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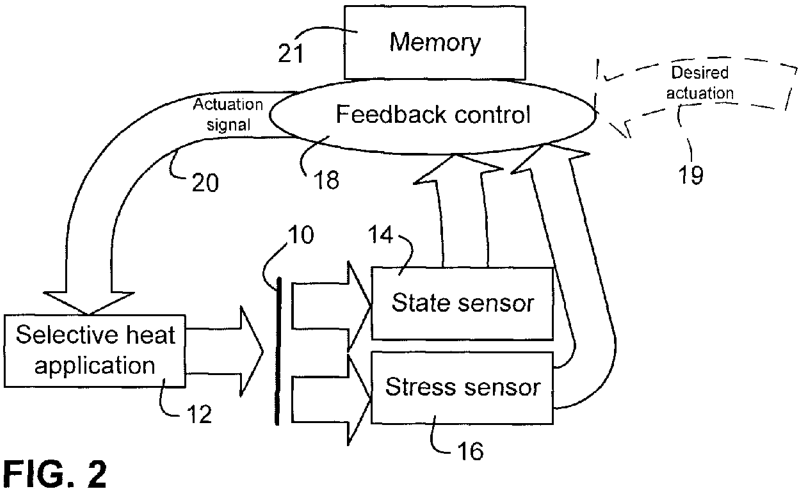

FIG. 2

(57) Abstract: A technique for controlling output of a shape memory alloy (SMA) actuator in the presence of fatigue involves a control system for selectively controlling a heater in dependence on a desired actuation of the SMA element, a monitored stress on the SMA actuator, and a monitored resistance of the SMA element, wherein the control system is adapted to compare an electrical resistance exhibited by the SMA element in an austenitic phase during a first actuation of the SMA actuator, with an electrical resistance of the SMA element in a recent austenitic phase to estimate a degree of fatigue. This estimate may be used to improve actuator replacement schedules, and may further be used to compensate for the effect of fatigue.

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FATIGUE ASSESSMENT FOR SMA ACTUATOR

Field of the Invention

[0001] The present invention relates in general to control of shape-memory alloys (SMA), and in particular to control of SMAs that permit *in situ* assessment, enabling mitigation of fatigue-type plastic deformation.

Background of the Invention

[0002] Shape Memory Alloys (SMAs) are used, and proposed for use in, a wide and growing variety of applications in medical devices, aerospace, automotive, and in a variety of applications where precision control is desired. Some applications require higher subsystem precision, durability, and reliability with reduced mass and cost, which SMAs can offer. Simplicity of maintenance and design are also desired of SMAs. In short, SMAs offer advantages over competing technologies to meet these requirements and thus have become interesting subjects for current and future technology developments.

[0003] SMAs are materials that can be used as small displacement actuators. A typical SMA actuator is in the form of a Ni-Ti alloy wire, or a Ni-Ti-Cu alloy wire, for example. The actuation is based on a reversible phase transformation of SMA material from Martensite to Austenite crystal phases, which occur as a function of temperature. Typically either external heating or joule heating is used to raise the temperature of the SMA material, and cooling is provided by conduction, convection and/or radiation. While the SMA is being actuated, the phase transformation gives rise to a change in electrical resistance of SMA actuator because the SMA has different electrical resistance in Martensitic and Austenite states. When the SMA is cooled, the power to the SMA is off, the SMA actuator is relaxed (deactivated) and it reverts back to Martensitic phase.

[0004] One of the major challenges in the design and deployment of SMA actuators, for a variety of systems, is assessing its fatigue state resulting from multi-cycle applications. A number of studies have demonstrated that SMAs are prone to two cumulative errors [1-5] after prolonged use under load: fatigue, a permanent plastic deformation of the SMA material akin to mechanical fatigue of other materials; and degradation, a loss in the shape memory effect (i.e. a difference between a length of the SMA in the activated and deactivated states).

[0005] It has been noted that substantial differences in the degree of degradation and fatigue have been observed under different loading and cycling conditions. For example, [1] states: "From the investigation in the changes of these two factors [fatigue and degradation] with repeated motions under several loads (i.e. pre-stresses), it was found that, in the case of large load, ΔU [fatigue] was large and inversely in the case of small load, ΔD [degradation] was dominant among two degradation factors..." Thus under some operating conditions, it is expected that fatigue will be the most critical parameter.

[0006] Fatigue in SMA actuators results in the gradual loss of actuation position control, i.e., when the SMA actuator is fully actuated, it will under-shoot its expected position. For example, loss of elongation of the SMA actuator due to fatigue may result in under-shooting the expected position at a known state of actuation. When the fatigue becomes significant, beyond the allowable design margin, a system relying on the SMA actuation, may fail. To design SMA actuators for applications, design parameters need to be set to ensure envisioned fatigue would not exceed an established limit. Alternatively methods or techniques need to be developed to determine the state of fatigue of the SMA actuator if operational parameters can be adjusted to ensure continuing operation and functionality of the SMA actuators and systems incorporating SMA actuators.

[0007] Accordingly SMA actuators have been studied with a view to ascertaining reliable operating life under various loading and operating conditions. Such systems typically include high accuracy displacement measurement systems, such as LDVTs for accurately determining strain output of the SMA. The premise is that better knowledge of the factors affecting degradation and fatigue, the better systems can be designed for longevity, and reliability.

[0008] The content of Applicant's co-pending US 12/867,933 filed August 17, 2010, entitled Feedback Control for Shape Memory Alloy Actuators is incorporated herein by reference. It teaches a SMA actuator control scheme with improved control precision. The SMA actuator control scheme includes an on-board stress sensor that, coupled with a state sensor, provides feedback for high precision output control. Advantageously the stress sensor may be a low cost strain gauge that does not substantially complicate design or substantially increase cost of the actuator. The stress sensor values and state sensor readings are correlated with the actuation output to the extent that the SMA actuator is free of degradation and fatigue. Predicting degradation under varying load and use history is not known, and little is known about predicting fatigue under varying load and use history.

[0009] It is noted that [1] teaches that plastic deformation (ΔU) was able to be estimated by the change in electrical resistivity of the material. Specifically they found that a variation in resistivity between the activated and relaxed states (ΔR) divided by a variation in resistivity between the activated and relaxed states during a first cycle (ΔR1), somewhat follows a percent elongation ($\Delta U/L_0$). It is stated that a linear relation exists between the elongation and electrical resistance. FIG. 5 does show a somewhat linear correlation over a limited number of cycles (1058), but it is less linear in the second half of the cycles, which does not give great confidence in the extent of the linear regime.

[0010] Accordingly there is a need for a technique for controlling SMA actuators that allows for the assessment of fatigue. There is also need for a technique of controlling SMA actuators that accounts for fatigue in the SMA output.

Summary of the Invention

[0011] Applicant has conceived of a technique for assessing fatigue that can permit fatigue monitoring or compensation. Advantageously the SMA actuator may include a stress sensor and a state sensor for verifying a fatigue state of the SMA material, such that the improved control precision provided by Applicant's co-pending application can be provided. The state sensor indicates a resistance across the SMA material, and the stress sensor may be a strain gauge.

[0012] Ref [1] teaches ($\Delta R/\Delta R1$) is linear with fatigue elongation, where $\Delta R1=R1_M - R1_A$. However Applicant has found that ΔR_A, i.e. the $R_A - R1_A$, is a more reliable index of plastic deformation over a substantially larger number of fatigue cycles. Applicant has found that R_M varies substantially as a function of cycle number, especially during the lower cycle numbers, even under a fixed load, and accordingly ΔR (as defined in [1]) would not vary directly with ΔR_A. Furthermore ΔR_A is assessed more easily than ΔR, which requires assessing of both minimum and maximum resistance values.

[0013] Accordingly, a processor with a non-transitory memory is provided for assessing fatigue of a shape memory alloy (SMA) element. The processor comprises program instructions for calculating a difference between a resistance of the SMA element in the Austenitic state during a first actuation, with a recent resistance of the SMA element in the Austenitic state. The difference may be used to compute an estimate of fatigue of the SMA element, for example, a known, estimated, or monitored load on the SMA may be used with the difference to derive the estimate.

[0014] The processor may comprise program instructions for accessing the resistance of the SMA element in the Austenitic state during the first actuation from the memory, and determining the recent resistance of the SMA element in the Austenitic state by sampling a resistance exhibited by the SMA element during at least one actuation cycle.

[0015] Determining the recent resistance in the Austenitic state may comprise selecting from the samples: a sample having a minimum resistance; or a sample time aligned with an expected state given a known duration and degree of heating applied to the SMA element.

[0016] The processor may be a part of a control system of the SMA element, along with a state sensor, and a stress sensor, wherein the processor monitors a resistance of the SMA element through the state sensor and a load on the SMA element through the stress sensor. A fatigue assessment given an identified change in Austenitic state resistance, may depend on a range of stresses applied on the SMA element in operation, as monitored by the processor. The processor may control a heating of the SMA element by controlling an electrical power conducted therethrough, wherein the processor further comprises program instructions for systematically altering heating commands subsequent to a fatigue assessment, to mitigate the fatigue.

[0017] Also a shape memory alloy (SMA) actuator is provided, the actuator comprising: a SMA element composed of a SMA material; a heater for heating the SMA element; and a control system for selectively controlling the heater in dependence on a desired actuation of the SMA element, a monitored stress on the SMA actuator, and a monitored resistance of the SMA element. The control system is adapted to compare an electrical resistance exhibited by the SMA element in an austenitic phase during a first actuation of the SMA actuator, with an electrical resistance of the SMA element in a recent austenitic phase to estimate a degree of fatigue.

[0018] The resistance in the austenitic phase may be inferred to be a minimum resistance during an actuation cycle. The resistance in the austenitic phase is inferred by a model of heating of the SMA material in dependence on a duration and degree of heat applied by the heater.

[0019] The resistance in the austenitic phase may be inferred from one or more of: a minimum resistance during an actuation cycle; a resistance concurrent with a maximum stress; and a resistance after a known duration and degree of heating applied by the heater.

[0020] The control system may be further adapted to use the estimated degree of fatigue to apply a correction to a control signal for controlling the heater, to mitigate fatigue-based error. The correction to be applied may be determined having regard to a parameter of an actuation history of the SMA actuator, such as to one or more of the following parameters of an actuation history of the SMA actuator stored by the control system in a non-transitory memory: a statistic of a static or dynamic load on the SMA actuator, especially a minimum load, a statistic of the monitored stress, a number of actuation cycles, a number of actuation cycles at a given stress, and a statistic of a monitored value that depends on a degree, duration or frequency of actuation of the SMA actuator. The correction to be applied may be determined having regard to a lower limit of a variable loading stress applied to the SMA actuator throughout its use history.

[0021] The heater may be an electrical circuit passing controlled electrical power through the SMA element, and if so, the controller controls the power on the electrical circuit to induce Joule heating within the SMA material.

[0022] The SMA element may be a linear small displacement actuator, in ribbon, wire, rod, or cylinder form, having a dimension of 0.5-50 mil.

[0023] Further features of the invention will be described or will become apparent in the course of the following detailed description.

Brief Description of the Drawings

[0024] In order that the invention may be more clearly understood, embodiments thereof will now be described in detail by way of example, with reference to the accompanying drawings, in which:
FIG. 1 is a graph of strain output as a function of time, showing degradation and fatigue effects;
FIG. 2 is a schematic illustration of a control system for a SMA actuator in accordance with a first embodiment of the invention;
FIGs. 3a,b are schematic illustrations of how stress sensors may be embedded in a SMA actuator;
FIGs. 4a,b are schematic circuit diagrams of SMA actuator control system;
FIGs. 5a,b are schematic illustrations of a second embodiment of the present invention, that does not involve strain monitoring, and is adapted to intermittent test by non-permanently coupled test equipment;
FIG. 6 is a plot of the correlation between accumulated plastic deformation of the SMA element as a function of number of cycles, under two different loadings; and
FIG. 7 is a plot of a percent change in resistance in the Austenitic phase (ΔR_A) as a function of accumulated plastic deformation $\Delta\varepsilon$.

Description of Preferred Embodiments

[0025] A technique is provided for controlling SMA actuation while permitting fatigue assessment. Advantageously the assessment may be used to correct an estimated fatigue, to mitigate errors that result from this phenomenon.

[0026] FIG. 1 is a graph showing how strain output varies with cycle for 25 cycles in which a nominally same heating and cooling cycle is applied in each period. This illustrates the two cumulative errors: fatigue, a plastic deformation symbolized by $\Delta\varepsilon$; and degradation symbolized by $\Delta S = (S_t - S_0)/S_0$, where S_0 is the full extension in the first cycle, and S_t is the extension in the t^{th} cycle.

[0027] FIG. 1 shows the fatigue at the 25th cycle. This fatigue amounts to a failure of the SMA material to contract under full actuation, and is an important parameter for many SMA actuation systems. Equally important in some applications, is the overall loss of actuation extension ΔS, and consequently the gradual extension of the SMA element in the relaxed state. As noted above, in some operating regimes ΔS is less pronounced than in others. Furthermore in other applications, ΔS is only problematic once it exceeds a threshold that can be set high.

[0028] FIG. 2 is a schematic illustration of a control system for a SMA actuator in accordance with a first embodiment of the invention. The controller of FIG. 2 is the same as that disclosed in Applicant's co-pending application, except for specific functionality of the feedback control 18, content of a memory 21, and possibly an actuation singal 20 in response to a desired actuation signal, given a state and stress sensor date, in the event that fatigue is mitigated. A contraction-type shape memory alloy (SMA) actuator having a ribbon, wire, rod, or cylinder SMA element 10 is adapted to be controlled by the selective application of heat 12 with the SMA element 10 in an environment that cools the SMA element 10 quickly enough to provide a desired control response time. The SMA actuator can have an SMA element composed of a Ni-Ti alloy, or a Ni-Ti-Cu alloy, or any other suitable SMA actuator. The selective application of heat 12 may be provided using any currently known or yet to be proposed methods, provided they produce heating at a desired rate without damaging the SMA element 10. While this application of heat 12 is preferably by electric resistive heating by direct application of current through the SMA element 10, in other embodiments, electric resistive heating of a medium in which the SMA element 10 is placed, or other resistive masses in the neighbourhood of the SMA element 10, or laser, ultrasonic, or eddy current heating, of the SMA element 10, the medium or other masses, could be used. Furthermore movement of the actuator with respect to an extreme thermal gradient field could effectively produce the same result of controlling a temperature of the SMA element 10.

[0029] The SMA element 10 is monitored in two respects: for a state of actuation, and a load on the SMA element 10. The load on the SMA element 10 has previously been found to change the electrical resistance–strain output relation of SMA elements. As was demonstrated in Applicants co-pending application, a high precision control feedback loop is possible using only feedback from the SMA element 10 in the form of an indicator of a state of actuation of the SMA actuator, and an indicator of a load on the SMA actuator. A stress sensor 14 and a state sensor 16 are provided accordingly.

[0030] In principle, the stress sensor 14 can be provided by the computation of a force applied on the SMA element 10, for example, from sensed knowledge of, or a computed model of that which applies the stress on the SMA actuator. However, in many applications, direct measurement of the stress applied to the SMA actuator in the direction opposing motion of the actuator, is preferable. Direct determination can be performed in a number of ways. In general, it is convenient to measure the stress in terms of strain or deformation, which are related by Young's modulus of a reliable material. Thus commonly known strain gauges can be used as the stress sensor. Advantageously some of these are compact, lightweight, and/or are controlled with minimal or robust electronics, as may be desired. Typically it is preferred to measure strain locally, as close to the SMA element 10 as possible, so that flexure of intervening material does not interfere with the reading. By using much less compliant materials between the SMA element 10 and the stress sensor 14, this flexure can be minimized, and thus the strain may be measured less locally, as some applications may require. Optical strain gauges could also be used, such as a fiber Bragg grating sensor.

[0031] One advantage of using direct electric resistance as the selective application of heat 12 is that while current flows across the SMA actuator, it is possible to directly determine a resistance across the SMA. However the SMA element is heated, it is possible to assess an electrical resistance of the SMA element using a very small charge with little impact on the temperature of the SMA element. Changes in resistance are attributable to changes in the state of the SMA actuator. The state sensor 16 includes electronic circuit elements for outputting a signal that varies with the resistance across the SMA element 10. The signal output by the state sensor 16 may be in the form of voltage-modulated electrical signals that may be compared using known analog circuit elements and/or a digital processor to produce an analog or digital signal representing the resistance across the SMA element 10, or electronics may be used to output a derived value.

[0032] The feedback from the state sensor 16 and stress sensor 14 are received by the feedback control 18 to produce the actuation signal 20 for controlling the selective application of heat 12. Some applications may require a SMA actuator to continuously apply a prescribed pressure on a supported element, or to retain the actuator in a given state of actuation in the face of changing environmental or mechanical conditions. If so, this feedback mechanism is satisfactory. In many applications, an indication of a desired actuation 19 comes from elsewhere. For example, a user interface, a command derived from a user interface, or a control program may provide an indication of a desired actuation 19, or change therein. The desired actuation 19 may be an analog signal provided directly by a user input, which can be compared with the state and stress sensor feedback to derive a suitable actuation signal. Alternatively the feedback control may be provided by a digital processor which may receive the feedback in analog or digital format and compute the actuation signal required for effecting the desired actuation.

[0033] Analog circuitry for combining the inputs from the two sensors may be used to continuously derive the actuation signal 20, which may be a current-modulated electrical signal, to the SMA element 10 to directly control electric resistive heating, for example; however in practice, it is expected that feedback control 18 is more likely to be embodied in a digital processor. In accordance with the present invention, the control system is adapted to compare an electrical resistance exhibited by the SMA element in an austenitic phase during a first actuation of the SMA actuator, with an electrical resistance of the SMA element in a recent austenitic phase to estimate a degree of fatigue. As such, after the SMA element 10 is fabricated, it is preferably attached to the stress sensor 16 and a circuit that serves as the state sensor (if not also the heating circuit), and feedback controller, and to a mechanical load. Operation during a first cycle, initial length, and initial displacement of the SMA element may be recorded, along with R_{A1} and R_{M1}, for recording of the production parameters of the SMA element. At least the R_{A1} parameter is stored by a memory 21 of the feedback control 18.

[0034] The memory 21 also stores program instructions for comparing a recently exhibited resistance of the SMA element in the austenitic phase R_A, with the stored R_{A1} parameter. The resistance in an austenitic phase (R_A) may be inferred from a minimum resistance during an actuation cycle; a resistance concurrent with, or corresponding to, a maximum stress; and a resistance after a known duration and degree of heating applied by the heater, or a decision procedure based on two or more of these parameters. In the examples below, a minimum resistance in a cycle of predetermined duration is taken to be R_A. This is possible because a fixed cycle period is used that has sufficient time for complete heating to a completely austenitic phase. Naturally, if actuation degree changes non-periodically, an assessment of degree of actuation and resistance may be required to compute a current R_A.

[0035] The fatigue assessment may be performed according to a fixed schedule, on demand, and in response to a change in operating conditions, for example. An optimum schedule for estimating fatigue may be defined for a particular SMA actuator, or for a given application.

[0036] As readings from the stress sensor are available, the memory 21 may further store program instructions for monitoring a strain on the SMA element 10, to continuously track whether loads applied by SMA actuator are within an established range of operating parameters. Specifically, the memory 21 may store a statistic of a static or dynamic load on the SMA actuator, especially a minimum load, a statistic of the monitored stress, a number of actuation cycles, a number of actuation cycles at a given stress, and a statistic of a monitored value that depends on a degree, duration or frequency of actuation of the SMA actuator.

[0037] This permits different estimations of fatigue based on different monitored operating conditions. It has been observed that large deviations in fatigue are observed, when SMA actuators are operated with different constant loads. When SMA actuators operate under varying loading conditions, extreme loading conditions, actuation frequencies, degrees of actuation, and rates of heating may be particularly useful in assessing a fatigue state, given the observed R_A. Thus different monitored operating regimes may lead to different estimates of fatigue for a given R_A value. This may be performed by interpolating between, or extrapolating from, a fixed number of fatigue estimates as a function of R_A for a given set of operating regimes, or using any of a wide variety of models of fatigue at mixed loading conditions.

[0038] Once the fatigue is estimated, the plastic deformation can be compensated, by altering some aspect of the system that interfaces with the SMA actuator (e.g. re-aligning the SMA actuator by a corresponding distance), by reducing a degree of actuation to ensure that the SMA element does not exceed a given extension. If the SMA element is controlled by a model of the SMA extension, adding the plastic deformation term to the model of the SMA element can improve a precision of the control.

[0039] FIGs. 3a,b are schematic illustrations of SMA elements with particular stress sensors in accordance with Applicant's co-pending United States application. FIG. 3a shows the SMA actuator with an embedded stress sensor, in accordance with an embodiment of the invention. The SMA element 10 is mechanically secured at an anchoring end to a support frame, and at an opposite end to a small displacement slider, which may be mechanically coupled to other simple machines to effect a desired motion of a desired piece.

[0040] The SMA element 10 is secured to couplers 105 and 106 at opposite ends, by respective crimps 101. The couplers 105 and 106 have threaded through bores for mechanical attachment to the small displacement slider or support frame. Coupler 106 is different from coupler 105 in that it has an extended section that is of a composition, thickness, and/or position to be favourably strained by a load applied to the SMA element 10.

[0041] The stress sensor is a strain gauge 160 mounted on the extended section. Knowing the Young's modulus of the extended section, and the area of its cross-section, the force applied on the SMA wire can be calculated based on reading (elastic deformation of the flat section) of by the strain gauge 160. The stress sensor illustrated is specifically a foil-type strain gauge that operates on the principle of electrical resistance varying with length and cross-sectional area of a conductor, as are commonly available, small, and sensitive enough for the present use. Advantageously they are selectively sensitive to strain in one direction, and naturally the orientation of the strain gauge 160 is in the direction of contraction and extension of the SMA element 10. The strain gauge 160 is electrically connected by conductors 162 for supplying electricity to, and for outputting temperature data from, the strain gauge 160, via a quarter-bridge circuit. Some foil-type strain gauges are sensitive to thermal variations as a change in temperature of the conductor cause corresponding thermal contraction and expansion, which would otherwise be detected as strain. Several solutions for the temperature dependence are known and can be applied in various cases.

[0042] In the embodiment of FIG. 3a, direct electric resistance heating may be provided by connecting a circuit to the conductive crimps 101, or the circuit may pass through the couplers 105, and 106.

[0043] The illustrated embodiment includes a thermocouple 165 (not in view) on an opposite side of the extended section of the coupler 106. The thermocouple 165 is electrically connected by conductors 166 for supplying electricity to, and for outputting temperature data from, the thermocouple 165. The thermocouple is one solution for the temperature dependence on the strain gauge 160. The output of the thermocouple 165 and strain gauge 160 are jointly received by a controller that computes an electrical power applied across the SMA element 100 in accordance with a desired actuation.

[0044] FIG. 3b is a schematic illustration of an alternative embodiment of the stress sensor. Like features are identified with like reference numerals and their descriptions are not repeated here. The principle difference between the embodiments of FIGs. 3a and 3b is an off-axis support for one end, which results in a shearing force applied at a rigid section running substantially perpendicular to the SMA element 10. In the specific drawing, this is provided with a crimp head bent 90° and rigidly secured to a coupler 107 (by a bolt). An elongated section between the bolt and a through bore for coupling with the support structure or small displacement slider provides the place for determining strain. Knowing a stiffness of the cantilevering section of coupler 107 and its bending strain, the force applied to its end can be calculated. By using two strain gauges 160a,b (each connected by conductors 162a,b) on opposite sides of the elongated section, compressive strain will tend to register a compression on the near strain gauge 160a, and an expansive strain on the far strain gauge 160b. A change in temperature of the two strain gauges 160a,b will tend to cause both to expand or contract, but a difference between the strain readings of these two strain gauges 160a,b will be self regulating with respect to temperature. Preferably the two strain gauges 160a,b are connected in a half bridge configuration to simplify output.

[0045] The coupler 107 may further be made of a thermally insulating material such as plastic to limit the temperature fluctuations of the strain gauges 160a,b. The contacts for direct electric resistance heating of the SMA element 10 may be provided via the crimps, for example.

[0046] The advantage of this construction is the plastic arm can effectively isolate the heat transfer from the SMA actuator to the strain gauge so as to minimize the influence of temperature on the strain reading of the cantilever arm. Two strain gauges, one on the right (tension) and one on the left (compression), can effectively provide self-temperature compensation, to the extent that they are equally affected by the heated SMA element.

[0047] With output of strain gauges, such as those exemplified in FIGs. 3a,b, a circuit such as shown in FIGs. 4a,b may be used to allow a control processor 180 to provide SMA control with mitigated fatigue, or at least with the estimate of fatigue.

[0048] FIG. 4a is a schematic circuit diagram of an SMA actuator control system. Feedback control is provided for a pair of SMA actuators. While two SMA actuators are shown, it will be appreciated that other numbers of SMA actuators could equally be embodied in an enlarged circuit by replication of the circuit patterns shown here, or a single SMA actuator may be controlled.

[0049] FIG. 4a shows two SMA elements 10 (SMA1 and SMA2), which appear collinear and distant, but it will be appreciated that they could have any desired spatial arrangement, subject to the limitations of independent electrical coupling and a desired thermal coupling. Typically, thermal isolation is preferred if the SMA elements are to be independently actuated. The SMA elements 10 are both in parallel branches of a circuit. Each branch is effectively a serial connection of a DC power source 120, a reference resistor 121 (R_f), and a switch. The DC power source 120 can be a direct power unit, a battery, or any other suitable direct current power source.

[0050] The function of the switch is to selectively actuate the circuit for supplying current to the respective SMA element 10 to control direct electric resistive heating. It will be appreciated by those of skill in the electronic arts that there are several circuit means for accomplishing this, and that some may be preferred in certain applications. There may be value in providing a plurality of currents to SMA1 and/or SMA2, for providing a continuously varying range of currents, for simplicity of design, or for providing response to certain control signals in different embodiments.

[0051] The illustrated design, preferred for its simplicity, uses a transistor to effectively eliminate the need for a sophisticated power supply unit adapted for signal amplification, which is generally regarded as necessary for feedback position control of SMA actuators. This significantly simplifies the requirement for the hardware, reducing the mass and volume and providing great simplicity in the design and operation of SMA actuator, particularly when the strain output regulation of multiple SMA actuators is required.

[0052] The use of a transistor overcomes a technical challenge if continuous measurement of electrical resistance across the SMA element 10 is desired. If intermittent (regular or sporadic) sampling of the state of the SMA element 10 is unsatisfactory, and actuation for a period of time that is sufficient to provide a reliable reading of the state does not generally apply enough heat to significantly alter the state of the SMA element 10, it may be preferred to simply provide a transistor.

[0053] If it is desired to provide a fast acting switch that changes states within the shortest duration, which requires that the SMA element 10 draw as much power in the measurement interval as it can safely absorb and dissipate, it may be preferable to provide continuous monitoring of the state of the SMA element 10. This is here provided by permitting some minimal electrical current to pass through the SMA actuator and the first resistor when the transistor is set to its off state.

[0054] Both switches are embodied as a transistor 125 in parallel with a bypass resistor 126. The bypass resistor 126 ensures that some minimal electrical current passes through the SMA actuator continuously so that the electrical resistance can continuously be measured. The bypass resistor 126 has a relatively large resistance to provide a minimum current that is far less than the current required for SMA actuation. This minimal current may be selected to minimize impact on strain output regulation precision. Bypass resistor 126 should have a resistance value of at least about 10 times bigger than the combined resistance value of R_f and R_{SMA}.

[0055] It will be appreciated that a further branch parallel to both the transistor 125 and bypass resistor 126, featuring a resistor and transistor could be used. For example, if the resistor has an intermediate resistance value (between R_f and that of the bypass resistor 126), it may be used to provide three heating states (both transistors on, or only one or the other on), and one essentially passive state for monitoring. The intermediate resistance may be chosen to provide a minimum heat to the SMA element 10 that can be steadily dissipated without any transition of the SMA element 10 from the completely excited state to a lower excited state. With both transistors on, the sum current flowing will be greater than the first transistor (T1 or T2) alone and this may be used for initial heating to increase a response time, for example if controls are in place to ensure that both transistors are not on when the SMA element is in a state of actuation above a given threshold.

[0056] Each of the tapped signals outputs a voltage, which is detected by control processor 180, for example via analog voltage modulated interface cards at a computer, such as a data acquisition board. The control processor 180 receives these voltage values for SMA1 and SMA2, and computes for each a current state of actuation thereof. The control processor 180 also issues control signals 201 to the transistors 125 for controlling the closing and opening of the corresponding circuit branches. DCH1 and DCH2 are digital signal channels used to set the transistors 125.

[0057] ACH7/8 are used for the signals indicating a measure of the force applied to the SMA element 10. For each SMA actuator, there is an integrated stress sensor, consisting of a pair of the foil-type strain gauges 160 (S1a,b and S2a,b), such as shown in FIG. 3b. The stress sensor data is forwarded to a multiplex signal conditioner that may be powered by the DC power source 120, or the computer, depending on specific requirements of the system. The multiplex signal conditioner receives analog data from the individual foil type strain gauges, derives or computes a strain on the SMA element 10, and forwards these values in accordance with a pre-established sampling protocol over a multiplexed channel, to the control processor 180.

[0058] The elements above permit the selective application of heat to the SMA element 10. The state sensor is also provided with electrical taps to the above described circuit. ACH1/4, ACH2/5, ACH3/6 are analogue signal input lines used for measurements of voltages ($V_{11/21}$, $V_{12/22}$, $V_{13/23}$) at the output of the first resistor (R_F), at the output of the SMA element 10, and at the input of the respective SMA element 10, respectively. With knowledge of the resistance R_f, the resistance across the SMA1 (R_{SMA1}) can be calculated from the following equation (and similarly for SMA2 with the corresponding substitutions): $(V12-V11)/R_f = (V13-V12)/R_{SMA1}$.

[0059] By monitoring the resistance of SMA1 when fully actuated, the instantaneous austenitic resistance value (R_A) of SMA1 is obtained. Comparison of R_A with R_{A1} (the austenitic resistance of SMA1 in the first cycle of use) yields SMA1's current ΔR_A. In some instances, this is all that is required. In others, determining a point in the R_{SMA1} stream that corresponds with the austenitic state may be subject to uncertainty. In such cases it may be advantageous to consider a plurality of data points. Simply monitoring the R_{SMA1} can provide an estimate of a recent R_A value, as long as the SMA1 has recently been fully actuated, as every local minimum of the R_{SMA1} is a candidate R_A value. If the desired actuation rarely achieves full actuation, and an estimated or monitored desired actuation is known, a model of the SMA1's element having fractions in actuated austenitic, and relaxed deformed martensitic (possibly further assuming a fraction in a twinned martensitic state), may be used to estimate the R_A value. Alternatively, and more directly, the SMA1 may be actuated by a control program during an interval, where the control program involves a complete actuation for a period of time, and the determination of ΔR_A may be performed during the interval.

[0060] Furthermore, coordination between the control processor's DCH1 signal, which selectively applies power to the SMA1, can be used to determine a candidate R_A value. This assumes that cooling rates are stable, and that actuation is only applied by the Joule heating. Typically SMA elements are arranged for controlled heat dissipation. Finally, in other embodiments, the R_A value may be concurrent with a maximum stress on the SMA element. If, in the actuated state, the contraction of the SMA element applies a greater load on the mechanical system than during relaxation, temporal coordination of the stress sensor readings may be used to identify the R_A value, and therefore ΔR_A. In mechanically noisy environments loads may fluctuate over the interval of measurement, and these may result in errors too. A combination of minimum resistance, maximum strain, and maximum heating may be a preferred solution for identification of R_A values, which may further be associated with an uncertainty or a confidence estimation.

[0061] The ΔR_A value may be used as an index of fatigue. For example, under constant, known loading conditions, fatigue $\Delta\varepsilon$ has been shown to vary linearly with ΔR_A, and the load determines the constant of proportionality, when the SMA element is driven sinusoidally. In a more general context different estimations may be required to approximate the fatigue given ΔR_A. Advantageously, the SMA actuation system having the stress sensor and resistance monitor integrated with it, has all of the information required to ascertain how the SMA has been used, and can therefore predict the fatigue. At least under prescribed operating conditions, the fatigue can be experimentally verified prior to deployment.

[0062] While it was known from Applicant's co-pending application that this structure can be used to accurately control strain output, it has now been realized that a degree of fatigue can be assessed, and even compensated for, using this structure, with suitable software updates, for example by providing a method for determining ΔR_A, and optionally using this value to compute $\Delta\varepsilon$.

[0063] In some cases, after the first actuation is performed to determine R_{A1}, the SMA is operated with a programmed limit, to achieve at most partial actuation, such that during operation, the SMA element is never fully constricted (actuated). In some cases, an actuation limit is mechanically imposed on the SMA element. In such cases, plastic deformation may be compensated by increasing the programmed limit, and the degree of actuation. This strategy can prolong a service life of the SMA element, both by less utilization of the actuation, and by increasing the programmed limit in lock-step with the plastic deformation as it occurs. These come at the cost of the usable actuation range. Programmed limitation is particularly useful when the SMA actuator has a low tolerance for the actuated displacement. If there is low tolerance for position in the relaxed state too, the degradation must be controlled.

[0064] As will be understood by those of skill in the art, the ACH and DCH channels of FIG. 4a can be collected and sent over a single multiplexed channel saving wiring complexity, and costs. Signaling requirements, protocols and spatial constraints all factor into decisions about how and where to group these signals. It may be preferred to group all of the ACH and DCH channels through a single multiplex signal conditioner, or to have one for each SMA actuator. The circuits of FIGs. 4a,b may be implemented in a circuit board, a gate array, or other structured circuit.

[0065] FIG. 4b schematically illustrates modifications to the circuit for effecting feedback control of a pair of SMA actuators shown in FIG. 4a to avoid use of a multiplex signal conditioner. Each voltage regulated output tap is fed directly to the control processor 180, and the circuits are provided from the DC power supply + to the DC – in a conventional manner.

[0066] FIGs. 5a,b are schematic illustrations of circuits for determining R_A values in an alternate embodiment, where strain is not monitored by an on-board strain gauge. If a known load is applied to the SMA element at a time when the SMA element is in a known state of at least partial actuation (preferably completely actuated) R_A is correlated with a degree of fatigue, to the extent that the operating conditions of the SMA element are known. Thus fatigue assessment can be performed without requiring a precise length measurement, by mechanically interacting with the SMA actuator, and determining R_A, without continuous monitoring. The mechanical interaction may be provided by any simple machine or device that may reside on the SMA actuator, may or be brought into contact with the SMA actuator, that provides accurate mechanical load.

[0067] FIG. 5a is a schematic diagram of a circuit for obtaining R_{SMA} values when a SMA actuator is subjected to a known force. This embodiment requires a stable power supply (V_0 AC/DC). The SMA element 10 is shown mechanically joined to two similar ends, each having a proximal feature for electrical coupling of the SMA element 10 and a distal feature for mechanical coupling to a frame, slider, or other component of the mechanical system. The power supply has the SMA element 10 in series, along with reference resistor 121. A potential difference across reference resistor 121 is measured by placing a voltage measurement device 188, such as a digital multimeter, or data acquisition card and computer, or other processor, in parallel with the reference resistor 121. In the illustrated embodiment, the SMA circuit has a plug end 185 for coupling to the voltage measurement device 188 when desired (e.g. in the event of scheduled maintenance). The voltage measurement device 188 has a complementary plug end 186.

[0068] Preferably voltage measurement device 188 includes or is coupled with a memory and display, for presenting and recording minimum and maximum resistance values, or at least minimum resistance values. Preferably, while the SMA actuator is in operation (with duty cycles), the voltage measurement device 188 samples the voltage drop across the reference resistor at a rate (per second) greater than 200/P, where P is the period of the duty cycle of SMA actuator. For example, if the duty cycle of a SMA actuator is 20s (2s actuated and 18s relaxed), the sampling rate would thus be at least 10 Hz.

[0069] To compute R_{SMA}, we assume that V_0 and R_{ref} are known. V_{ref} is preferably measured during at least one full actuation cycle in which the SMA element is fully actuated, to obtain a stream of data stored as an array of successive time points (V_{ref_1}, V_{ref_2}, ..., V_{ref_n}). The following equation may be applied at each point, or at one or more candidate austenitic resistance measures (i.e. maximum V_{ref} values): $R_{SMA} = R_{ref} (V_0/V_{ref\_i} - 1)$. If multiple cycles of resistance data are obtained, it may be assumed that fatigue is constant throughout the assessment, and an improved accuracy may be obtained by averaging. Furthermore, a model of subsample curve fitting may be used to improve accuracy of the R_A measure.

[0070] It will be appreciated by those of ordinary skill that the SMA need not be cycled during the assessment, and a resistance may be initially computed and then computed again continuously as the SMA element heats up. The force may be applied during the heating, or only after the SMA element is fully actuated.

[0071] ΔR_A may be computed by subtracting the observed R_A values from the original R_{A1} value, as provided by manufacturer data, or as computed when the SMA actuator was installed. The ΔR_A may be then used to correlate with fatigue state.

[0072] FIG. 5b schematically illustrates an embodiment that is preferred in the event that the power supply is subject to variations. In comparison with FIG. 5a, FIG. 5b includes a second pair of plug ends, this second in parallel with the SMA element 10. The voltage measurement device is replaced with a computer-based data acquisition system 189, although all that is required of the device is to measure two voltages at nominally the same time.

[0073] To compute R_{SMA}, with known R_{ref}, V_{ref} is measured as before, and concurrently V_{ref} is measured, recorded, and preferably displayed, yielding two arrays of time points (V_{ref_1} , V_{ref_2} , ..., V_{ref_n}), and (V_{SMA_1} , V_{SMA_2} , ..., V_{SMA_n}). The following equation may be applied at each point, or at one or more candidate austenitic resistance measures: $R_{SMA} = R_{ref} (V_{SMA\_i}/V_{ref\_i})$.

Examples

[0074] A substantially conventional test rig for measuring fatigue in SMA elements was used to examine a SMA element. The rig includes a mounting with a strain gauge for gripping a top end of the SMA element, an LVDT for accurate displacement measurement below the bottom end of the SMA element, a load below the LVDT for applying a steady force on the SMA element, and circuitry for actuating the SMA element, and for recording measurements from the sensors. The setup is substantially as shown in FIG. 5 of applicants co-pending application.

[0075] The SMA element is in wire form (6 mil diameter) supplied by Dynalloy Inc. The Austenite finishing temperature is approximately 90°C, the maximum recommended applied force is 330 g (3.23 N), and the recommended electrical current input is 400mA.

[0076] FIG. 6 is a plot of the correlation between accumulated plastic deformation of the SMA element as a function of number of cycles, under two different loadings. In each case the SMA element was fully actuated in each cycle, and the cycle was periodic. It will be noted that when the pressure was under 172 MPa, the experiment continued to nearly 100,000 cycles, whereas with a pressure of under 375 MPa, the experiment continued only for less than 5000 cycles.

[0077] FIG. 7 is a plot of a percent change in resistance in the Austenitic phase (ΔR_A) as a function of accumulated plastic deformation $\Delta\varepsilon$. These plots show a high linearity, suggesting a very simple relationship between fatigue and ΔR_A.

[0078] *References*: The contents of the entirety of each of which are incorporated by this reference:

[1] Furuya, Y., H. Shimada, "Fatigue and degradation of shape memory effect in Ni-Ti wire", Proc. Of MRS Intl. Mtg. on Advanced Materials, Tokyo, Japan, 1998, pp269-274

[2] Brailovski, V. et al, “Fatigue and degradation of SME” in “Shape memory Alloys: Fundamentals, modelling and applications”, edited by V. Brailovski , S. Prokoshkin, P. Terriault, F. Trochu, Published by University of Quebec, 2003, Montreal, Canada, pp311-340.

[3] Miller, D. A. & D. C. Lagoudas, "Thermomechnical characterization of Ni-TiCu and Ni-Ti SMA actuators: Influence of plastic strains", Smart. Mat. & Struct., 9(2000) pp640-652.

[4] Lagoudas, Dimitris C; Li, Changcheng; Miller, David A; Rong, Lijian, "Thermomechanical transformation fatigue of SMA actuators", Adaptive structures and material systems-2000; Proceedings of the Symposium from the 2000 ASME International Mechanical Engineering Congress and Exposition, Orlando, FL; UNITED STATES; 5-10 Nov. 2000. pp. 1-6. 2000.

[5] HORNBOGEN, E., Thermo-mechanical fatigue and rupture of shape memory alloys (SMA), National Science Council, Proceedings (Germany). Vol. 14, Part A: Physical Science and Engineering, pp. 350-356. Sept. 1990.

[0079] Other advantages that are inherent to the structure are obvious to one skilled in the art. The embodiments are described herein illustratively and are not meant to limit the scope of the invention as claimed. Variations of the foregoing embodiments will be evident to a person of ordinary skill and are intended by the inventor to be encompassed by the following claims.

Claims:

1. A processor with non-transitory memory for assessing fatigue of a shape memory alloy (SMA) element, the processor comprising program instructions for calculating a difference between a resistance of the SMA element in an Austenitic state during a first actuation, with a recent resistance of the SMA element in the Austenitic state.

2. A processor of claim 1 wherein the difference is used to compute an estimate of a fatigue state of the SMA element.

3. A processor of claim 1 wherein the difference is used with a load on the SMA element to derive an estimate of a fatigue state of the SMA element.

4. A processor of claim 1 wherein the processor further comprises program instructions for accessing the resistance of the SMA element in the Austenitic state during the first actuation from the memory, and determining the recent resistance of the SMA element in the Austenitic state by sampling a resistance exhibited by the SMA element during at least one actuation cycle.

5. A processor of claim 4 wherein determining the recent resistance in the Austenitic state comprises: selecting from samples of the SMA resistances, a sample having a minimum resistance; and a sample time aligned with an expected state given a known duration and degree of heating applied to the SMA element.

6. A processor of claim 1 wherein the processor is a part of a control system of the SMA element, along with a state sensor, and a stress sensor, wherein the processor monitors a resistance of the SMA element through the state sensor and a load on the SMA element through the stress sensor.

7. A processor of claim 6 wherein a fatigue assessment given an identified change in Austenitic state resistance, depends on a range of stresses applied on the SMA element in operation, as monitored by the processor.

8. A processor of claim 6 where the processor controls a heating of the SMA element by controlling an electrical power conducted therethrough, wherein the processor further comprises program instructions for systematically altering heating commands subsequent to a fatigue assessment, to mitigate development of fatigue.

9. A shape memory alloy (SMA) actuator comprising:
    a SMA element composed of a SMA material;
    a heater for heating the SMA element; and

a control system for selectively controlling the heater in dependence on a desired actuation of the SMA element, a monitored stress on the SMA actuator, and a monitored resistance of the SMA element,

wherein the control system is adapted to compare an electrical resistance exhibited by the SMA element in an austenitic phase during a first actuation of the SMA actuator, with a recent electrical resistance of the SMA element in an austenitic phase to estimate a degree of fatigue.

10. The SMA actuator of claim 9 wherein resistance in the austenitic phase is inferred to be a minimum resistance during an actuation cycle.

11. The SMA actuator of claim 9 wherein resistance in the austenitic phase is inferred by a model of heating of the SMA material in dependence on a duration and degree of heat applied by the heater.

12. The SMA actuator of claim 9 wherein resistance in the austenitic phase is inferred from one or more of: a minimum resistance during an actuation cycle; and a resistance after a known duration and degree of heating applied by the heater.

13. The SMA actuator of claim 9 wherein the control system is further adapted to use the estimated degree of fatigue to apply a correction to a control signal for controlling the heater, to mitigate fatigue-based error.

14. The SMA actuator of claim 13 wherein the control system is further adapted to determine a correction to be applied, having regard to a parameter of an actuation history of the SMA actuator.

15. The SMA actuator of claim 13 wherein the control system is further adapted to determine a correction to be applied, having regard to one or more of the following parameters of an actuation history of the SMA actuator stored by the control system in a non-transitory memory: a statistic of a static or dynamic load on the SMA actuator, especially a minimum load, a statistic of the monitored stress, a number of actuation cycles, a number of actuation cycles at a given stress, and a statistic of a monitored value that depends on a degree, duration or frequency of actuation of the SMA actuator.

16. The SMA actuator of claim 13 wherein the control system is further adapted to determine a correction to be applied, having regard to a lower limit of a variable loading stress applied to the SMA actuator throughout its use history.

17. The SMA actuator of claim 9 wherein the heater is an electrical circuit passing controlled electrical power through the SMA element, and the controller controls the power on the electrical circuit to induce Joule heating within the SMA material.

18. The SMA actuator of claim 9 wherein the SMA element is a linear small displacement actuator, in ribbon, wire, rod, or cylinder form, having a dimension of 0.5-50 mil.

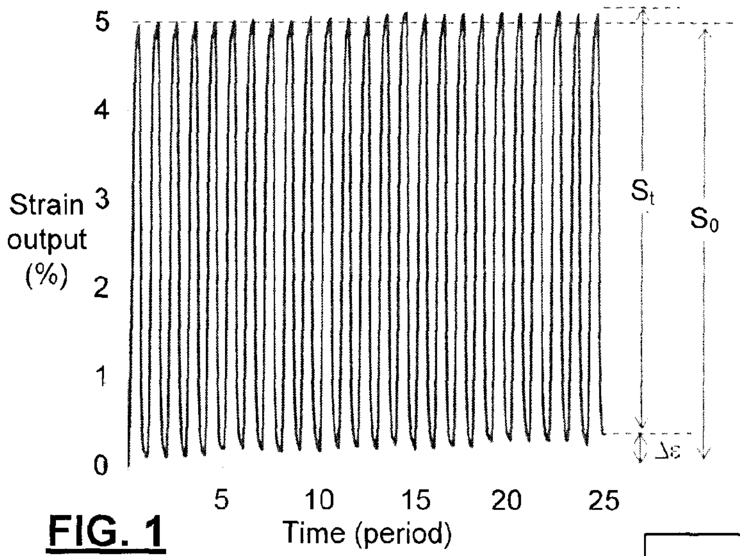

FIG. 1

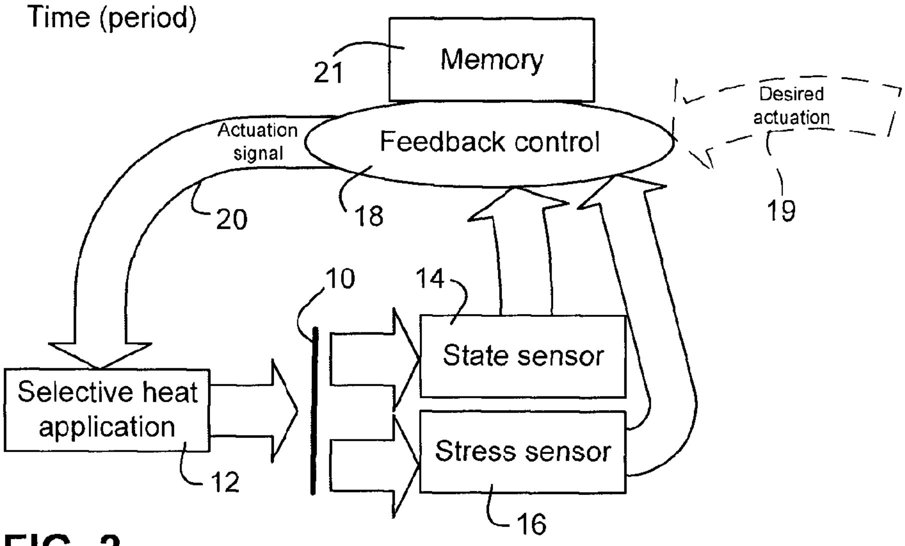

FIG. 2

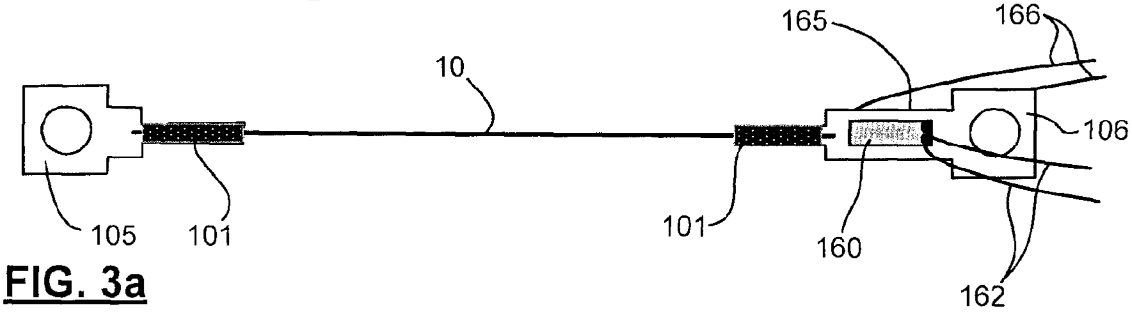

FIG. 3a

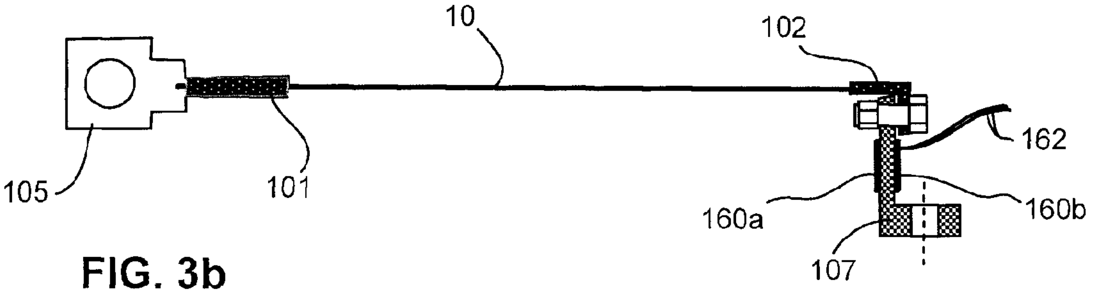

FIG. 3b

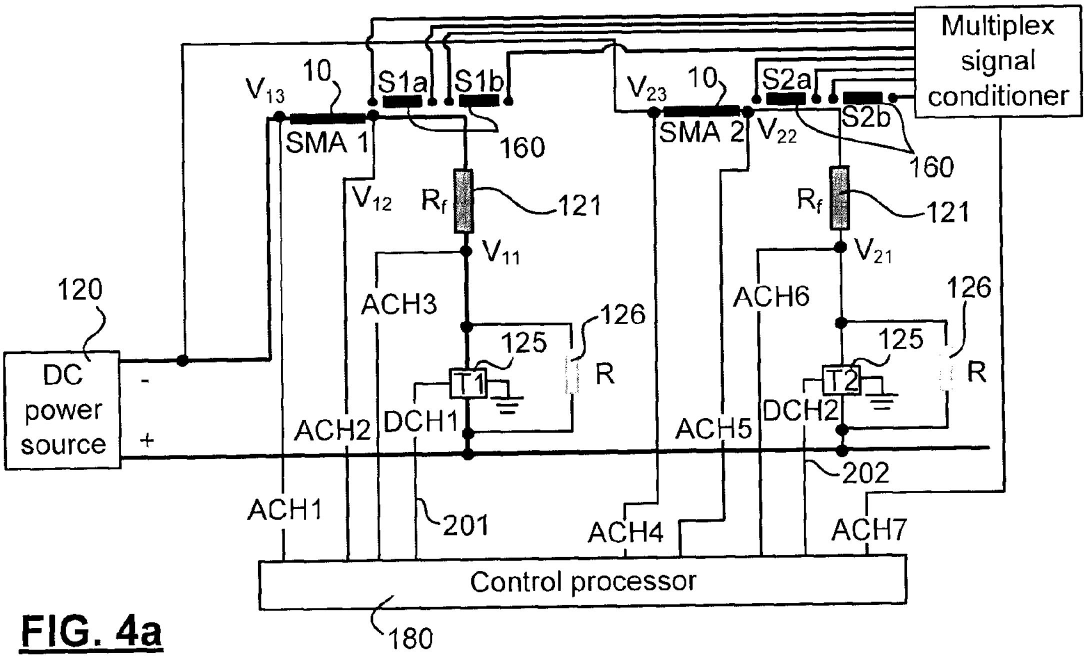
Multiplex
signal
conditioner
V13
10
S1a
S1b
SMA 1
160
V12
Rf
121
V11
ACH3
126
125
R
T1
DCH1
ACH2
120
DC
power
source
-
+
ACH1
201
V23
10
S2a
S2b
SMA 2
V22
160
Rf
121
V21
ACH6
126
125
T2
R
DCH2
ACH5
202
ACH4
ACH7
Control processor
180

FIG. 4a

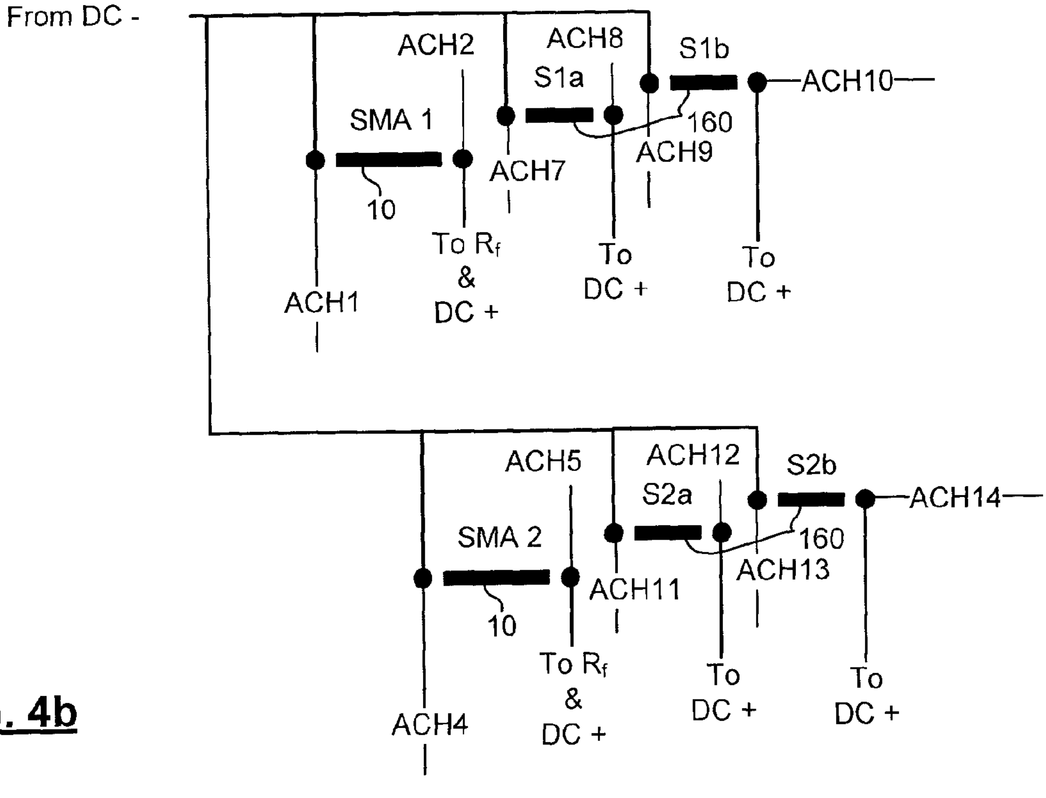
From DC -
ACH2
ACH8
S1b
S1a
ACH10
SMA 1
160
ACH9
ACH7
10
To Rf & DC +
To DC +
To DC +
ACH1
ACH5
ACH12
S2b
S2a
ACH14
SMA 2
160
ACH13
ACH11
10
To Rf & DC +
To DC +
To DC +
ACH4

FIG. 4b

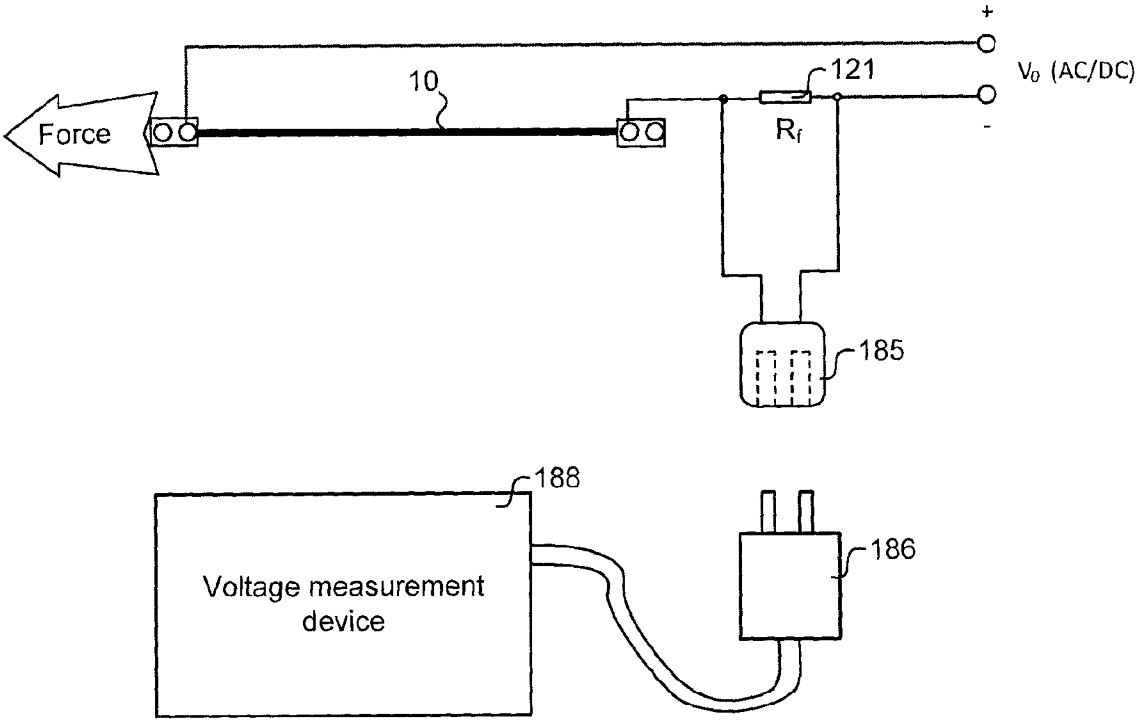
+
121
V₀ (AC/DC)
10
Force
Rf
-
185
188
186
Voltage measurement device

FIG. 5a

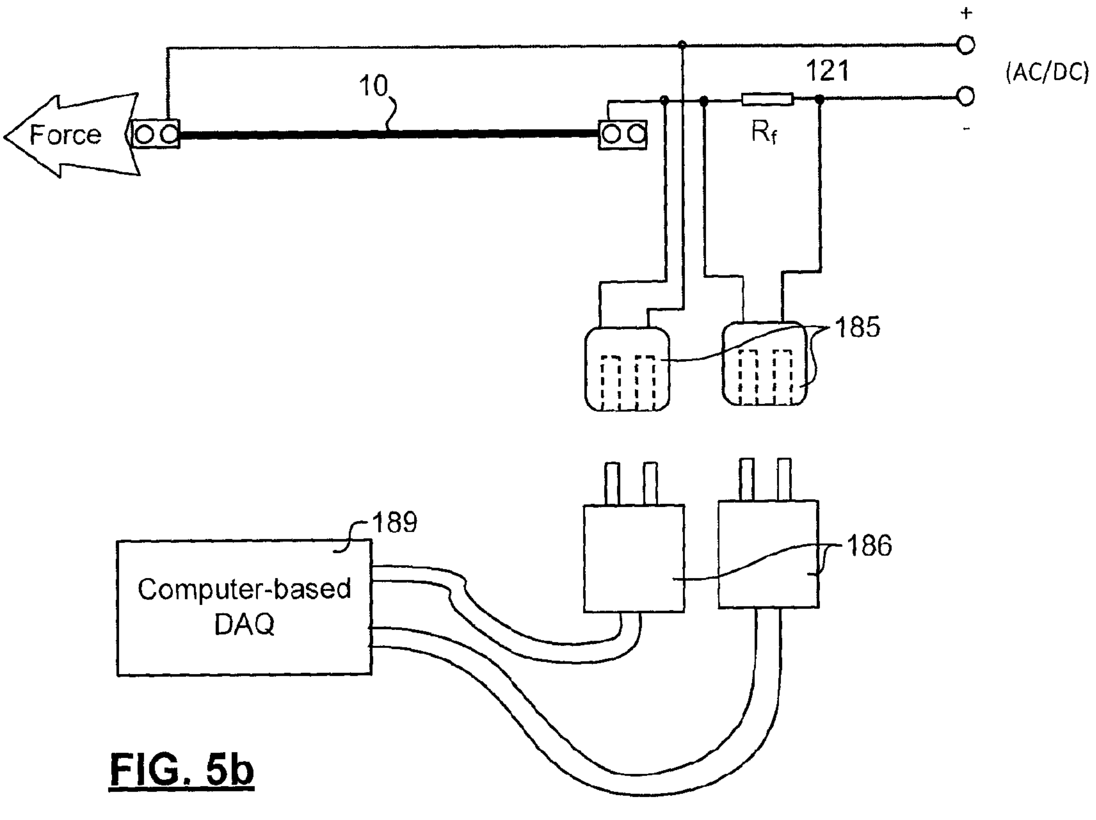
+
121
(AC/DC)
10
Force
Rf
-
185
189
186
Computer-based DAQ

FIG. 5b

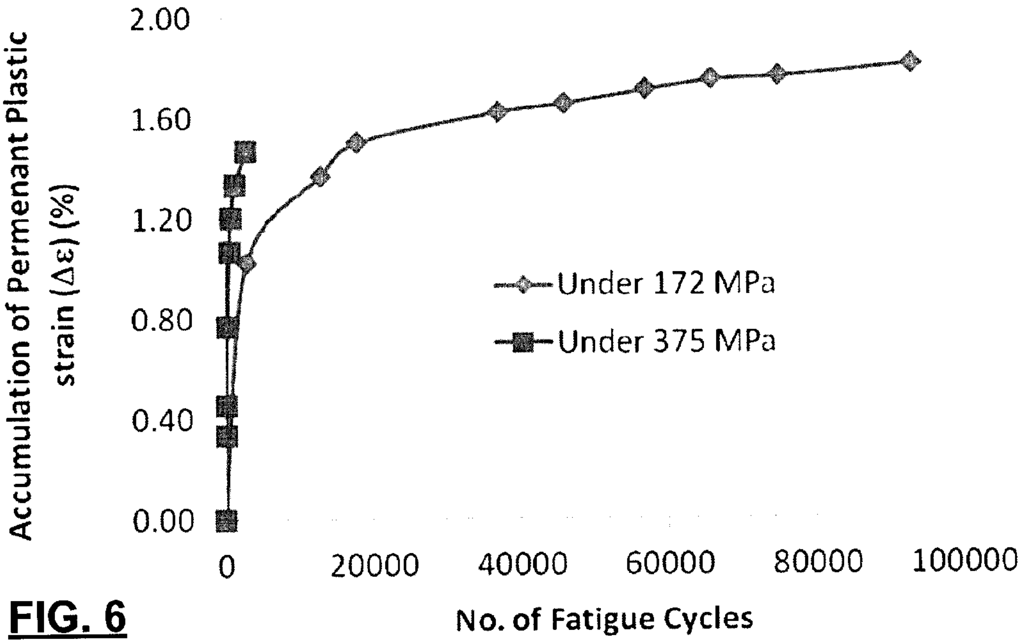
Accumulation of Permenant Plastic strain (Δε) (%)
2.00
1.60
1.20
0.80
0.40
0.00
0
20000
40000
60000
80000
100000
No. of Fatigue Cycles
Under 172 MPa
Under 375 MPa

FIG. 6

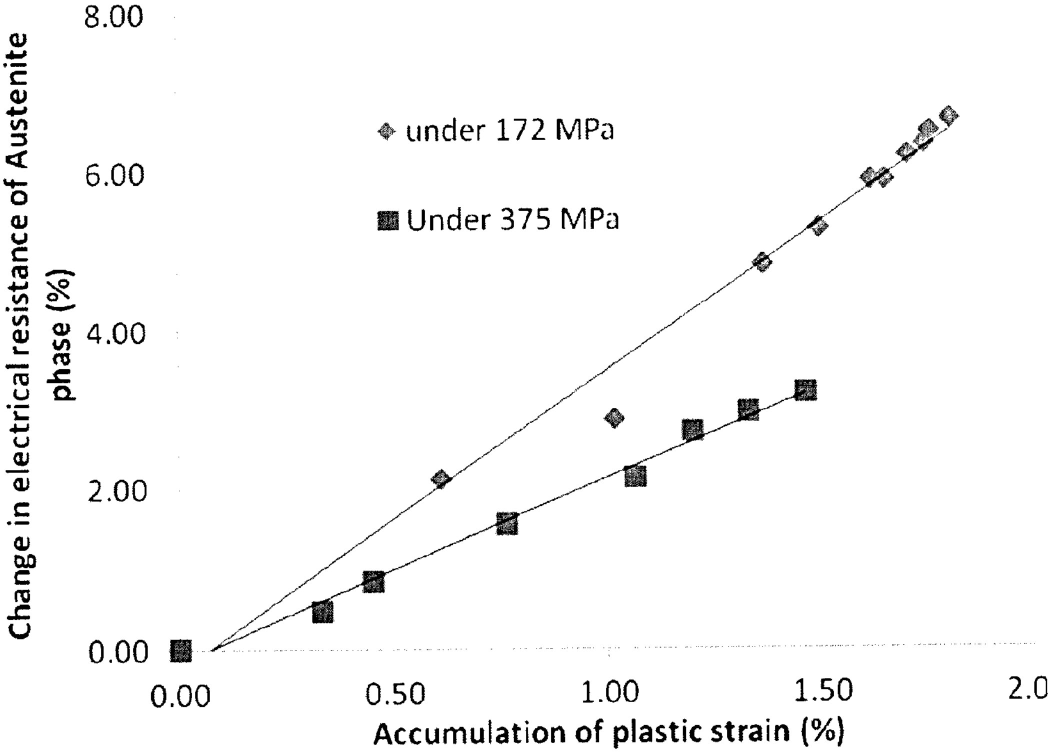
Change in electrical resistance of Austenite phase (%)
8.00
6.00
4.00
2.00
0.00
0.00
0.50
1.00
1.50
2.0
Accumulation of plastic strain (%)
under 172 MPa
Under 375 MPa

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2014/000114

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***G01N 27/20*** (2006.01) , ***G12B 1/00*** (2006.01) , ***H02N 99/00*** (2006.01)
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: ***G01N*** (2006.01) , ***G12B*** (2006.01) , ***H02N*** (2006.01) (using keyworks)

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Canadian Patent Database, Esp@cenet, TotalPatent, United States Patent Database (USPTO).
Keywords: actuator, austenitic, control, fatigue, heat, memory, processor, resistance, shape memory alloy, SMA, stress.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 20110004346 (Jiang et al.) 6 January 2011 (06-01-2011) - Abstract - Page 1 [0002], [0003] - Page 2 [0011]-[0023] - Page 3 [0044]-[0049] - Page 4 [0050]-[0057] - Page 5 [0064] - Page 6 [0072]-[0080] - Page 7 [0084]-[0090] - Drawings 1-8b	1-12, 17, 18

☑ Further documents are listed in the continuation of Box C.

☑ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier application or patent but published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search
24 April 2014 (24-04-2014)

Date of mailing of the international search report
08 May 2014 (08-05-2014)

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Facsimile No.: 001-819-953-2476

Authorized officer

Tung Nguyen (819) 956-3859

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Song et at., "Smart Materials, Structures & NDT in Aerospace", Cansmart Cinde Izfp, Montreal, Quebec, Canada, 2-4 November 2011	1-12, 17, 18
A	CA 2276289 (Maynard) 9 July 1998 (09-07-1998) - See entire document	1-18
A	US 20030155539 (Ginggen) 21 August 2003 (21-08-2003) - See entire document	1-18
A	US 20100060776 (Topliss et al.) 11 March 2010 (11-03-2010) - See entire document	1-18
A	CA 2391746 (Macgregor) 22 February 2001 (22-02-2001) - See entire document	1-18
A	McCluskey et al., "Precipitation and Thermal Fatigue in Ni-Ti-Zr Shape Memory Alloy Thin Films by Combonatorial nanoCalorimetry", Acta Mater, January 2011	1-18

Patent Document Cited in Search Report	**Publication Date**	**Patent Family Member(s)**	**Publication Date**
US2011004346A1	06 January 2011 (06-01-2011)	US2011004346A1	06 January 2011 (06-01-2011)
		US8706305B2	22 April 2014 (22-04-2014)
		CA2714496A1	27 August 2009 (27-08-2009)
		WO2009103159A1	27 August 2009 (27-08-2009)
		EP2255260A1	01 December 2010 (01-12-2010)
CA2276289A1	09 July 1998 (09-07-1998)	CA2276289A1	09 July 1998 (09-07-1998)
		AT259937T	15 March 2004 (15-03-2004)
		AT298543T	15 July 2005 (15-07-2005)
		AU725617B2	12 October 2000 (12-10-2000)
		AU4245997A	26 March 1998 (26-03-1998)
		AU736910B2	02 August 2001 (02-08-2001)
		AU5096998A	31 July 1998 (31-07-1998)
		AU5151298A	22 June 1998 (22-06-1998)
		CA2236522A1	12 March 1998 (12-03-1998)
		CA2236522C	11 May 2004 (11-05-2004)
		CA2272655A1	04 June 1998 (04-06-1998)
		CA2272655C	21 November 2006 (21-11-2006)
		DE69727698D1	25 March 2004 (25-03-2004)
		DE69727698T2	15 July 2004 (15-07-2004)
		DE69733667D1	04 August 2005 (04-08-2005)
		DE69733667T2	27 April 2006 (27-04-2006)
		DE69737410D1	12 April 2007 (12-04-2007)
		DE69737410T2	29 November 2007 (29-11-2007)
		DK0953110T3	21 June 2004 (21-06-2004)
		EP0953110A1	03 November 1999 (03-11-1999)
		EP0953110B1	18 February 2004 (18-02-2004)
		EP0858558A1	19 August 1998 (19-08-1998)
		EP0858558B1	28 February 2007 (28-02-2007)
		EP0957823A1	24 November 1999 (24-11-1999)
		EP0957823B1	29 June 2005 (29-06-2005)
		ES2216135T3	16 October 2004 (16-10-2004)
		JPH11515073A	21 December 1999 (21-12-1999)
		JP2001505109A	17 April 2001 (17-04-2001)
		JP4142108B2	27 August 2008 (27-08-2008)
		JP2001509231A	10 July 2001 (10-07-2001)
		PT953110E	31 May 2004 (31-05-2004)
		WO9810190A1	12 March 1998 (12-03-1998)
		WO9823227A1	04 June 1998 (04-06-1998)
		WO9829657A1	09 July 1998 (09-07-1998)
		US6409749B1	25 June 2002 (25-06-2002)
		US6169269B1	02 January 2001 (02-01-2001)
		US6278084B1	21 August 2001 (21-08-2001)
		US6323459B1	27 November 2001 (27-11-2001)
		US6133547A	17 October 2000 (17-10-2000)
		US5941249A	24 August 1999 (24-08-1999)
		US6072154A	06 June 2000 (06-06-2000)
US2003155539A1	21 August 2003 (21-08-2003)	US2003155539A1	21 August 2003 (21-08-2003)
		US6926246B2	09 August 2005 (09-08-2005)
		AT322625T	15 April 2006 (15-04-2006)
		AU2002341249B2	05 March 2009 (05-03-2009)
		BR0213130A	19 October 2004 (19-10-2004)
		CA2462968A1	17 April 2003 (17-04-2003)
		CA2462968C	20 November 2012 (20-11-2012)

		DE60118540D1	18 May 2006 (18-05-2006)
		DE60118540T2	10 May 2007 (10-05-2007)
		EP1273808A1	08 January 2003 (08-01-2003)
		EP1273808B1	05 April 2006 (05-04-2006)
		WO03031828A1	17 April 2003 (17-04-2003)
		JP2005504939A	17 February 2005 (17-02-2005)
		US2005252553A1	17 November 2005 (17-11-2005)
US2010060776A1	11 March 2010 (11-03-2010)	US2010060776A1	11 March 2010 (11-03-2010)
		US8446475B2	21 May 2013 (21-05-2013)
		AT503928T	15 April 2011 (15-04-2011)
		AT553591T	15 April 2012 (15-04-2012)
		CN101668947A	10 March 2010 (10-03-2010)
		CN101668947B	02 October 2013 (02-10-2013)
		DE602008005847D1	12 May 2011 (12-05-2011)
		EP2111507A2	28 October 2009 (28-10-2009)
		EP2111507B1	30 March 2011 (30-03-2011)
		EP2140138A2	06 January 2010 (06-01-2010)
		EP2140138B1	11 April 2012 (11-04-2012)
		EP2261507A1	15 December 2010 (15-12-2010)
		GB0702674D0	21 March 2007 (21-03-2007)
		GB0702676D0	21 March 2007 (21-03-2007)
		GB0707788D0	30 May 2007 (30-05-2007)
		GB0708214D0	06 June 2007 (06-06-2007)
		GB0709311D0	20 June 2007 (20-06-2007)
		GB0709338D0	27 June 2007 (27-06-2007)
		GB0711558D0	25 July 2007 (25-07-2007)
		GB0714718D0	05 September 2007 (05-09-2007)
		GB0716469D0	03 October 2007 (03-10-2007)
		GB0718828D0	07 November 2007 (07-11-2007)
		WO2008099156A2	21 August 2008 (21-08-2008)
		WO2008099156A3	20 November 2008 (20-11-2008)
		WO2008129290A1	30 October 2008 (30-10-2008)
		WO2008129291A2	30 October 2008 (30-10-2008)
		WO2008129291A3	30 December 2009 (30-12-2009)
		JP2010518438A	27 May 2010 (27-05-2010)
		JP5039794B2	03 October 2012 (03-10-2012)
		JP2012123406A	28 June 2012 (28-06-2012)
		KR20090129986A	17 December 2009 (17-12-2009)
		US2010074608A1	25 March 2010 (25-03-2010)
		US7974025B2	05 July 2011 (05-07-2011)
CA2391746A1	22 February 2001 (22-02-2001)	CA2391746A1	22 February 2001 (22-02-2001)
		AT344388T	15 November 2006 (15-11-2006)
		AU772107B2	08 April 2004 (08-04-2004)
		AU6639000A	13 March 2001 (13-03-2001)
		CN1369038A	11 September 2002 (11-09-2002)
		DE60031687D1	14 December 2006 (14-12-2006)
		DE60031687T2	06 September 2007 (06-09-2007)
		EP1203156A1	08 May 2002 (08-05-2002)
		EP1203156B1	02 November 2006 (02-11-2006)
		HK1047306A1	05 January 2007 (05-01-2007)
		JP2003507625A	25 February 2003 (25-02-2003)
		MXPA02001452A	21 July 2003 (21-07-2003)
		NZ516970A	30 January 2004 (30-01-2004)
		WO0112985A1	22 February 2001 (22-02-2001)
		US2004261411A1	30 December 2004 (30-12-2004)
		US6574958B1	10 June 2003 (10-06-2003)