to the fabricating system. The electrical connection may provide for the fabricating system to send to, or receive from the vibration control system information such as abling or disabling signals, system status signals, or fault/error status signals. In another embodiment, a circuit according to the invention further comprises a control system comprising at least one controller. Such a control system may permit auto-tuning, gain scheduling, external gain control, or it may be a linear feed forward control, or may serve as another source of feedback control.

In an embodiment of the invention wherein the vibration control system has an auto-tuning control, prior to operation, the control system injects one or more test signals into the system and measures the response. The measured response is used to refine an internal model of the plant, and the control gains are modified accordingly. Control gains are kept constant while the loop is closed.

In an embodiment of the invention wherein the vibration control system has a gain scheduling control, the controllers are designed for the system at several different operating points. In the case of a pick and place machine, these points would be different positions of the pick and place head. The controllers are stored in memory in the digital control system. During operation, sensors feed information to the controller describing the configuration of the machine in real time. As the system moves through each operating point, the control system switches to the optimal control gains for that point. A variant of this is that the control gains used at any point in time are a linear interpolation of the gains from several controllers stored in memory for several nearby operating points.

In an embodiment of the invention wherein the vibration control system has an external gain control, the control system includes an input which connects to the computer system which monitors the overall performance of the machine. The controller implemented at any instant in time has a gain which is proportional to this signal. The monitoring system modifies this gain until optimal performance is achieved. If performance begins to move out of specification due to slow time variation, the monitoring system would repeat the gain optimization sequence.

In an embodiment of the invention wherein the vibration control system has a feed forward control, in addition to the feedback control (controller driven by signals originating from sensors which monitor the structural vibration), an additional signal which is in phase with a harmonic disturbance (such as motor rotation) provided to the controller. The controller feeds forward a filtered version of this signal. The gains which adjust the magnitude and phase of the feed forward control relative to the disturbance signal are adjusted adaptively to minimize the influence of the disturbance on the performance.

In certain embodiments of the invention, the actuator assembly may comprise a strain actuator, an electroactive strain actuator, a piezoceramic strain actuator, an electroactive stack actuator, or at least two actuators. In yet another embodiment of the invention, the actuator assembly is in electrical communication with the sensor.

Also in certain embodiments of the invention, the sensor may comprise a strain sensor, an accelerometer, laser displacement sensor, laser interferometer, or at least two sensors. In another embodiment of the invention, the sensor may comprise at least two sensors measuring at least two different signals. In a preferred embodiment, the sensor directly measures some aspect directly related to performance of the systems in which the present invention is useful.

In a particularly preferred embodiment of the invention, the vibration control system comprises an electronic link or cable providing information about the trajectory of a gantry and head.

An actuator assembly according to the present invention may include one or more strain elements, such as a piezoelectric or electrostrictive plate, shell, fiber or composite; a housing forming a protective body about the element; and electrical contacts mounted in the housing and connecting to the strain element; these parts together forming a flexible card. At least one side of the assembly includes a thin sheet which is attached to a major face of the strain element, and by bonding the outside of the sheet to an object a stiff shear-free coupling is obtained between the object and the strain element in the housing.

In a preferred embodiment, the strain elements are piezoceramic plates, which are quite thin, preferably between slightly under an eighth of a millimeter to several millimeters thick, and which have a relatively large surface area, with one or both of their width and length dimensions being tens or hundreds of times greater than the thickness dimension. A metallized film makes electrode contact, while a bonding agent and insulating material hermetically seal the device against delamination, cracking and environmental exposure. The bonding agent used may be an epoxy, such as B-stage or C-stage epoxy, a thermoplastic, or any other material useful in bonding together the piezoceramic plate, metallized film and insulating material. The specific bonding agent used will depend on the intended application of the device. In a preferred embodiment, the metallized film and insulating material are both provided in a flexible circuit of tough polymer material, which thus provides robust mechanical and electrical coupling to the enclosed elements. Alternatively, the metallized film may be located directly on the piezoceramic plate, and the insulating material may have electrical contacts.

By way of illustration, an example below describes a construction utilizing rectangular PZT plates a quarter millimeter thick, with length and width dimensions each of one to three centimeters, each element thus having an active strain-generating face one to ten square centimeters in area. The PZT plates are mounted on or between sheets of a stiff strong polymer, e.g., one half, one or two mil polyimide, which is copper clad on one or both sides and has a suitable conductive electrode pattern formed in the copper layer for contacting the PZT plates. Various spacers surround the plates, and the entire structure is bonded together with a structural polymer into a waterproof, insulated closed package, having a thickness about the same as the plate thickness, e.g., .30 to .50 millimeters. So enclosed, the package may bend, extend and flex, and undergo sharp impacts, without fracturing the fragile PZT elements which are contained within. Further, because the conductor pattern is firmly attached to the polyimide sheet, even cracking of the PZT element does not sever the electrodes, or prevent actuation over the full area of the element, or otherwise significantly degrade its performance.

The thin package forms a complete modular unit, in the form of a small "card", complete with electrodes. The package may then conveniently be attached by bonding one face to a structure so that it couples strain between the enclosed strain element and the structure. This may be done for example, by simply attaching the package with an adhesive to establish a thin, high shear strength, coupling with the PZT plates, while adding minimal mass to the system as a whole. The plates may be actuators, which couple energy into the attached structure, or sensors which respond to strain coupled from the attached structure.

In different embodiments, particular electrode patterns are selectively formed on the sheet to either pole the PZT plates in-plane or cross-plane, and multiple layers of PZT elements may be arranged or stacked in a single card to result in bending or shear, and even specialized torsional actuation.

In accordance with a further aspect of the invention, circuit elements are formed in, or with, the vibration control system to filter, shunt, or process the signal produced by the PZT elements, to sense the mechanical environment, or even to locally perform switching or power amplification for driving the actuation elements. The actuator package may be formed with pre-shaped PZT elements, such as half-cylinders, into modular surface-mount shells suitable for attaching about a pipe, rod or shaft.

Brief Description of the Drawings

These and other desirable properties of the invention will be understood from the detailed description of illustrative embodiments, wherein:

FIGURE 1A is a system illustration of a typical prior art actuator;

FIGURE 1B and 1C are corresponding illustrations of two systems in accordance with the present invention;

FIGURES 2A and 2B show top and cross-sectional views, respectively, of a basic actuator or sensor card in accordance with the present invention; FIGURE 2C illustrates an actuator or sensor card with circuit elements;

FIGURE 3 illustrates another card;

FIGURES 4A and 4B show sections through the card of FIGURE 3;

FIGURES 5 and 5A show details of the layer structure of the card of FIGURE 3;

FIGURE 6 shows an actuator package comb electrodes for in-plane actuation;

FIGURE 7 illustrates a torsional actuator package using the cards of FIGURE 6;

FIGURES 8A and 8B show actuators mounted as surface mount actuators on a surface or rod, respectively;

FIGURE 9 shows actuators mounted as mechanical elements;

FIGURE 10 shows a block diagram of an embodiment of an electroactive vibration control system for a gantry;

FIGURE 11 shows a simulated frequency response on a collect and place head at the tip of a gantry, without and with electroactive vibration control;

FIGURE 12 shows the simulated time response of a collect and place head without and with electroactive control;

FIGURE 13 shows extensional strain energy concentration;

FIGURE 14 shows the results of a closed loop test on the frequency response of a pick and place machine having a vibration control system in accordance with the invention;

FIGURE 15 shows the results of a closed loop test on the gain control of a pick and place machine having a vibration control system in accordance with the invention;

FIGURE 16 shows the power spectral density of error signals recorded by a laser metrology system in a lithography machine;

FIGURES 17-20 show different embodiments of the invention as used with a fabricating system;

FIGURE 21 shows an embodiment of the invention as used with a fabricating system;

FIGURE 22 shows a simplified two-dimensional physics model of a wafer stage and wafer stage base;

FIGURE 23 shows controller results;

FIGURE 24 shows a block diagram for stage control;

FIGURE 25 shows experimental and analytical results;

FIGURE 26 shows experimental and analytical results.

Detailed Description of the Invention

Applicants have developed a vibration control system particularly useful for controlling vibration in a system for fabricating electronics components. The vibration control system of the invention is useful for controlling vibration that is either externally produced in the system for fabricating components, or is internal to or inherent in the system. Internal vibration may be caused by various motors, such as step or D.C. motors, or hydraulic or pneumatic actuators used in a fabricating system.

A vibration control system according to the invention may comprise electroactive actuators and sensors, integrated with the fabricating system. The control and power electronics may be separate units, located adjacent to the equipment and connected to the actuators and sensors through appropriate linking cabling. Alternatively, the control and power electronics may be a fully integrated system with the fabricating system.

The electroactive actuator may be secured to or within the fabricating system in various ways. As shown in Figures 17, 19, and 20, for example, the actuator may be fixed into place by a bolt 414 either pushing against or going through the actuator. Alternatively, the actuator may be secured by friction, tension, or otherwise force fit. In one embodiment , as shown in Figure 18, the actuator is bonded to a plate 412, which, in turn, is bolted to a component of a the fabricating system with bolts 414, 414', 414", and 414'''. In another embodiment, the actuator is bonded to a plate, which is bolted to a second plate, and the second plate is then bolted to a component of the fabricating component. In another embodiment, the actuator assembly is detachably secured within the vibration control system, or detachably secured to a component of a fabricating system.

Figure 21 shows an embodiment of the invention as used in a fabricating system. In this embodiment, the fabricating system comprises a wafer stage 400, a reticle stage 402, laser interferometers 404, 404', 404", and 404''' with X&Y mirrors, and a support structure 406. The support structure 406 supports a lens assembly 410. The interferometers 404, 404', 404", and 404''' are located on the wafer stage 400, the reticle stage 402, and on the lens assembly 410. Mounted on the support structure 406 are two actuators 408 and 408' comprising, for example, an electroactive element. Each of the actuators 408 and 408' are in electrical communication with a circuit. Signals from the interferometers 404, 404', 404", and 404''' are relayed through an SBC analog I/O channel and amplifiers to the actuators 408 and 408', which, in response, controls vibration within the fabricating system. By controlling the vibration within the fabricating system, the accuracy of the placement and absolute size of the metallized traces in the semiconductor on a wafer stage may be improved. Alternatively or in addition, the through-put of the fabrication system may be increased without decreasing accuracy.

Useful in this invention are electroactive actuator assemblies. Figure 1A illustrates in schema the process and overall arrangement of a prior art surface mounted piezoelectric actuator assembly 10. A structure 20, which may be a structural or machine element, a plate, airfoil or other interactive sheet, or a device or part thereof has a sheet 12 of smart material bonded thereto by some combination of conductive and structural polymers, 14, 16. An insulator 18, which may be formed entirely or in part of the structural polymer 16, encloses and protects the smart material, while conductive leads or surface electrodes are formed or attached by the conductive polymer. An external control system 30 provides drive signals along lines 32a, 32b to the smart material, and may receive measurement signals from surface-mounted instrumentation such as a strain gauge 35, from which it derives appropriate drive signals. Various forms of control are possible. For example, the strain gauge may be positioned to sense the excitation of a natural resonance, and the control system 30 may simply actuate the PZT element in response to a sensor output, so as to stiffen the structure, and thereby shift its resonant frequency. Alternatively, a vibration sensed by the sensor may be fed back as a processed phase-delayed driving signal to null out an evolving dynamic state, or the actuator may be driven for motion control. In better-understood mechanical systems, the controller may be programmed to recognize empirical conditions, i.e., aerodynamic states or events, and to select special control laws that specify the gain and phase of a driving signal for each actuator 12 to achieve a desired change.

For all such applications, major work is required to attach the bare PZT plate to its control circuitry and to the workpiece, and many of the assembly steps are subject to failure or, when quantitative control is desired, may require extensive modeling of the device after it has been assembled, in order to establish control parameters for a useful mode of operation that are appropriate for the specific thicknesses and mechanical stiffnesses achieved in the fabrication process. A benefit of packaging an electroactive element when bonding to the plate is that electrical isolation or capacitive decoupling from the plate, structure or any part of the fabrication system may be achieved.

FIGURE 1B shows an actuator assembly useful in one embodiment of the present invention. As shown, it is a modular pack or card 40 that simply attaches to a structure 20 with a quick setting adhesive, such as a five-minute epoxy 13, or in other configurations attaches at a point or line. The operations of sensing and control thus benefit from a more readily installable and uniformly modeled actuator structure. In particular, the modular pack 40 has the form of a card, a stiff but bendable plate, with one or more electrical connectors preferably in the form of pads located at its edge (not shown) to plug into a multi-pin socket so that it may connect to a simplified control system 50. As discussed in greater detail below with respect to FIGURE 2C, the modular package 40 may also incorporate planar or low-profile circuit elements, which may include signal processing elements, such as weighting or shunting resistors, impedance matchers, filters and signal conditioning preamplifiers, and may further include switching transistors and other elements to operate under direct digital control, so that the only external electrical connections necessary are those of a microprocessor or logic controller, and a power supply.

In a further embodiment particularly applicable to some low power control situations, a modular package 60 as shown in Figure 1C may include its own power source, such as a battery or power cell, and may include a controller, such as a microprocessor chip or programmable logic array, to operate on-board drivers and shunts, thus effecting a complete set of sensing and control operations without any external circuit connections.

The present invention specifically pertains to piezoelectric polymers, and to materials such as sintered metal zirconate, niobate crystal or similar piezoceramic materials that are stiff, yet happen to be quite brittle. It also pertains to electrostrictive materials. As used in the claims below, both piezoelectric and electrostrictive elements, in which the material of the elements has an electromechanical property, will be referred to as electroactive elements. High stiffness is essential for efficiently transferring strain across the surface of the element to an outside structure or workpiece, typically made of metal or a hard structural polymer, and the invention in its actuator aspect does not generally contemplate soft polymer piezoelectric materials. While the terms "stiff" and "soft" are relative, it will be understood that in this context, the stiffness, as applied to an actuator, is approximately that of a metal, cured epoxy, high-tech composite, or other stiff material, with a Young's modulus greater than $.1 \times 10^6$, and preferably greater than $.2 \times 10^6$. When constructing sensors, instead of actuators, the invention also contemplates the use of low-stiffness piezoelectric materials, such as polyvinylidene difluoride (PVDF) film and the substitution of lower cure temperature bonding or adhesive materials. The principal construction challenges, however, arise with the first class of piezo material noted above, and these will now be described.

In general, the invention includes novel forms of actuators and methods of making such actuators, where "actuator" is understood to mean a complete and mechanically useful device which, when powered, couples force, motion or the like to an object or structure. In its broad form, the making of an actuator involves "packaging" a raw electroactive element to make it mechanically useful. By way of example, raw electroactive piezoelectric materials or "elements" are commonly available in a variety of semi-processed bulk material forms, including raw piezoelectric material in basic shapes, such as sheets, rings, washers, cylinders and plates, as well as more complex or composite forms, such as stacks, or hybrid forms that include a bulk material with a mechanical element, such as a lever. These materials or raw elements may have metal coated on one or more surfaces to act as electrical contacts, or may be non-metallized. In the discussion below, piezoelectric materials shall be discussed by way of example, and all these forms of raw materials shall be referred to as "elements", "materials", or "electroactive elements". As noted above, the invention further includes structures or devices made by these methods and operating as transducers to sense, rather than actuate, a strain, vibration, position or other physical characteristic, so that where applicable below, the term "actuator" may include sensing transducers.

Embodiments of the invention employ these stiff electrically-actuated materials in thin sheets - discs, annuli, plates and cylinders or shells - that are below several millimeters in thickness, and illustratively about one fifth to one quarter millimeter thick. Advantageously, this thin dimension allows the achievement of high electric field strengths across a distance comparable to the thickness dimension of the plate at a relatively low overall potential difference, so that full scale piezoelectric actuation may be obtained with driving voltages of ten to fifty volts, or less. Such a thin dimension also allows the element to be attached to an object without greatly changing the structural or physical response characteristics of the object. However, in the prior art, such thin elements are fragile, and may break due to irregular stresses when handled, assembled or cured. The impact from falling even a few centimeters may fracture a piezoceramic plate, and only extremely small bending deflections are tolerated before breaking.

In accordance with the present invention, the thin electrically actuated element is encased by layers of stiff insulating material, at least one of which is a tough film which has patterned conductors on one of its surfaces, and is thinner than the element itself. A package is assembled from the piezo elements, insulating layers, and various spacers or structural fill material, such that altogether the electrodes, piezo element(s), and enclosing films or layers form a sealed card of a thickness not substantially greater than that of the bare actuating element. Where elements are placed in several layers, as will be described below, the package thickness is not appreciably greater than the sum of the thicknesses of the stacked actuating elements.

FIGURE 2A illustrates a basic embodiment 100 of the invention. A thin film 110 of a highly insulating material, such as a polyimide material, is metallized, typically copper clad, on at least one side, and forms a rectangle which is coextensive with or slightly larger than the finished actuator package. A suitable material available for use in fabricating multilayer circuit boards is distributed by the Rogers Corporation of Chandler, Arizona as their Flex-I-Mid 3000 adhesiveless circuit material, and consists of a polyimide film formed on a rolled copper foil. A range of sizes are available commercially, with the metal foils being of 18 to 70 micrometer thickness, integrally coated with a polyimide film of 13 to 50 micrometer thickness. Other thicknesses may be fabricated. In this commercial material, the foil and polymer film are directly attached without adhesives, so the metal layer may be patterned by conventional masking and etching, and multiple patterned layers may be built up into a multilayer board in a manner described more fully below, without residual adhesive weakening the assembly or causing delamination. The rolled copper foil provides high in-plane tensile strength, while the polyimide film presents a strong, tough and defect-free electrically insulating barrier.

In constructions described below, the film constitutes not only an insulator over the electrodes, but also an outer surface of the device. It is therefore required to have high dielectric strength, high shear strength, water resistance and an ability to bond to other surfaces. High thermal resistance is necessary in view of the temperature cure used in the preferred fabrication process, and is also required for some application environments. In general, polyamide/imides have been found useful, but other materials, such as polyesters or thermoplastics with similar properties, may also be used.

In the present constructions, the foil layer is patterned by conventional masking and etch techniques (for example, photoresist masking and patterning, followed by a ferric chloride etch), to form electrodes for contacting the surface of piezo plate elements. Alternatively, a more ductile, thin conductive layer may be used. For example, a thin conductive layer may be printed on the polymer film or directly on the piezoelectric element using silver conductive ink. In FIGURE 2A, electrodes 111 extend over one or more sub-regions of the interior of the rectangle, and lead to reinforced pads or lands 111a, 111b extending at the edge of the device. The electrodes are arranged in a pattern to contact a piezoelectric element along a broadly-turning path, which crosses the full length and width of the element, and thus assures that the element remains connected despite the occurrence of a few cracks or local breaks in the electrode or the piezo element. Frame members 120 are positioned about the perimeter of sheet 110, and at least one piezoelectric plate element 112 is situated in the central region so that it is contacted by the electrodes 111. The frame members serve as edge binding, so that the thin laminations do not extend to the edge, and they also function as thickness spacers for the hot-press assembly operation described further below, and as position-markers which define the location of piezo plates that are inserted during the initial stages of assembling the laminated package.

FIGURE 2A is a somewhat schematic view, inasmuch as it does not show the layer structure of the device which secures it together, including a further semi-transparent top layer 116 (FIGURE 2B), which in practice extends over the plate 112 and together with the spacers 120 and sheet 110 closes the assembly. A similar layer 114 is placed under the piezo element, with suitable cut-outs to allow the electrodes 111 to contact the element. Layers 114, 116 are preferably formed of a curable epoxy sheet material, which has a cured thickness equal to the thickness of the metal electrode layer, and which acts as an adhesive layer to join together the material contacting it on each side. When cured, this epoxy constitutes the structural body of the device, and stiffens the assembly, extending entirely over a substantial portion of the surface of the piezo element to strengthen the element and arrest crack growth, thereby enhancing its longevity. Furthermore, epoxy from this layer actually spreads in a microscopically thin but highly discontinuous film, about .0025 mm thick, over the electrodes, bonding them firmly to the piezo plate, but with a sufficient number of voids and pinholes so that direct electrical contact between the electrodes and piezo elements still occurs over a substantial and distributed contact area.

FIGURE 2B shows a cross-sectional view, not drawn to scale, of the embodiment of FIGURE 2A. By way of rough proportions, taking the piezoelectric plate 112 as .2 - .25 millimeters in thickness, the insulating film 110 is much thinner, no more than one-tenth to one-fifth the plate thickness, and the conductive copper electrode layer 111 may have a thickness typically of ten to fifty microns, although the latter range is not a set of strict limits, but represents a useful range of electrode thicknesses that are electrically serviceable, convenient to manufacture and not so thick as to either impair the efficiency of strain transfer or introduce delamination problems. The structural epoxy 114 fills the spaces between electrodes 111 in each layer, and has approximately the same thickness as those electrodes, so that the entire assembly forms a solid block. The spacers 120 are formed of a relatively compressible material, having a low modulus of elasticity, such as a relatively uncrosslinked polymer, and, when used with a pressure-cured epoxy as described below, are preferably of a thickness roughly equivalent to the piezoceramic plate or stack of elements, so that they form an edge binding about the other components between the top and bottom layers of film 110.

A preferred method of manufacture involves applying pressure to the entire package as the layer 116 cures. The spacers 120 serve to align the piezoceramic plates and any circuit elements, as described below with reference to FIGURES 3-5, and they form a frame that is compressed slightly during assembly in the cure step, at which time it may deform to seal the edges without leaving any stress or irregularities. Compression eliminates voids and provides a dense and crack-free solid medium, while the curing heat effects a high degree of cross-linking, resulting in high strength and stiffness.

An assembly process for the embodiment of FIGURES 2A, 2B is as follows. One or more pieces of copper clad polyimide film, each approximately .025 to .050 millimeters thick in total, are cut to a size slightly larger than the ultimate actuator package dimensions. The copper side of the film is masked and patterned to form the desired shape of electrodes for contacting a piezo element together with conductive leads and any desired lands or access terminals. A pitchfork electrode pattern is shown, having three tines which are positioned to contact the center and both sides of one face of a piezo element, but in other embodiments an H- or a comb-shape is used. The patterning may be done by masking, etching and then cleaning, as is familiar from circuit board or semiconductor processing technology. The masking is effected by photoresist patterning, screening, tape masking, or other suitable process. Each of these electroded pieces of polyimide film, like a classical printed circuit board, defines the positions of circuit elements or actuator sheets, and will be referred to below simply as a "flex circuit." However, methods and devices of the invention also contemplate using an electroded piezo element, an insulator, and electrical contacts, rather than a "flex circuit".

Next, uncured sheet epoxy material having approximately the same thickness or slightly thicker than the electrode foil layer is cut, optionally with through-apertures matching the electrode pattern to allow enhanced electrical contact when assembled, and is placed over each flex circuit, so it adheres to the flex circuit and forms a planarizing layer between and around the electroded portions. The backing is then removed from the epoxy layers attached to the flex circuits, and pre-cut spacers 120 are placed in position at corner and edges of the flex circuit. The spacers outline a frame which extends above the plane of the electrodes, and defines one or more recesses into which the piezo elements are to be fitted in subsequent assembly steps. The piezo element or elements are then placed in the recesses defined by the spacers, and a second electroded film 111, 112 with its own planarizing/bonding layer 114 is placed over the element in a position to form electrode contacts for the top of the piezo element. If the device is to have several layers of piezo elements, as would be the case for some bending actuator constructions, these assembly steps are repeated for each additional electroded film and piezoelectric plate, bearing in mind that a polyimide film which is clad and patterned on both sides may be used when forming an intermediate electrode layer that is to contact actuator elements both above and below the intermediate sheet.

Once all elements are in place, the completed sandwich assembly of patterned flex circuits, piezo sheets, spacers and curable patterned epoxy layers is placed in a press between heated platens, and is cured at an elevated temperature and pressure to harden the assembly into a stiff, crack-free actuator card. In a representative embodiment, a cure cycle of thirty minutes at 350°F and 50-100 psi pressure is used. The epoxy is selected to have a curing temperature below the depoling temperature of the piezo elements, yet achieve a high degree of stiffness.

The above construction illustrates a simple actuator card having a single piezo plate sandwiched between two electroded films, so that the plate transfers shear strain efficiently through a thin film to the surface of the actuator card. The measure of transfer efficiency, given by the shear modulus divided by layer thickness squared, and referred to as gamma (Γ), depends on the moduli and thickness of the epoxy 114, the rolled foil electrodes 111, and the polyimide film 110. In a representative embodiment in which the epoxy and copper electrode layers are 1.4 mils thick and the epoxy has a modulus of $.5x10^6$, a gamma of approximately $9x10^{10}$ pounds/inch^4 is achieved. Using a thinner epoxy layer and film with .8 mil foil, substantially higher Γ is achieved. In general, the gamma of the electrode/epoxy layer is greater than $5x10^{10}$ pounds/inch^4, while that of the film is greater than $2x10^{10}$ pounds/inch^4.

It should be noted that using PZT actuator plates ten mils thick, a card having two PZT plates stacked over each other with three flex circuit electroded film layers (the middle one being double clad to contact both plates) has a total thickness of 28 mils, only forty percent greater than the plates alone. In terms of mass loading, the weight of the actuator elements represents 90% of the total weight of this assembly. Generally, the plates occupy fifty to seventy percent of the package thickness, and constitute seventy to ninety percent of its mass, in other constructions. Thus, the actuator itself allows near-theoretical performance modeling. This construction offers a high degree of versatility as well, for implementing benders (as just described) as well as stacks or arrays of single sheets.

Another useful performance index of the actuator constructed in accordance with the present invention is the high ratio of actuator strain ε to the free piezo element strain Λ, which is approximately (.8) for the two layer embodiment described herein, and in general is greater than (.5). Similarly, the ratio of package to free element curvatures, K, is approximately .85 - .90 for the described constructions, and in general is greater than .7.

Thus, overall, the packaging involved in constructing a piezo element embedded in a flex circuit impairs its weight and electromechanical operating characteristics by well under 50%, and as little as 10%, while profoundly enhancing its hardiness and mechanical operating range in other important respects. For example, while the addition of sheet packaging structure to the base element would appear to decrease attainable K, in practical use the flex card construction results in piezo bender constructions wherein much greater total deflection may be achieved, since large plate structures may be fabricated and high curvature may be repeatedly actuated, without crack failure or other mechanical failure modes arising. Several Figures will illustrate the variety of constructions to which such enhanced physical characteristics are brought.

First, the structure of an electroactive element embedded between flex circuits not only provides a low mass unified mechanical structure with predictable response characteristics, but also allows the incorporation of circuit elements into or onto the actuator card. FIGURE 2C shows a top view of one device 70 of this type, wherein regions 71, 73 each contain broad electroactive sheets, while a central region 72 contains circuit or power elements, including a battery 75, a planar power amplification or set of amplifiers 77, a microprocessor 79, and a plurality of strain gauges 78. Other circuit elements 82a, 82b may be located elsewhere along the path of circuit conductors 81 about the periphery. As with the other embodiments, spacers 120 define layout and seal edges of the device, while electrodes 111 attach the electroactive elements to the processing or control circuitry which is now built-in. The circuit elements 82a, 82b may comprise weighting resistors if the device is operated as a sensor, or shunting resistors to implement passive damping control. Alternatively, they may be filtering, amplifying, impedance matching or storage elements, such as capacitors, amplifiers or the like. In any case, these elements also are located away from electroactive plates 84. The components collectively may sense strain and implement various patterns of actuation in response to sensed conditions, or perform other sensing or control tasks.

Returning now to the actuator aspect of the invention, FIGURE 3 shows a top view of an actuator package 200 having dimensions of about 1.25 x 9.00 x .030 inches and assembled with two layers of piezoelectric plates of four plates each. A rectangular polyimide sheet 210 with an end tab 210a carries an electrode 211 in the form of a lattice of H-shaped thin copper lines interconnected to each other and to a single runner 211a that leads out to the tab, thus providing a low impedance connection directly to each of four rectangular regions which hold the piezo plates.

Spacer elements 220a, 220b of H-shape, or 220c of L-shape mark off corners and delineate the rectangular spaces for location of the piezo plates 216. In this embodiment, a plurality of gaps 230, discussed further below, appear between adjacent the H- or L- spacers. As will be apparent from the description below, the use of these small discrete spacer elements (I-, T- or O-shaped spacers may also be convenient) is enhanced because they may be readily placed on the tacky bonding epoxy layer 114 during assembly to mark out assembly positions and form a receiving recess for the piezo elements. However, the spacer structure is not limited to such a collection of discrete elements, but may be a single or couple of frame pieces, formed as a punched-out sheet or molded frame, to provide all, or one or more, orienting and/or sealing edges, or recesses for holding actuation of circuit components.

FIGURE 5 illustrates a top view of each of the three sheet, electrode and piezo plate layers separately, while FIGURE 5A illustrates the general layering sequence of the film, conductor, and spacer/piezo layers. As shown, the spacers 220 and piezo plates 216 constitute a single layer between each pair of electrode layers.

FIGURES 4A and 4B (not drawn to scale) illustrate the layer structure of the assembled actuator along the vertical sections at the positions indicated by "A" and "B" in FIGURE 3. As more clearly shown in FIGURE 4A, a patterned bonding layer of epoxy sheet 214 is coplanar with each electrode layer 211 and fills the space between electrodes, while the spacer 220c is coplanar with the piezo plate 216 and substantially the same thickness as the plate or slightly thicker. Illustratively, the piezo plate 216 is a PZT-5A ceramic plate, available commercially in a five to twenty mil thickness, and has a continuous conductive layer 216a covering each face for contacting the electrodes 211. The spacers 220 are formed of somewhat compressible plastic with a softening temperature of about 250°C. This allows a fair degree of conformability at the cure temperature so the spacer material may fill slight voids 214a (FIGURE 4A) during the assembly process. As shown in FIGURE 4B, the gaps 230 (when provided) between spacers result in openings 214b which vent excess epoxy from the curable bonding layers 214, and fill with epoxy during the cure process. As illustrated in that FIGURE, a certain amount of epoxy also bleeds over into patches of film 215 between the electrodes 211 and the piezo plate 216. Because of the large and continuous extent of electrode 211, this patchy leakage of epoxy does not impair the electrical contact with the piezo elements, and the additional structural connection it provides helps prevent electrode delamination.

It will be appreciated that with the illustrated arrangements of electrodes, each vertically stacked pair of piezo plates may be actuated in opposition to each other to induce bending, or more numerous separate electrodes may be provided to allow different pairs of plates to be actuated in different ways. In general, as noted above, the invention contemplates even quite complex systems involving many separate elements actuated in different ways, with sensing, control, and power or damping elements all mounted on the same card. In this regard, great flexibility in adapting the card to practical tasks is further provided by its flexibility. In general, it has a supple flexibility comparable to that of an epoxy strip thirty mils thick, so that it may be bent, struck or vibrated without damage. It may also be sharply bent or curved in the region of its center line CL (FIGURE 3) where no piezo elements are encased, to conform to an attaching surface or corner. The elements may be poled to change dimension in-plane or cross-plane, and the actuators may therefore be attached to transmit strain to an adjacent surface in a manner effective to perform any of the above-described control actions, or to launch particular waveforms or types of acoustic energy, such as flexural, shear or compressional waves into an adjacent surface.

FIGURE 6 shows another actuator embodiment 300. In this embodiment, illustrated schematically, the epoxy bonding layer, film and spacer elements are not shown, but only electrode and piezo sheets are illustrated to convey the operative mechanisms. A first set of electrodes 340 and second set 342 are both provided in the same layer, each having the shape of a comb with the two combs interdigitated so that an electrical actuation field is set up between the tooth of one comb and an adjacent tooth of the other comb. In FIGURE 6, a parallel pair of combs 340a, 342a is provided on the other side of the piezo sheet, with comb electrode 340 tied to 340a, and comb electrode 342 tied to 342a, so as to set up an electric field with equipotential lines "e" extending through the piezo sheet, and in-plane potential gradient between each pair of teeth from different combs. In the embodiment shown, the piezoceramic plates are not metallized, so direct electrical contact is made between each comb and the plate. The plates are poled in-plane, by initially applying a high voltage across the combs to create a field strength above one two thousand volts per inch directed along the in-plane direction. This orients the piezo structure so that subsequent application of a potential difference across the two-comb electrodes results in in-plane (shear) actuation. Thus, the direct contact of interdigital electrodes provides to the piezo element an electrical field which is generally parallel to the actuation direction.

In addition to shear actuation, directional actuation and damping may be effected using methods or devices of the invention. For example, as shown in FIGURE 7, two such actuators 300 may be crossed to provide torsional actuation.

In discussing the embodiments above, the direct transfer of strain energy through the electrode/polyimide layer to any adjoining structure has been identified as a distinct and novel advantage. Such operation may be useful for actuation tasks or diverse as airfoil shape control actuation and noise or vibration cancellation or control. FIGURES 8A and 8B illustrates typical installations of flat (FIGURE 8A) and hemicylindrical (FIGURE 8B) embodiments 60 of the actuator, applied to a flat or slightly curved surface, and a shaft, respectively.

However, while the electromechanical materials of these actuators operate by strain energy conversion, applications of the present invention extend beyond strain-coupling through the actuator surface, and include numerous specialized mechanical constructions in which the motion, torque or force applied by the actuator as a whole is utilized. In each of these embodiments, the basic strip- or shell-shaped sealed actuator is employed as a robust, springy mechanical element, pinned or connected at one or more points along its length. As shown in FIGURE 9, when electrically actuated, the strip then functions, alone or with other elements, as a self-moving lever, flap, leaf spring, stack or bellows. In the diagrams of FIGURES 9(a) - 9(q), the elements A, A', A" . . . are strip or sheet actuators such as shown in the above FIGURES, while small triangles indicate fixed or pinned positions which correspond, for example, to rigid mounting points or points of connection to a structure. Arrows indicate a direction of movement or actuation or the contact point for such actuation, while L indicates a lever attached to the actuator and S indicates a stack element or actuator.

The configurations of FIGURES 9(a)-9(c) as stacks, benders, or pinned benders may replace many conventional actuators. For example, a cantilevered beam may carry a stylus to provide highly controlled single-axis displacement to constitute a highly linear, large displacement positioning mechanism of a pen plotter. Especially interesting mechanical properties and actuation characteristics are expected from multi-element configurations 9(d) et seq., which capitalize on the actuators having a sheet extent and being mechanically robust. Thus, as shown in FIGURES 9(d) and (e), a pin-pin bellows configuration may be useful for extended and precise one-axis Z-movement positioning, by simple face-contacting movement, for applications such as camera focusing; or may be useful for implementing a peristalsis-type pump by utilizing the movement of the entire face bearing against a fluid. As noted in connection with FIGURE 3, the flex circuit is highly compliant, so hinged or folded edges may be implemented by simply folding along positions such as the centerline in FIGURE 3, allowing a closed bellows assembly to be made with small number of large, multi-element actuator units. The flex circuit construction allows strips or checkerboards of actuator elements to be laid out with fold lines between each adjacent pair of elements, and the fold lines may be impressed with a thin profile by using a contoured (e.g. waffle-iron) press platen during the cure stage. With such a construction, an entire seamless bellows or other folded actuator may be made from a single flex circuit assembly.

As noted above, the piezo element need not be a stiff ceramic element, and if the flex circuit is to be used only as a sensor, then either a ceramic element, or a soft material such as PVDF may be employed. In the case of the polymer, a thinner more pliant low temperature adhesive is used for coupling the element, rather than a hard curable epoxy bonding layer.

Certain embodiments of the invention are exemplified below.

EXAMPLE 1

In this example, a vibration control system was designed to determine certain parameters of functional requirements of a gantry active control system. The functional requirements defined included (but were not limited to) the following:

- Accuracy
- Settling time
- Mass, size and location of the actuators and sensors
- Power
- Peak strains
- Lifetime
- Temperature range
- Exposure to humidity and solvents
- Cost
- Interfaces with existing gantry control system

In order to gather data on the structural response of a gantry during operation, the gantry was equipped with an array of piezoelectric strain sensors and accelerometers. Placement and sizing of the piezoelectric actuators required accurate strain mode shape information, which were obtained from this data, and were compared to the Finite Element Model ("FEM"). One important piece of information obtained in this phase of the project involved the effect of different head positions on the dynamics. Both the actuator design and any control software design depended on when the vibration control was applied, i.e., while the head was moving along the gantry, and/or after it had stopped at an arbitrary position on the gantry.

Data was acquired both with and without a friction block in place, to allow at least analytical evaluation of the potential for complete replacement of the friction block by the electroactive vibration control system.

Using the data acquired above, along with finite element modeling information, the system-level design was performed. This design involved selecting a system architecture, including actuator placement, type of sensor, and the type of control algorithm. As discussed above, with the moving head having a significant effect on the gantry dynamics, the electroactive vibration control system's effectiveness was improved by making the trajectory information available in the motion control system. This information may be relayed to the motion control system with a simple clip lead attached to the proper point in the motion controller's circuitry. For example, information such as the plots of motor current, which is often easily accessible, may be provided to the vibration control system.

After selecting the system architecture, an analytical "input/output" model of the system was developed, to design the control algorithm for vibration control, and to simulate its performance. The system design was compared to the functional requirements, to ensure compliance. This analysis served to define the specifications on the various components of the control system, especially the analog sensor signal conditioning electronics, the digital signal processor (DSP) based control unit, and the power amplifier used to provide the necessary voltage and current to the electroactive actuators.

Each of the components of the electroactive vibration control system were then designed, including the various electronic components. The electroactive actuators themselves were fabricated using methods disclosed herein. Each actuator was tested using standard quality control methods. All electronics were fabricated and tested for functionality and for compliance with the specifications devised in the system design task.

An important aspect of the design involved the integration of the actuators and sensors with the gantry. For example, for a given gantry, a 0.5 mm actuator thickness may be determined to not likely interfere with motion of the head along the gantry. The types of cable used to connect the actuators and sensor on the gantry to the electronic equipment were then determined.

In this particular example, the gantry of an automated SMT electronics collect and place equipment was equipped with actuators, sensors and electronics, and analyzed using an FEM with plate elements. The basic concept, shown in block diagram in Figure 10, includes electroactive strain actuators and sensors bonded to the gantry, along with the necessary power, signal, and digital control electronics to achieve vibration reduction. For the purposes of this study, the head was assumed to be fixed at the end of the gantry. The installation of actuators was done using a vacuum-bonding procedure.

"Open loop" testing was then performed. Open loop testing involves injecting signals into the actuators and measuring the response of the gantry to confirm experimentally the analytical modeling done earlier in this study. This testing was performed with the gantry and head stationary, as well as moving along some "standard" trajectories. The signal(s) to be passed from the gantry and head motion controller to the vibration control system were measured as well during these tests. The electoactive actuators were distributed over 10% of the surface area of the gantry having the maximum strain energy in the first natural mode of vibration. The effectiveness of the actuator distribution at exciting the first three modes of vibration was modeled using design software. Between 80-84% of all strain energy is in the plate elements; and between 62-75% of the plates' energy is extensional strain, and therefore available for capture by electroactive control devices bonded to the surface. Thus, at least 52% of the strain energy in a mode is available. Some of this energy is in the frame/support for the moving head. As shown in FIGURE 13, the extensional strain energy was sorted to maximize performance for a given amount of electroactive element.

Damping was added to the structural model. Plots of acceleration versus time at the head, after impact by a hammer, showed roughly 5% of critical damping in the first mode with the friction block in place.

Feedback control was designed using the standard Linear Quadratic Regulator (LQR) approach, ensuring that piezoelectric actuation control voltages did not exceed the actuator device limits. Actuation voltages in the closed feedback loop are proportional to the input disturbance forces associated with the motion of the gantry. Here, the gantry was assumed to accelerate in the y-direction (transverse to the gantry axis) at a constant 25 m/s^2 until maximum velocity of 3 m/s was reached. The D'Alembert inertial force associated with a 10 kg mass was applied at the center of gravity of the head. This mass included the 5 kg head mass, plus 5 kg of effective gantry mass.

The improvements in damping and settling time were then determined after simulating the vibration-controlled system's frequency and time domain responses. Frequency responses are simulated in Figure 11, measured at a point on the underside of the pick and place head, in the y-direction. The reduction in dynamic response to a unit input force is evident in this figure. As shown in FIGURE 11, as well as Table I, mode 1 closed loop damping was about 12%, mode 2 closed loop damping was about 11%, and mode 3 closed loop damping was about 10%. Time responses at the same point, in the same direction, are simulated in Figure 12. This simulation shows a dramatic reduction in settling time with the electroactive control. Thus, very effective control can be achieved with very little additional mass.

Table I: Gantry structural dynamic parameters.

Mode	Description	Frequency (Hz)	Inherent Damping Ratio (% of critical)	Damping Ratio with Piezo Control (%)
1	Twisting about gantry axis	46	5	12
2	Bending in xy (scanning) plane	93	5	11
3	Coupled bend/twist	136	5	10

The gantry/head structural dynamic properties, from FEM, are shown in Table I. The representative actuator distribution designed here was 0.5 mm thick, with an area of 330 cm^2, and a mass of less than 100g. The closed loop modal damping, also shown in Table I, was at least twice the assumed 5% value inherent to the gantry with the friction block, for all three modes of vibration included in the analysis. Thus, the vibration amplitude and settling time were significantly reduced.

As shown in Figures 14 and 15, the vibration control system induced changes in the frequency response and gain control. In this study, the damping was increased by over one order of magnitude. This increase corresponds to an increase in placement accuracy of a factor of ten.

Following the open loop tests, the data was analyzed and the final control algorithm design was performed. If necessary, the actuator and sensor hardware may be modified to ensure compliance with the functional requirements. Then, "closed loop" testing of the final electroactive vibration control system may be performed. Closed loop testing is generally when actuators are driven at least in part by signals generated by sensors.

This study demonstrated that effective active electroactive vibration control of the gantry is possible.

EXAMPLE 2

A vibration control system in accordance with the invention was used in a lithography machine. As shown in Figure 16, which shows the power spectral density of error signals recorded by a laser metrology system, use of the vibration control system resulted in a three-fold reduction in system response in the band from 75 to 125 Hz. The reduction in the peak using the vibration control system would be expected to reduce the system image blur by a factor of two-three after conventional methods are used to reduce peaks at 50 Hz and 225 Hz. Alternatively, in some cases, the vibration control system might be used to reduce the peaks at 50 Hz or 225 Hz or at other levels. Reducing the image blur allows the fabrication system to produce finer trace dimensions and feature sizes and improves the accuracy of the feature placement

The foregoing description of embodiments and examples of the present invention are presented to demonstrate the range of constructions to which the invention applies. Those skilled in the art will appreciate that many other modifications and variations of the invention as set forth herein above may be made without departing from the spirit and scope thereof.

An additional aspect of the invention discussed herein relates to actively stabilizing (controlling the motion of) wafer stages in lithography tools in six degrees of freedom. Figure 22,, illustrates an exemplary simplified two-dimensional physics model of a wafer stage base 501 and a wafer stage 500. This concept is readily generalizable to a real system in which three-dimensions are of concern.

The masses of the stage and the base are relatively similar and each weigh approximately 200 kg. The wafer stage base measures approximately 1m in length x 1 m in width x 0.15 m in thickness. The wafer stage measures approximately 1.25 m in length x 0.5 m in width x 0.5 m in thickness. Actuator (motor) inputs are represented by the symbol u_i, where i represents a specific voice coil motor. Alternative actuators are contemplated which include linear piezoceramic motors. Sensor outputs are represented by y_i, where i represents a laser displacement measurement that is collocated with the voice coil input. Alternative output sensors (including linear variable displacement transducers (LVDT's), accelerometers) and sensor locations (nearly co-located, sufficiently colocated) are contemplated for this example. Disturbances (represented by d_i) to the system include on-board (including motors, fans, and articulating arms) and off-board disturbances (including ground vibrations, air currents, thermal fluctuations).

The wafer stage 500 is supported on the wafer stage base by a pneumatic system 502 comprised of airbearings. This airbearing is provided to allow the wafer stage 500 to move nearly frictionless with respect to the wafer base stage 501. The wafer stage base 501 is supported on the ground by a pneumatic system of airmounts 503 and 504. The physical properties of the airmounts are represented by a spring (k1) and a dashpot (c1). The physical properties of the airbearing are represented by a spring (k2) and a dashpot (c2). The pneumatic system 503 and 504 offsets the weight of the wafer stage 500 and the wafer stage base 501 with respect to the ground. The pneumatic system 503 and 504 provides a low-frequency (approximately several Hertz) control of the plunge and tilt of the wafer stage base 501. Additional high frequency control of the base stage 501 is provided by the voice coil motors u1, u2. A microprocessor system 510 is typically used to sense the outputs and command (actuate) the inputs as a function of the control algorithm implemented by the microprocessor system 510. The system 510 attempts to move or position the wafer stage 500 relative to the wafer stage base 501 based upon the lithography system requirements. For example the lithography system may require a constant scanning motion of the wafer stage 500 to be performed during exposure of an image on a wafer. Alternatively, the lithography system may command a rapid acceleration of the wafer stage 500 to re-locate the wafer stage to an alternative position. The wafer stage 500 would be required to make these movements to meet requirements of speed, accuracy, and/or settling time. Settling time refers to the time required to achieve a given position within some allowable variation of the absolute position. These prescribed motions with very high accelerations (up to 2g), create significant reaction forces that are transmitted to the base. In addition, these motions cause the compound center of gravity of the base stage system to rapidly change position. Currently base stabilization control is accomplished by the microprocessor system 510 through the implementation of six independent single-input, single-output (SISO) controller. Typically a SISO controller is used for each degree of freedom in the specific application. Typical three-dimensional systems could possess six degrees of freedom for each independently controlled system component or stage. SISO controllers are generally susceptible to variations in the location of the stage relative to the base. This is because the individual controller is not provided with additional output information. In one embodiment, the invention described herein, uses a multi-input, multi-output controller (MIMO) to achieve better performance than a SISO implementation even with variations of the location of the stage relative to the base. In a MIMO implementation the control is accomplished with knowledge of the output and input of more than one sensor (output) and actuator (input). Additionally, MIMO control architecture allows for the implementation of modern control techniques, including but not limited to, linear quadratic Gaussian (LQG), H-infinity, and mu synthesis. These techniques cannot be efficiently combined with SISO architecture.

Figure 23 illustrates how well a MIMO controller can follow (indicated by ACX roll moment command) a commanded input (stage pitch disturbance) to the roll moment compared with typical performance of a SISO controller (indicated by Nominal roll moment command). The MIMO controller tracks very closely to the disturbance. Thus, it is capable of reacting very quickly to a disturbance force and reject it from the system. This improves some combination of the speed, accuracy, or throughput of the stage.

In another embodiment of a stage control application in a lithography system, it was desired to decrease the settling time for a system to accurately track a commanded position. Figure 24 illustrates the block diagram that describes the embodiment. In this embodiment, three accelerometers 600, 601, 602 are used as the sensor for feedback control. Accelerometers 600 and 601 represent accelerometers that measure x-axis acceleration. Accelerometer 602 represents a single accelerometer that measures y-axis acceleration. These measurements which are generally proportional to the acceleration are sent to a signal conditioner 606 that buffers the signals and then sends the signals which are generally proportional to the acceleration of the stage to a single board computer 607. A representative single board computer is Model SBC67 supplied by Innovative Integration Inc. with offices in Simi Valley, CA. This processor is a high performance stand-alone digital signal processor single board computer featuring analog input and output capability. The voltage signals 612 a,b,c are fed into analog inputs. These analog inputs are then converted to digital signals that the processor then applies a control algorithm or filter to. The algorithm creates a set of digital signals which are then converted to analog output signals 613 a,b,c,d. These output signals are then applied to each of the four motors 608, 609, 610, 611. Motors 608 and 609 are x-axis motors that control the position of the stage in the x-axis. Motors 610 and 611 are y-axis motors that control the position of the stage in the y-axis. X-axis interferometer 603 and Y-axis interferometer 604 are used to measure the x and y position of the stage relative to the base of the stage (which is not depicted here for simplification).

The filter (feedback control algorithm) may be designed using the standard Linear Quadratic Regulator approach, ensuring that the motor control signals do not exceed the motor or motor amplifier limits. Motor control signals in the closed feedback loop are proportional to the accelerometer 600,601,602 signals associated with acceleration of the stage. Control design was accomplished by first creating a state-space plant model from transfer function data using the Smart ID™ system identification software package commercially available from Active Control Experts, Inc. with offices in Cambridge, Massachusetts. The filter (or controller) was then designed through computer simulation and application of techniques discussed in Fanson and *The Control Handbook, William S. Levine, Editor, CRC Press, 1996.*

Figure 25 and 26 represent experimental and analytical results of the MIMO control applied in this embodiment. The MIMO results are compared with results in which multiple SISO loops are instead utilized. Figure 26 illustrates the results when zoomed in between the 0.15s and 0.30s time period. This figure illustrates that the MIMO control settles to within the settle range (approximately 100 on the y-axis of the graph) by approximately 0.19 s while the SISO (existing controller) only achieves this performance at approximately 0.26 s. This represents an improvement in settling time of approximately 30%.

What is claimed is:

CLAIMS

1. An motion control system for use with a lithography system, said motion control system comprising:

a wafer stage base;

at least two actuators for controlling motion;

at least two sensors for detecting at least one parameter of displacement of said wafer base and producing at least two signals in response thereto; and

at least one circuit in electrical communication with said actuators and said sensors;

wherein, upon the detection of said at least one parameter of displacement by said sensors, said sensors signal said circuit, which, in response, activates said actuators to stabilize the wafer stage base.

2. The motion control system of claim 1, said actuators are selected from the group consisting of a voice coil motor and electroactive stack actuator.

3. The motion control system of claim 1, said sensors selected from the group consisting of LVDT, accelerometer, laser interferometer, capacitive displacement sensor.

4. The motion control system of claim 1, said circuit comprising a digital signal processor.

5. The motion control system of claim 1, said circuit comprising:

at least one digital signal processor,

at least one analog to digital converter, and

at least one digital to analog converter.

6. The motion control system of claim 1, said circuit comprising a control technique.

7. The control technique of claim 6, said control technique selected from the group of linear quadratic gaussian, H-infinity, and mu-synthesis.

8. The motion control system of claim 1, wherein said actuators stabilize said wafer stage base to closely follow a commanded input.

9. An motion control system for use with a lithography system, said motion control system comprising:

a wafer stage;

at least two actuators for controlling motion;

at least two sensors for detecting at least one parameter of displacement of said wafer base and producing at least two signals in response thereto;

a signal conditioner; and

a single board computer

wherein, upon the detection of said at least one parameter of displacement by said sensors, said sensors feed a signal to said signal conditioner, said signal conditioner feeds a signal to said single board computer, and said single board computer commands said actuators to command said wafer stage to track a commanded position.

10. The motion control system of claim 9, wherein said actuators are selected from the group consisting of voice coil motor and electroactive stack actuator.

11. The motion control system of claim 9, wherein said sensors are selected from the group consisting of LVDT, accelerometer, laser interferometer, capacitive displacement sensor.

12. The motion control system of claim 9, wherein said wafer stage is commanded to track a commanded position within 0.19 seconds.

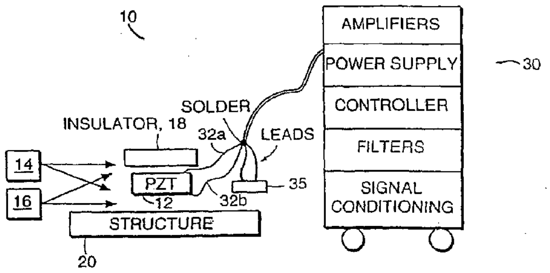


FIG. 1A
(PRIOR ART)

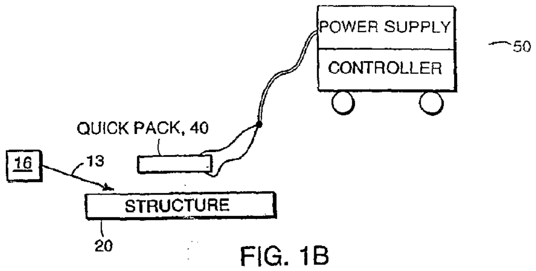


FIG. 1B

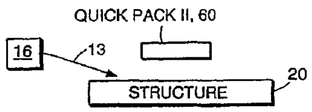


FIG. 1C

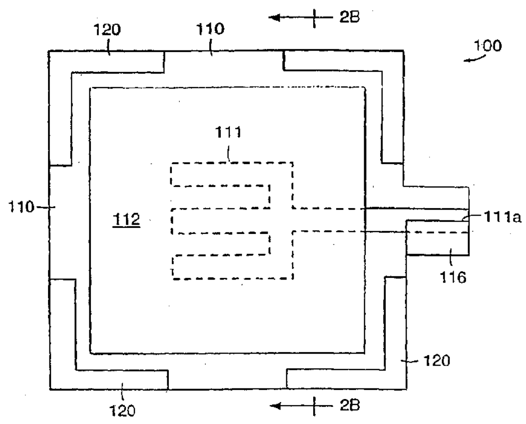

2B
120
110
100
111
110
112
111a
116
120
120
2B

FIG. 2A

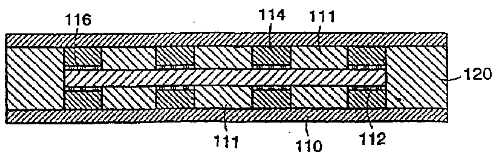

116
114
111
120
111
110
112

FIG. 2B

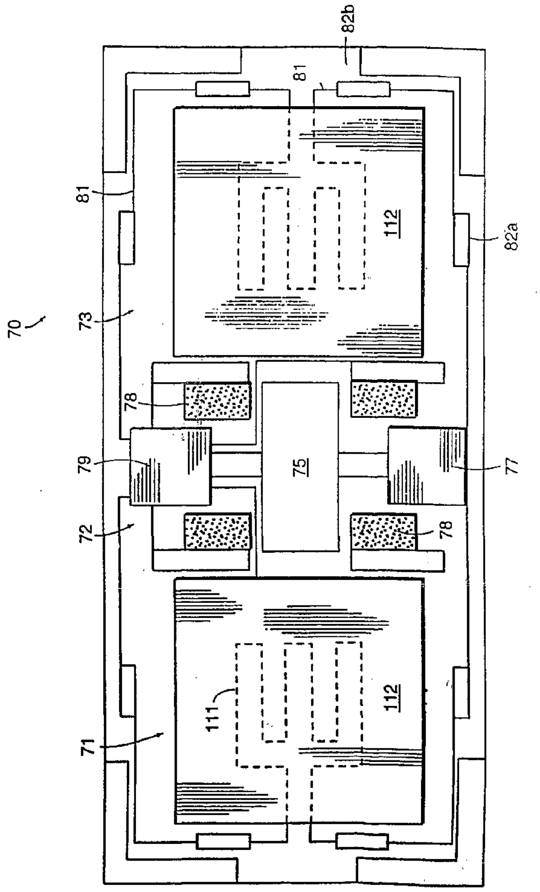


FIG. 2C

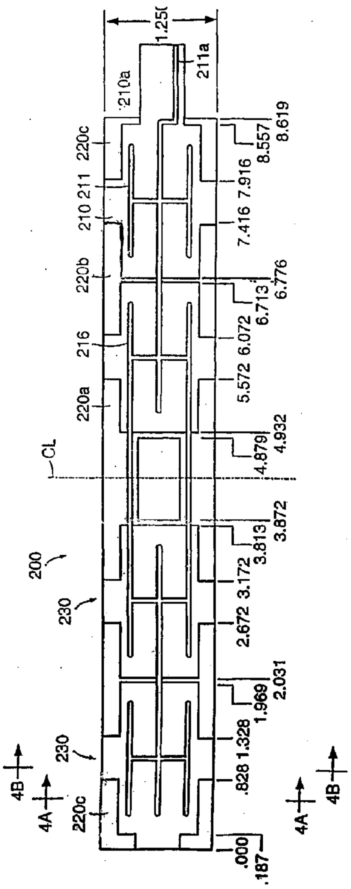

1.250
210a
211a
220c
210 211
220b
216
220a
CL
200
230
230
4B
4A
220c
4A
4B
8.557
8.619
7.416 7.916
6.713
6.776
5.572 6.072
4.879
4.932
3.813
3.872
2.672 3.172
1.969
2.031
.828 1.328
.000
.187

FIG. 3

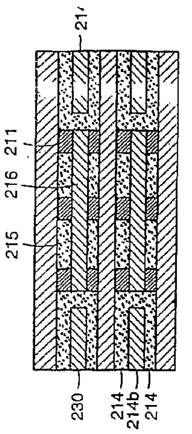

215
216
211
230
214
214b
214

FIG. 4B

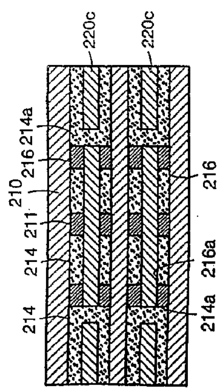

220c
220c
214
214
211
210
216
214a
216
216a
214a

FIG. 4A

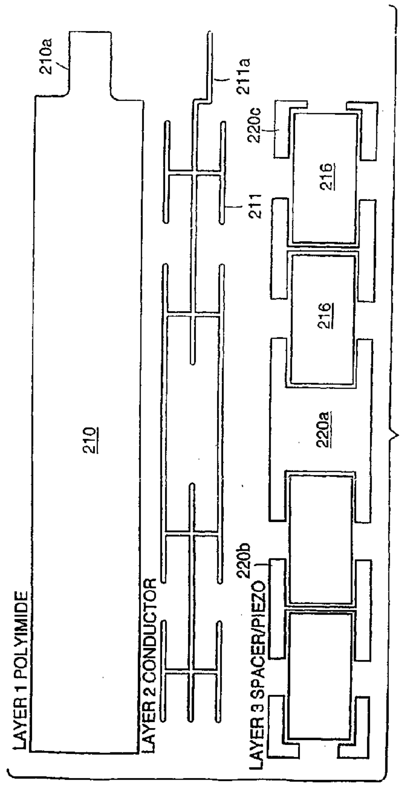

LAYER 1 POLYIMIDE
210
210a
LAYER 2 CONDUCTOR
211
211a
LAYER 3 SPACER/PIEZO
216
216
220a
220b
220c

FIG. 5

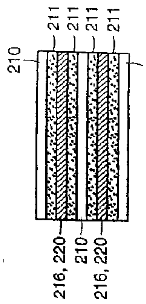

210
211
211
211
211
210
216, 220
210
216, 220

FIG. 5A

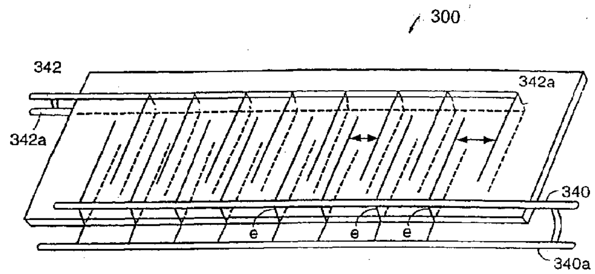


FIG. 6

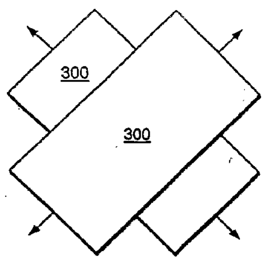


FIG. 7

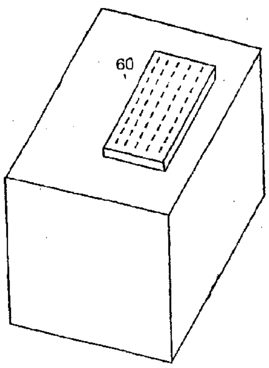


FIG. 8A

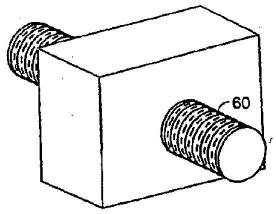


FIG. 8B

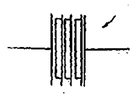


FIG. 9A

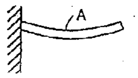


FIG. 9B

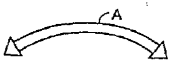


FIG. 9C

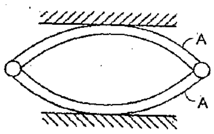


FIG. 9D

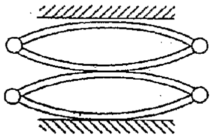


FIG. 9E

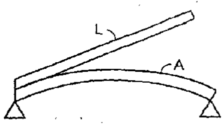


FIG. 9F

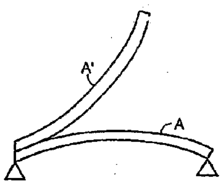


FIG. 9G

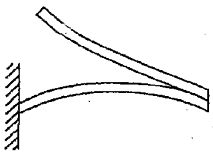


FIG. 9H

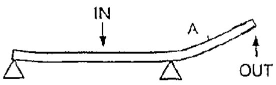


FIG. 9I

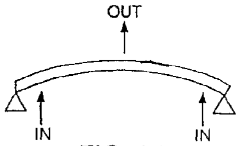


FIG. 9J

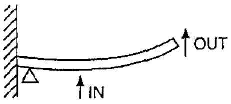


FIG. 9K

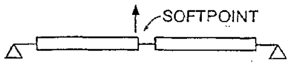


FIG. 9L

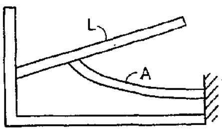


FIG. 9M

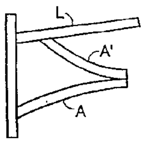


FIG. 9N

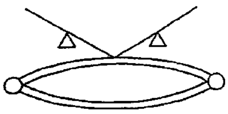


FIG. 9O

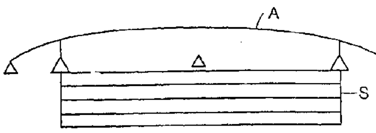


FIG. 9P

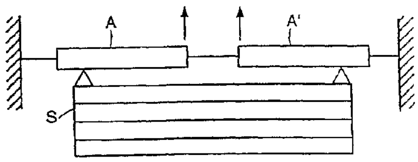


FIG. 9Q

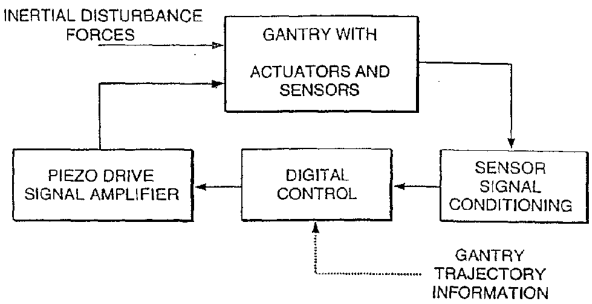

INERTIAL DISTURBANCE FORCES
GANTRY WITH
ACTUATORS AND SENSORS
SENSOR SIGNAL CONDITIONING
DIGITAL CONTROL
PIEZO DRIVE SIGNAL AMPLIFIER
GANTRY TRAJECTORY INFORMATION

FIG. 10

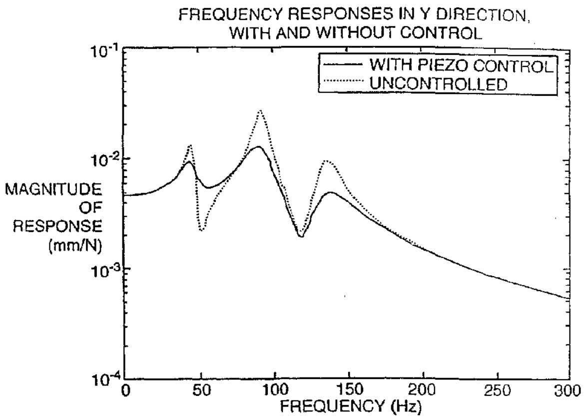

FREQUENCY RESPONSES IN Y DIRECTION, WITH AND WITHOUT CONTROL
WITH PIEZO CONTROL
UNCONTROLLED
MAGNITUDE OF RESPONSE (mm/N)
10^-1
10^-2
10^-3
10^-4
0
50
100
150
200
250
300
FREQUENCY (Hz)

FIG. 11

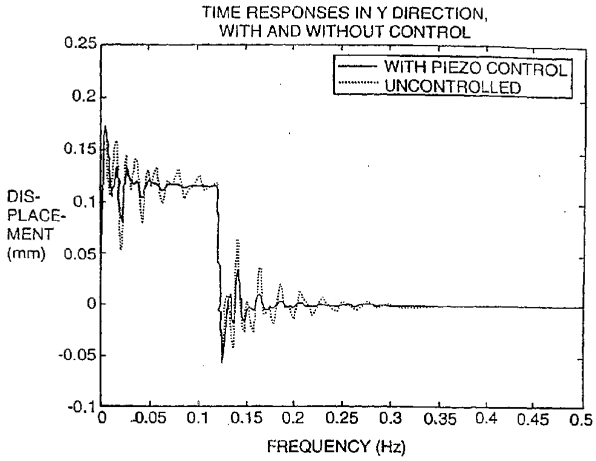

TIME RESPONSES IN Y DIRECTION,
WITH AND WITHOUT CONTROL
WITH PIEZO CONTROL
UNCONTROLLED
DIS-
PLACE-
MENT
(mm)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
FREQUENCY (Hz)

FIG. 12

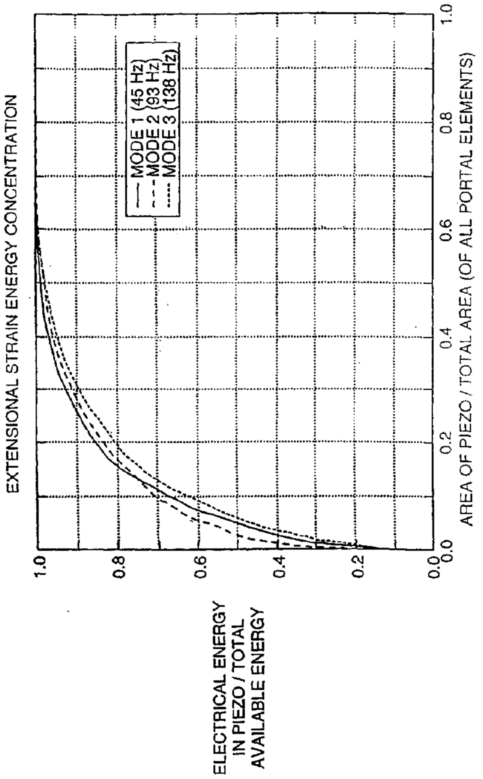

EXTENSIONAL STRAIN ENERGY CONCENTRATION
MODE 1 (45 Hz)
MODE 2 (93 Hz)
MODE 3 (138 Hz)
1.0
0.8
0.6
0.4
0.2
0.0
ELECTRICAL ENERGY IN PIEZO / TOTAL AVAILABLE ENERGY
0.0
0.2
0.4
0.6
0.8
1.0
AREA OF PIEZO / TOTAL AREA (OF ALL PORTAL ELEMENTS)

FIG. 13

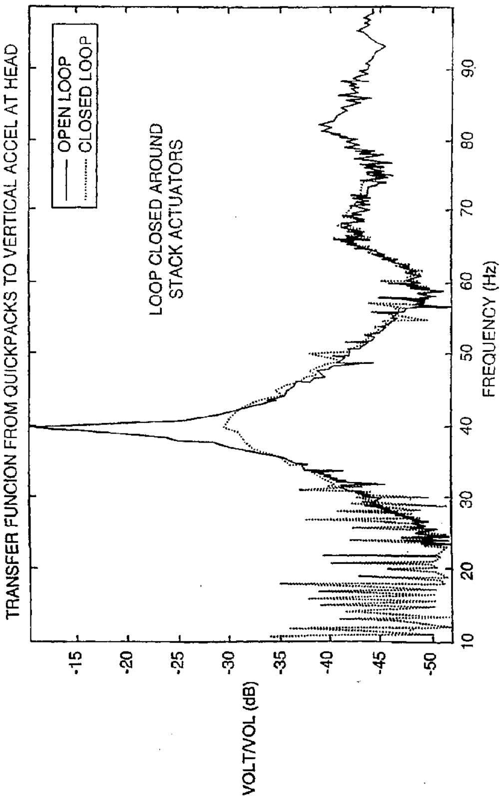

TRANSFER FUNCION FROM QUICKPACKS TO VERTICAL ACCEL AT HEAD
OPEN LOOP
CLOSED LOOP
LOOP CLOSED AROUND STACK ACTUATORS
VOLT/VOL (dB)
-15
-20
-25
-30
-35
-40
-45
-50
10
20
30
40
50
60
70
80
90
FREQUENCY (Hz)

FIG. 14

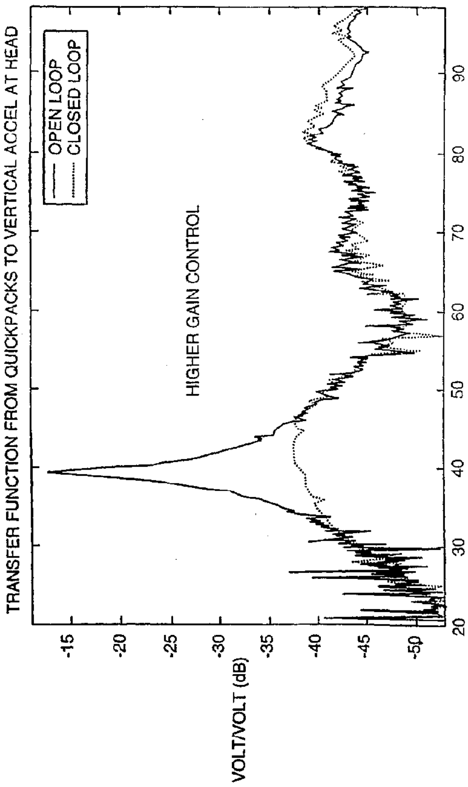

TRANSFER FUNCTION FROM QUICKPACKS TO VERTICAL ACCEL AT HEAD
OPEN LOOP
CLOSED LOOP
HIGHER GAIN CONTROL
VOLT/VOLT (dB)
-15
-20
-25
-30
-35
-40
-45
-50
20
30
40
50
60
70
80
90
FREQUENCY (Hz)

FIG. 15

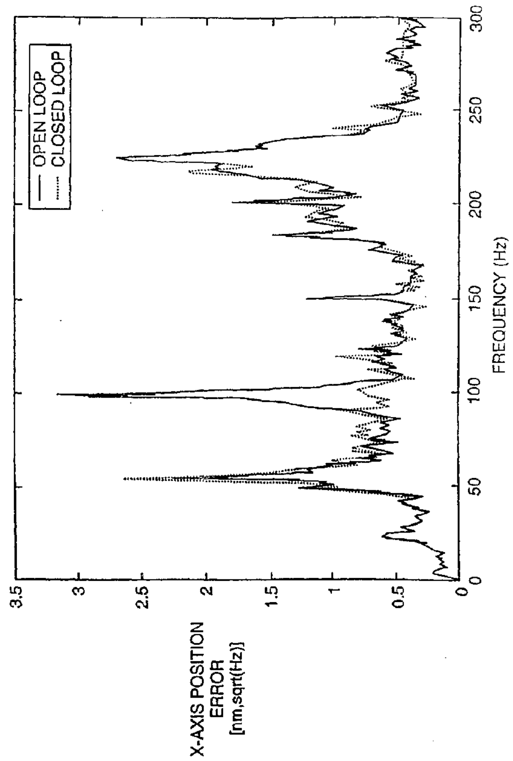

OPEN LOOP
CLOSED LOOP
X-AXIS POSITION ERROR [nm,sqrt(Hz)]
FREQUENCY (Hz)
0
0.5
1
1.5
2
2.5
3
3.5
0
50
100
150
200
250
300

FIG. 16

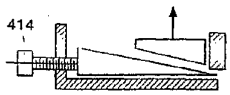


FIG. 17

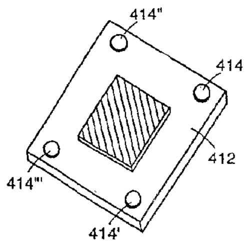


FIG. 18

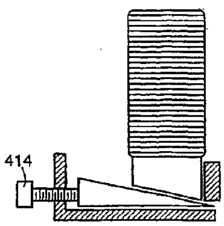


FIG. 19

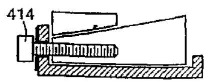


FIG. 20

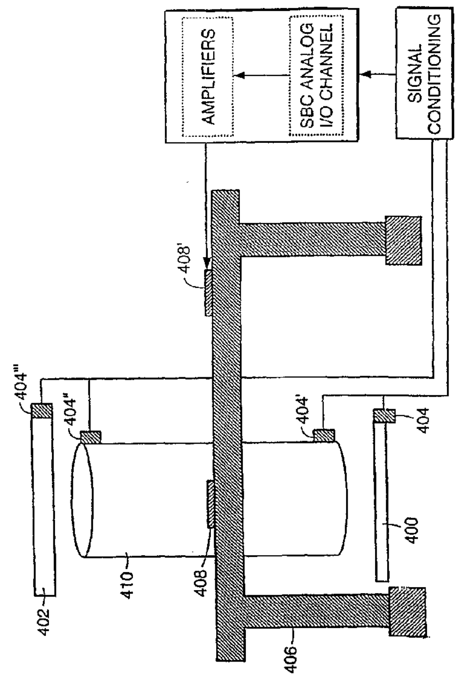
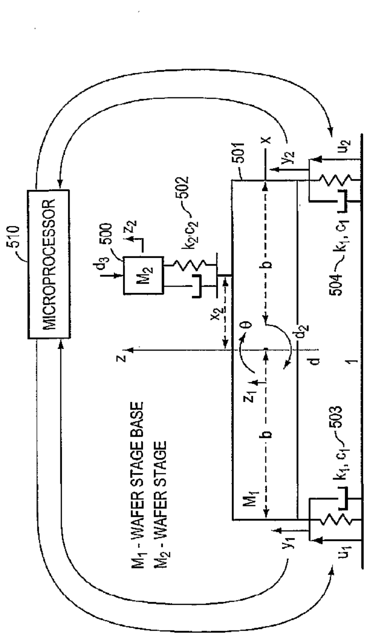

AMPLIFIERS
SBC ANALOG
I/O CHANNEL
SIGNAL
CONDITIONING
408'
404'''
404''
404'
404
400
402
410
408
406

FIG. 21



- INPUTS (u_i): VOICE COIL FORCES ON BASE IN Z
- OUTPUTS (y_i): LASER DISPLACEMENT MEASUREMENTS COLLOCATED WITH VOICE COIL INPUTS
- DISTURBANCES (d_i): Z-FORCE AND θ MOMENT ON BASE, Z FORCE ON STAGE

FIG. 22

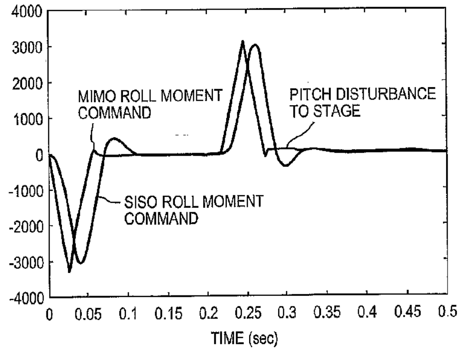

4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
TIME (sec)
MIMO ROLL MOMENT COMMAND
PITCH DISTURBANCE TO STAGE
SISO ROLL MOMENT COMMAND

FIG. 23

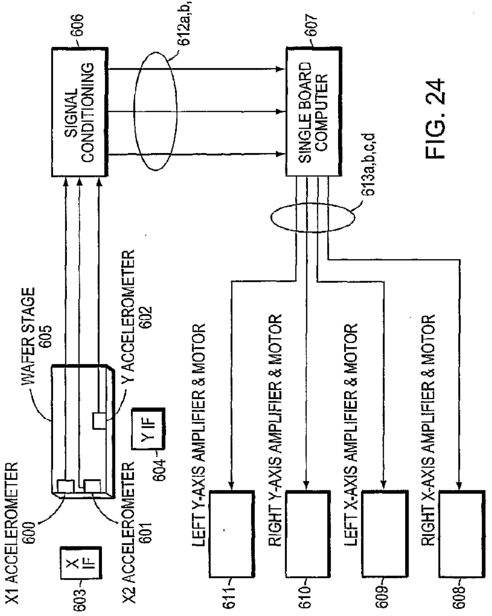

X1 ACCELEROMETER 600
X2 ACCELEROMETER 601
Y ACCELEROMETER 602
X IF
603
Y IF
604
WAFER STAGE 605
SIGNAL CONDITIONING
606
612a,b,c
SINGLE BOARD COMPUTER
607
613a,b,c,d
LEFT Y-AXIS AMPLIFIER & MOTOR
611
RIGHT Y-AXIS AMPLIFIER & MOTOR
610
LEFT X-AXIS AMPLIFIER & MOTOR
609
RIGHT X-AXIS AMPLIFIER & MOTOR
608

FIG. 24

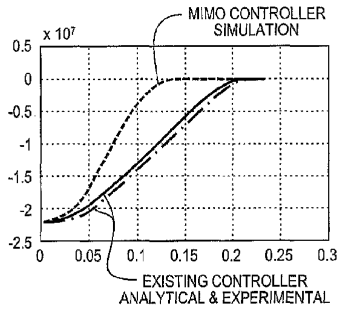

MIMO CONTROLLER
SIMULATION
x 10^7
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
0.05
0.1
0.15
0.2
0.25
0.3
EXISTING CONTROLLER
ANALYTICAL & EXPERIMENTAL

FIG. 25

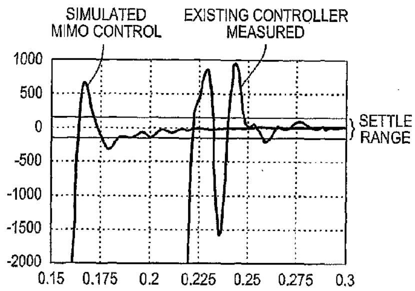

SIMULATED
MIMO CONTROL
EXISTING CONTROLLER
MEASURED
1000
500
0
-500
-1000
-1500
-2000
0.15
0.175
0.2
0.225
0.25
0.275
0.3
SETTLE
RANGE

FIG. 26

【国際公開パンフレット（コレクトバージョン）】

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(25) Filing Language: English

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(72) Inventors: **PLETNER, Baruch**; 87 Brandeis Road, Newton, MA 02459 (US). **PERKINS, Richard**; 36 Gould Avenue #3, Malden, MA 02148 (US). **LUBLIN, Leonard**; 46 MacArthur Road, Concord, MA 01742 (US).

(74) Agent: ROSS, John, R.; Cymer, Inc., Legal Dept. MS/1-2A, 16750 Via Del Campo Court, San Diego, CA 92127-1712 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
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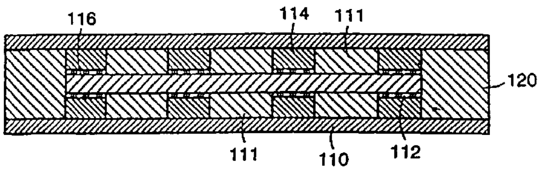
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: METHOD AND DEVICE FOR VIBRATION CONTROL



WO 02/073318 A3

(57) Abstract: A vibration control system comprising an actuator, and a sensor useful for controlling vibrations in systems for fabricating electronics equipment. The actuator may comprise one or more plates or elements of electroactive material bonded to an electroded sheet.

【国際調査報告】

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/06974

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G03F7/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G03F H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 812 420 A (TAKAHASHI MASATO) 22 September 1998 (1998-09-22) column 5, line 52 -column 8, line 17 column 9, line 8 - line 34 column 13, line 1 - line 24 figures 1-3 ---	1-12
X	US 6 089 525 A (WILLIAMS MARK) 18 July 2000 (2000-07-18) column 2, line 30 -column 4, line 11 figures 1-5 --- -/--	1-12

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 November 2002	28/11/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Heryet, C

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 02/06974

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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X	KAJIWARA K ET AL: "LARGE SCALE ACTIVE MICROVIBRATION CONTROL SYSTEM USING PIEZOELECTRIC ACTUATORS APPLIED TO SEMICONDUCTOR MANUFACTURING EQUIPMENT" NIHON KIKAI GAKKAI RONBUNSHU. C - TRANSACTIONS OF THE JAPAN SOCIETY OF MECHANICAL ENGINEERS. C, NIHON KIKAI GAKKAI, TOKYO, JP, vol. 63, no. 615, November 1997 (1997-11), pages 3735-3742, XP001052657 ISSN: 0387-5024 abstract; figures ---	1-12
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
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Ｆターム(参考) 5F046 AA23　CC01　CC03　CC16　CC18　DA04　DA07　DC14