



(19) **United States**

(12) **Patent Application Publication**

Swinton

(10) **Pub. No.: US 2002/0110450 A1**

(43) **Pub. Date: Aug. 15, 2002**

(54) **AIR BEARING ARTICULATED SHAFT AND FLOATING MODULE CONFIGURATION FOR A SMALL ROTARY COMPRESSOR**

(52) **U.S. Cl. 415/143**

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(57) **ABSTRACT**

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An apparatus for mounting a plurality of rotary compressors with minimal mechanical tolerances, wherein each of the compressors imparts axial forces on the structures with which they are mounted. The mounting apparatus includes an articulated shaft that rotationally couples and axially decouples the impeller wheels of the rotary compressors. The articulated shaft interoperates with compressors configured in a back-to-back configuration and, in addition, may be coupled to a motor. The articulated shaft and the impeller wheels may be supported by air bearings. It is emphasized that this abstract is provided to comply with the rules requiring an abstract which will allow a searcher or other reader to quickly ascertain the subject matter of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

(21) **Appl. No.: 10/012,972**

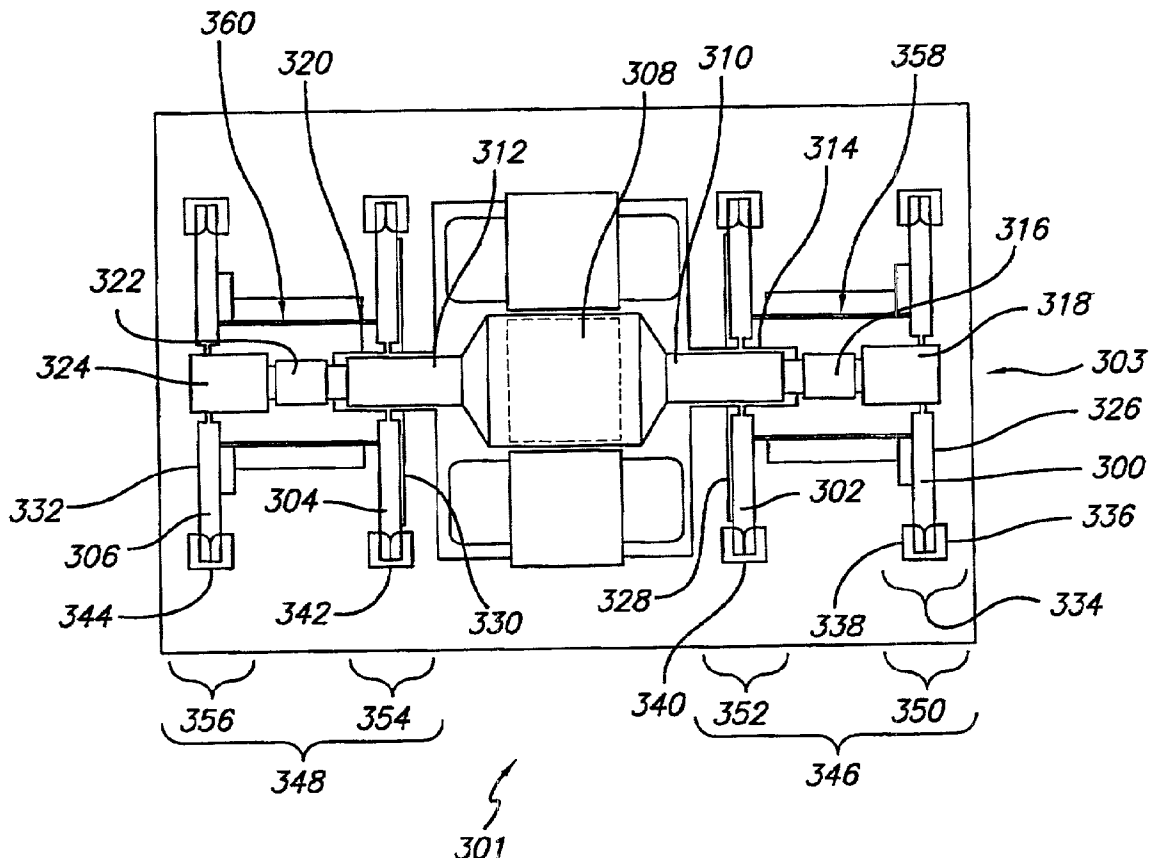
(22) **Filed: Nov. 5, 2001**

Related U.S. Application Data

(60) **Provisional application No. 60/245,835, filed on Nov. 3, 2000.**

Publication Classification

(51) **Int. Cl.⁷ F01D 13/00**



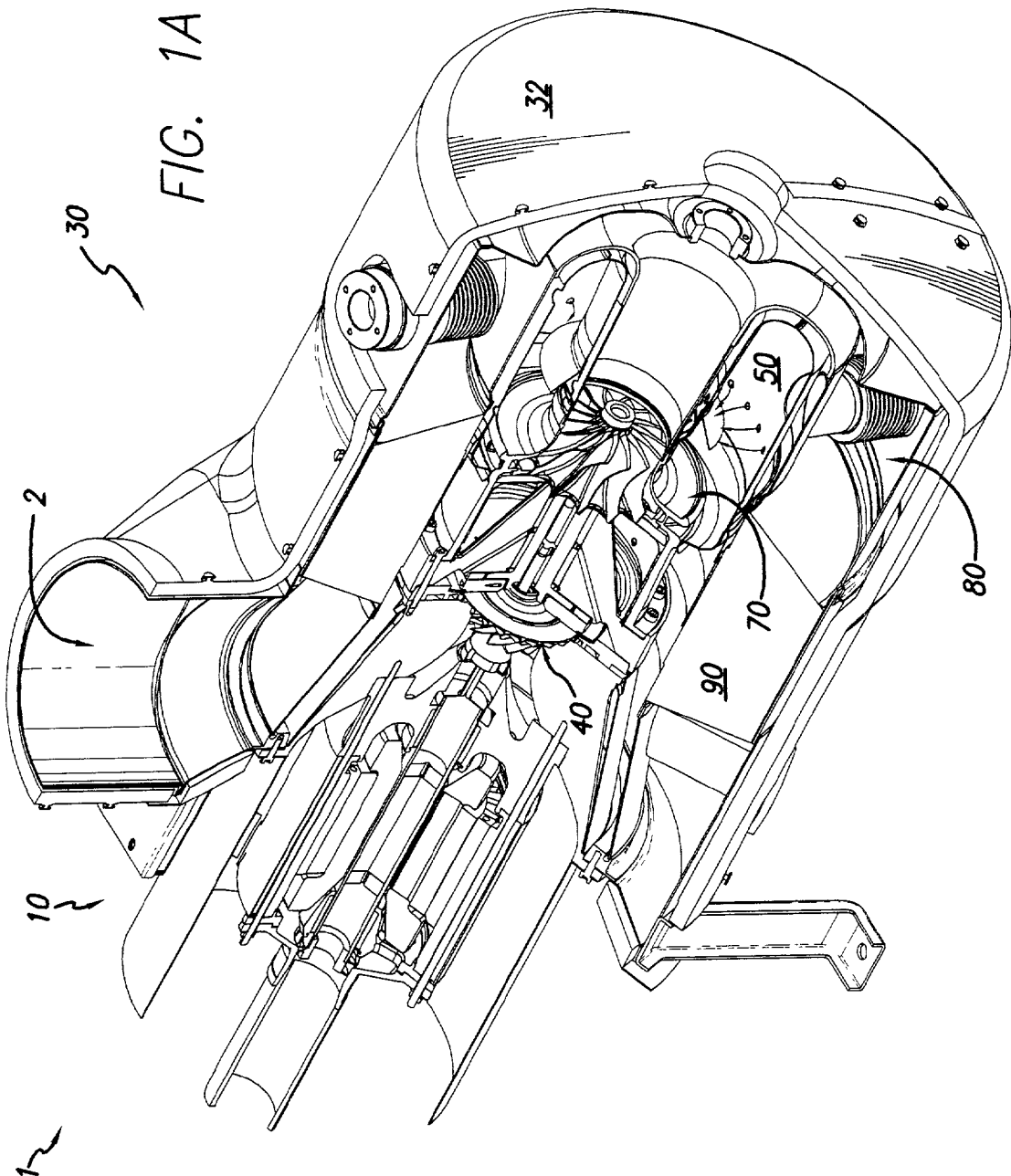
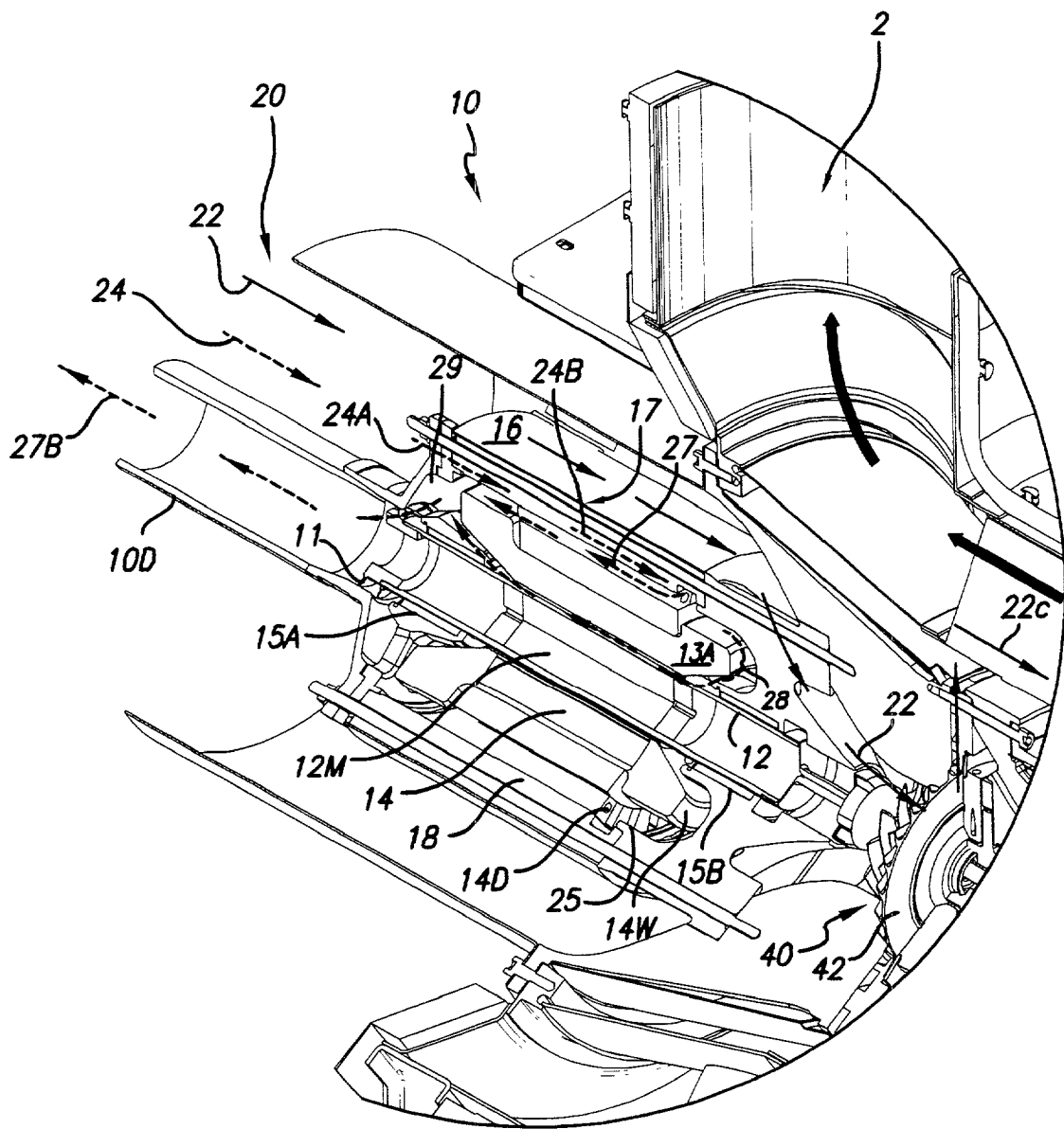


FIG. 1B



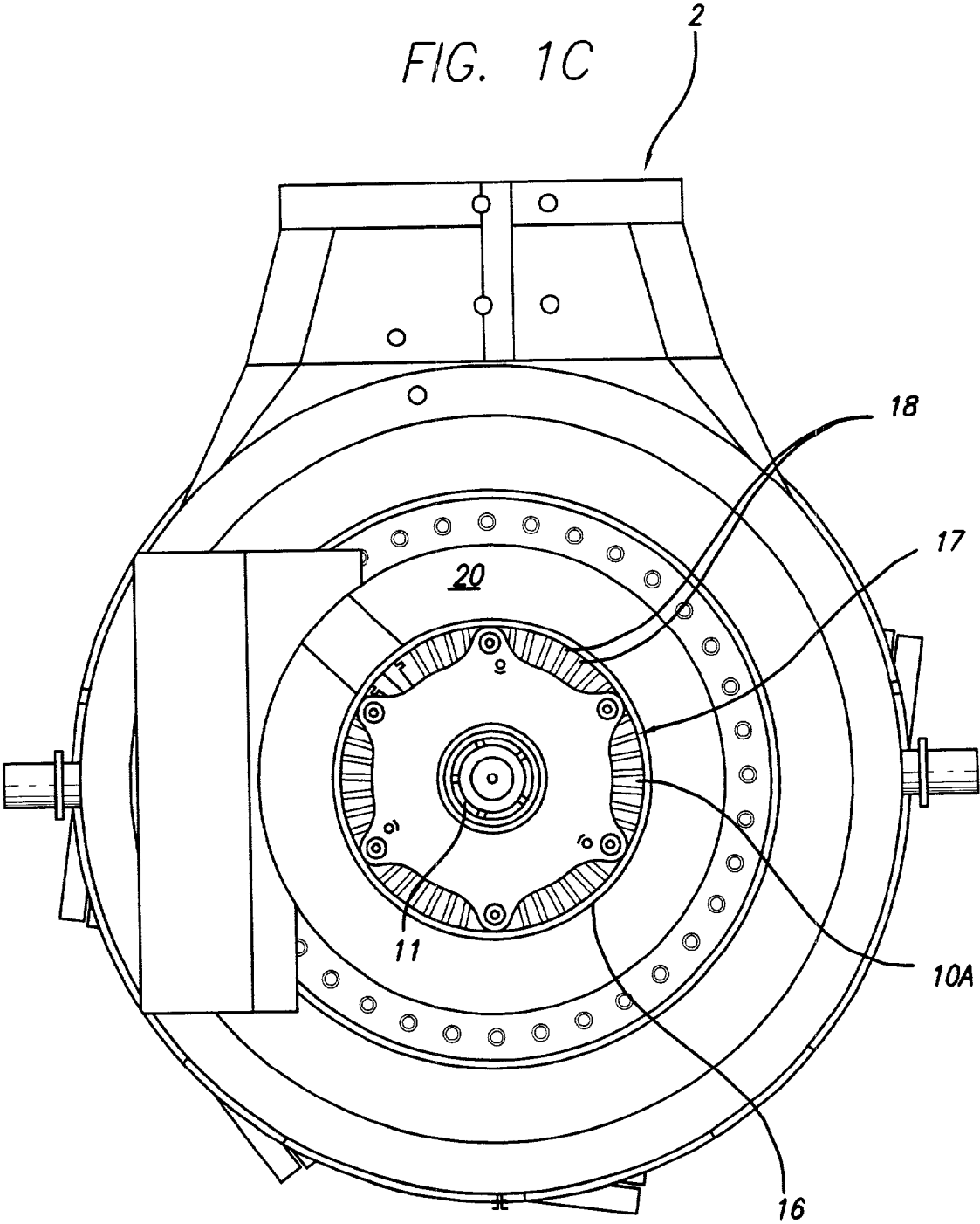
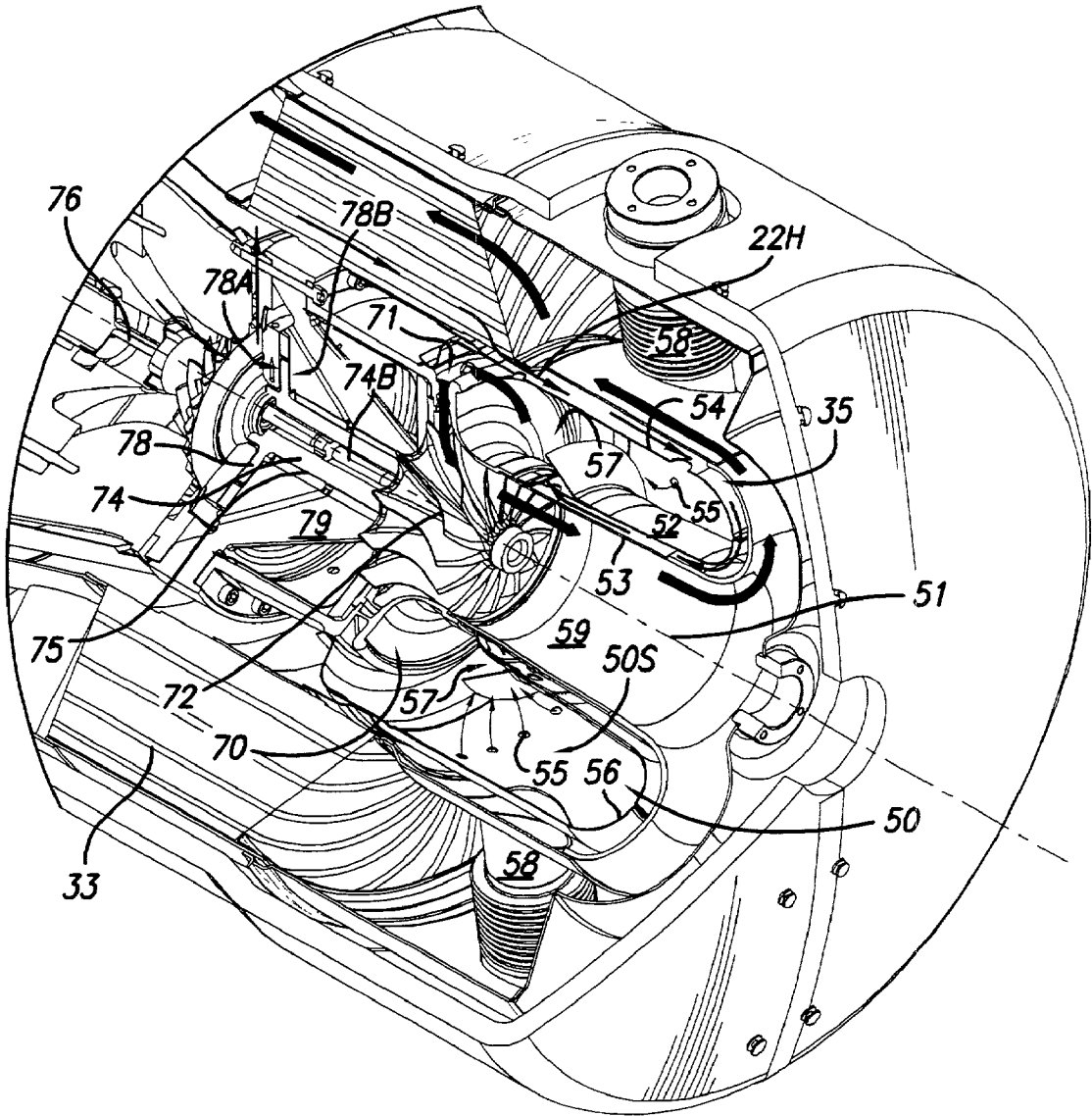
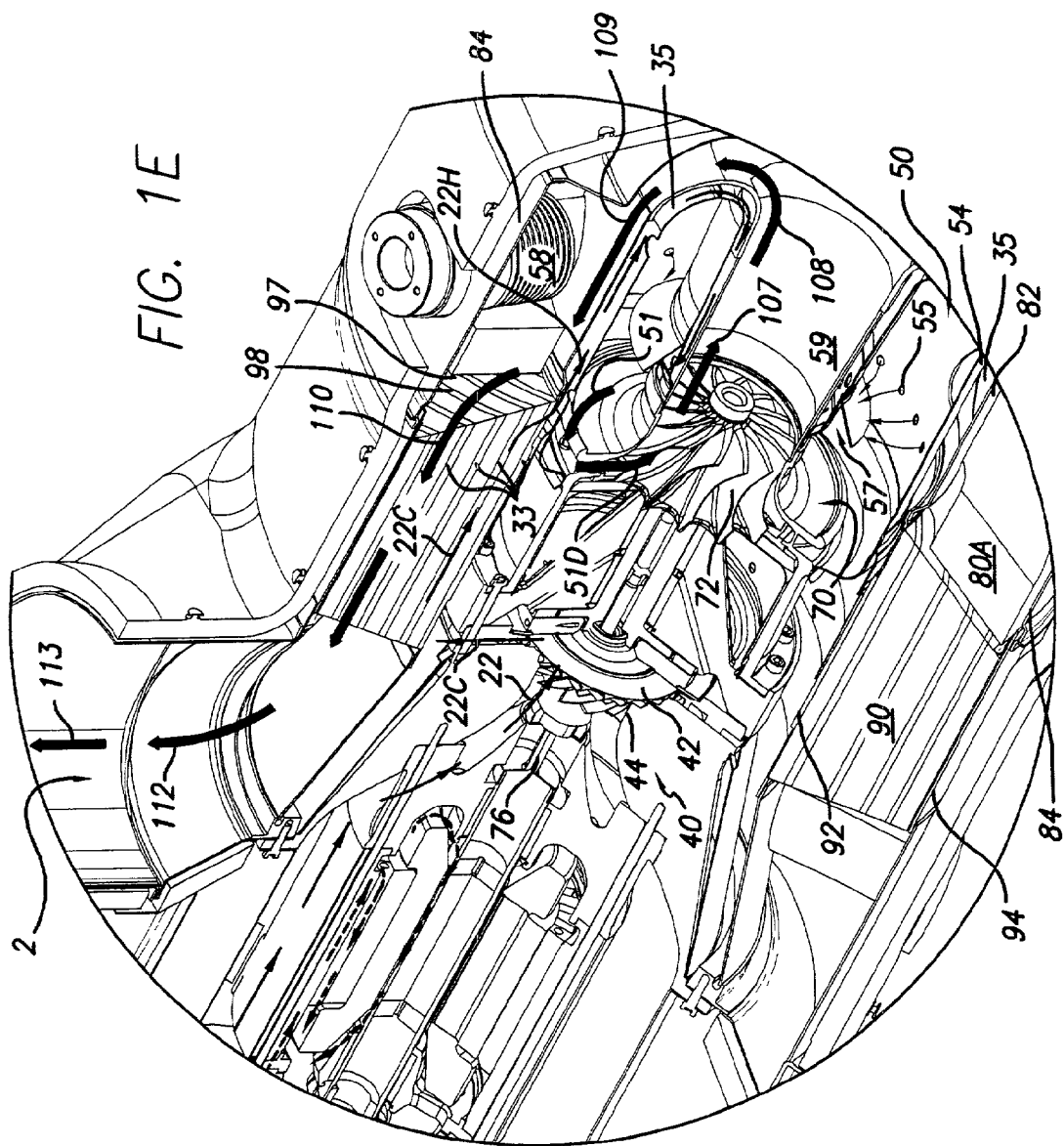


FIG. 1D





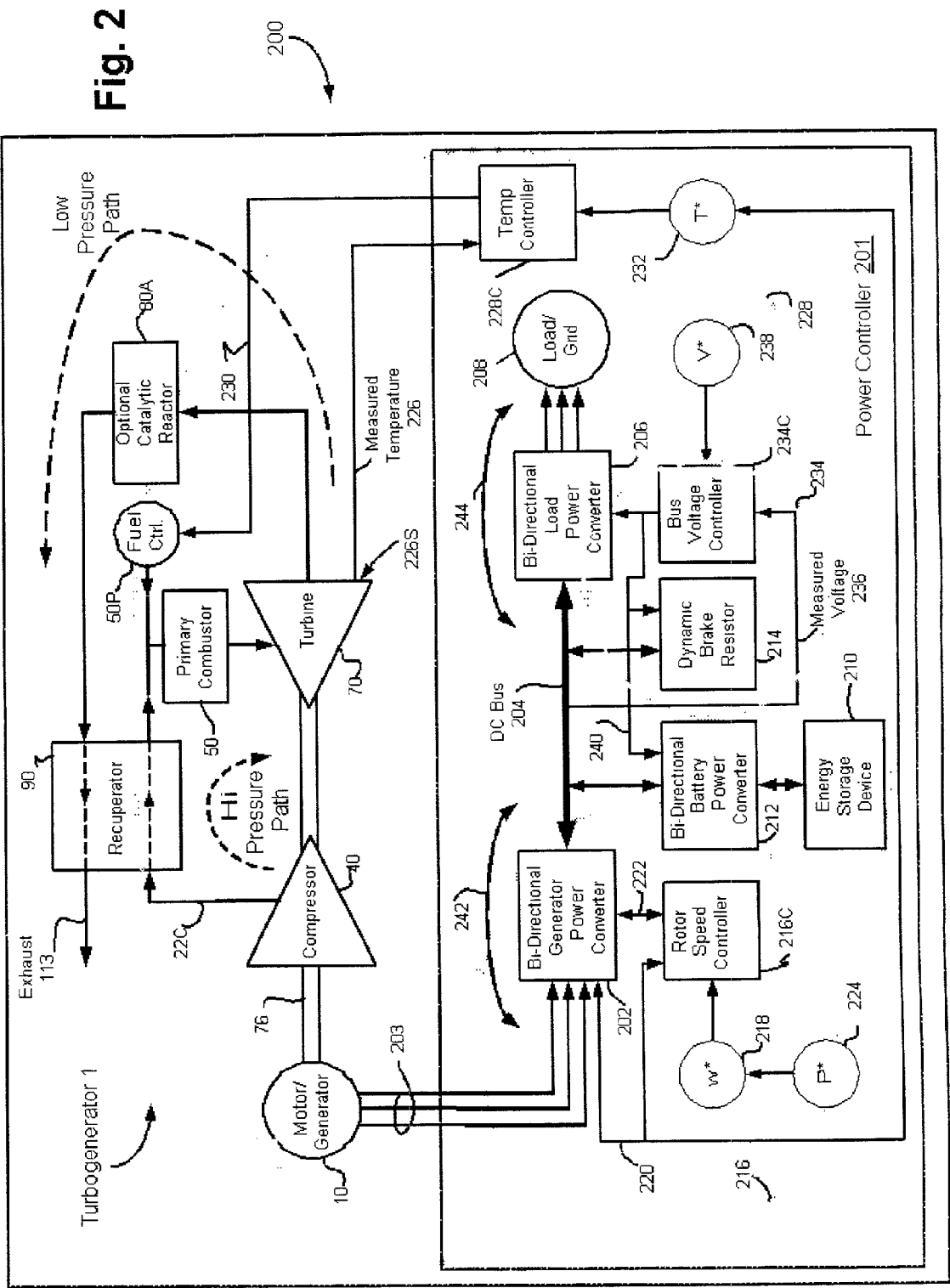
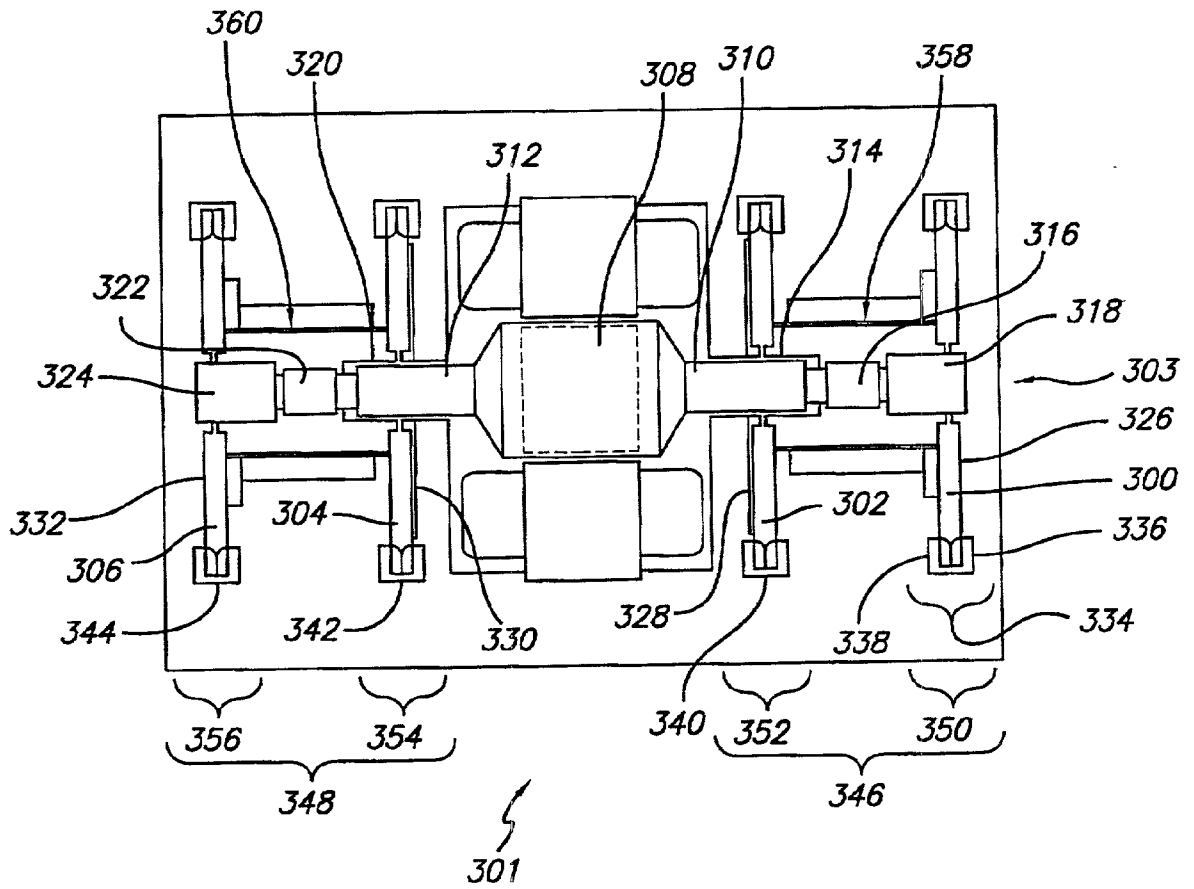


FIG. 3



AIR BEARING ARTICULATED SHAFT AND FLOATING MODULE CONFIGURATION FOR A SMALL ROTARY COMPRESSOR

RELATED APPLICATIONS

[0001] This application claims the priority of U.S. provisional patent application Serial No. 60/245,835 filed Nov. 3, 2000.

BACKGROUND OF THE INVENTION 1. Field of the Invention

[0002] This invention relates to compound rotary machines, and more specifically to driving multiple rotary compressors using an articulated shaft. 2. Description of the Prior Art

[0003] Conventional systems having multiple rotary compressors generally require significant mechanical tolerances, typically resulting in inefficient operation.

[0004] What is needed are methods and apparatus for driving multiple rotary compressors with tight tolerances, permitting highly efficient system operation.

SUMMARY OF THE INVENTION

[0005] In a first aspect, the present invention provides an apparatus comprising a plurality of rotary compressors, each having at least one impeller wheel, and an articulated shaft that rotationally couples and axially decouples at least one impeller wheel from each of the plurality of rotary compressors.

[0006] In another aspect, the present invention includes a system comprising a plurality of rotary compressors, each having at least one impeller wheel, and a multi-piece shaft that rotationally couples an impeller wheel from each of the compressors but permits relative axial movement of the impeller wheels.

[0007] In still another aspect, the present invention includes a method for rotationally driving a compound machine comprising the steps of rotationally coupling two or more rotating elements of the compound machine to permit relative axial translation between said rotating elements, and rotationally coupling said rotating elements to a driving shaft of the compound machine.

[0008] In still another aspect, the present invention includes a turbogenerator comprising a plurality of rotary compressors and means for rotationally coupling and axially decoupling at least one impeller wheel from each of the plurality of rotary compressors.

[0009] In yet another aspect, the present invention includes an apparatus comprising a rotating shaft, a first rotating element, a first coupling rotationally securing the first rotating element to the rotating shaft while permitting relative axial movement between the first rotating element and the rotating shaft, a second rotating element, and a second coupling rotationally securing the second rotating element to the rotating shaft while permitting relative axial movement between the first rotating element and the rotating shaft.

[0010] In still another aspect, the present invention includes a method for mounting components in a compound

machine comprising rotationally coupling a rotating shaft to a first rotating element using a coupling that permits relative axial movement between the first rotating element and the rotating shaft, and rotationally coupling a second rotating element to the rotating shaft using a coupling that permits relative axial movement between the second rotating element and the rotating shaft.

[0011] In yet another aspect, the present invention includes a compound machine comprising a rotating shaft, a first rotating component, a second rotating component, a first coupling rotationally securing the first rotating component to an intermediate coupling while permitting axial translation of the first rotating component relative to the intermediate coupling, and a second coupling rotationally securing the second rotating component to the intermediate coupling while permitting axial translation of the second rotating component relative to the intermediate coupling.

[0012] In still another aspect, the present invention includes a turbogenerator having a motor generator driven by a turbine wheel, wherein the improvement comprises a multi-stage rotary compressor comprising a plurality of rotating components and a structure that rotationally couples but does not axially couple said plurality of rotating components.

[0013] In still another aspect, the present invention includes a rotationally-driven compound machine comprising means for coupling two or more rotating elements of the compound machine to permit relative axial translation between said rotating elements, and means for rotationally coupling said rotating elements to a driving shaft of the compound machine.

[0014] These and other features and advantages of this invention will become further apparent from the detailed description and accompanying figures that follow. In the figures and description, numerals indicate the various features of the invention, like numerals referring to like features throughout both the drawings and the description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1A is perspective view, partially in section, of an integrated turbogenerator system.

[0016] FIG. 1B is a magnified perspective view, partially in section, of the motor/generator portion of the integrated turbogenerator of FIG. 1A.

[0017] FIG. 1C is an end view, from the motor/generator end, of the integrated turbogenerator of FIG. 1A.

[0018] FIG. 1D is a magnified perspective view, partially in section, of the combustor-turbine exhaust portion of the integrated turbogenerator of FIG. 1A.

[0019] FIG. 1E is a magnified perspective view, partially in section, of the compressor-turbine portion of the integrated turbogenerator of FIG. 1A.

[0020] FIG. 2 is a block diagram schematic of a turbogenerator system including a power controller having decoupled rotor speed, operating temperature, and DC bus voltage control loops.

[0021] FIG. 3 is a side view in cross section of an embodiment having four compressors mounted on an air bearing articulated shaft.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[0022] One preferred embodiment of the present invention is in connection with a turbogenerator, such as an integrated small-scale turbogeneration unit.

Mechanical Structural Embodiment of a Turbogenerator

[0023] With reference to FIG. 1A, an integrated turbogenerator 1 generally includes motor/generator section 10 and compressor-combustor section 30. Compressor-combustor section 30 includes exterior can 32, compressor 40, combustor 50 and turbine 70. A recuperator 90 may be optionally included.

[0024] Referring now to FIG. 1B and FIG. 1C, in a currently preferred embodiment, motor/generator section 10 may be a permanent magnet motor generator having a permanent magnet rotor or sleeve 12. Any other suitable type of motor generator may also be used. Permanent magnet rotor or sleeve 12 may contain a permanent magnet 12M. Permanent magnet rotor or sleeve 12 and the permanent magnet disposed therein are rotatably supported within permanent magnet motor/generator stator 14. Preferably, one or more compliant foil, fluid film, radial, or journal bearings 15A and 15B rotatably support permanent magnet rotor or sleeve 12 and the permanent magnet disposed therein. All bearings, thrust, radial or journal bearings, in turbogenerator 1 may be fluid film bearings or compliant foil bearings. Motor/generator housing 16 encloses stator heat exchanger 17 having a plurality of radially extending stator cooling fins 18. Stator cooling fins 18 connect to or form part of stator 14 and extend into annular space 10A between motor/generator housing 16 and stator 14. Wire windings 14W exist on permanent magnet motor/generator stator 14.

[0025] Referring now to FIG. 1D, combustor 50 may include cylindrical inner wall 52 and cylindrical outer wall 54. Cylindrical outer wall 54 may also include air inlets 55. Cylindrical walls 52 and 54 define an annular interior space 50S in combustor 50 defining an axis 51. Combustor 50 includes a generally annular wall 56 further defining one axial end of the annular interior space of combustor 50. Associated with combustor 50 may be one or more fuel injector inlets 58 to accommodate fuel injectors which receive fuel from fuel control element 50P as shown in FIG. 2, and inject fuel or a fuel air mixture to interior of 50S combustor 50. Inner cylindrical surface 53 is interior to cylindrical inner wall 52 and forms exhaust duct 59 for turbine 70.

[0026] Turbine 70 may include turbine wheel 72. An end of combustor 50 opposite annular wall 56 further defines an aperture 71 in turbine 70 exposed to turbine wheel 72. Bearing rotor 74 may include a radially extending thrust bearing portion, bearing rotor thrust disk 78, constrained by bilateral thrust bearings 78A and 78B. Bearing rotor 74 may be rotatably supported by one or more journal bearings 75 within center bearing housing 79. Bearing rotor thrust disk 78 at the compressor end of bearing rotor 76 is rotatably supported preferably by a bilateral thrust bearing 78A and 78B. Journal or radial bearing 75 and thrust bearings 78A and 78B may be fluid film or foil bearings.

[0027] Turbine wheel 72, Bearing rotor 74 and compressor impeller 42 may be mechanically constrained by tie bolt

74B, or other suitable technique, to rotate when turbine wheel 72 rotates. Mechanical link 76 mechanically constrains compressor impeller 42 to permanent magnet rotor or sleeve 12 and the permanent magnet disposed therein causing permanent magnet rotor or sleeve 12 and the permanent magnet disposed therein to rotate when compressor impeller 42 rotates.

[0028] Referring now to FIG. 1E, compressor 40 may include compressor impeller 42 and compressor impeller housing 44. Recuperator 90 may have an annular shape defined by cylindrical recuperator inner wall 92 and cylindrical recuperator outer wall 94. Recuperator 90 contains internal passages for gas flow, one set of passages, passages 33 connecting from compressor 40 to combustor 50, and one set of passages, passages 97, connecting from turbine exhaust 80 to turbogenerator exhaust output 2.

[0029] Referring again to FIG. 1B and FIG. 1C, in operation, air flows into primary inlet 20 and divides into compressor air 22 and motor/generator cooling air 24. Motor/generator cooling air 24 flows into annular space 10A between motor/generator housing 16 and permanent magnet motor/generator stator 14 along flow path 24A. Heat is exchanged from stator cooling fins 18 to generator cooling air 24 in flow path 24A, thereby cooling stator cooling fins 18 and stator 14 and forming heated air 24B. Warm stator cooling air 24B exits stator heat exchanger 17 into stator cavity 25 where it further divides into stator return cooling air 27 and rotor cooling air 28. Rotor cooling air 28 passes around stator end 13A and travels along rotor or sleeve 12. Stator return cooling air 27 enters one or more cooling ducts 14D and is conducted through stator 14 to provide further cooling. Stator return cooling air 27 and rotor cooling air 28 rejoin in stator cavity 29 and are drawn out of the motor/generator 10 by exhaust fan 11 which is connected to rotor or sleeve 12 and rotates with rotor or sleeve 12. Exhaust air 27B is conducted away from primary air inlet 20 by duct 10D.

[0030] Referring again to FIG. 1E, compressor 40 receives compressor air 22. Compressor impeller 42 compresses compressor air 22 and forces compressed gas 22C to flow into a set of passages 33 in recuperator 90 connecting compressor 40 to combustor 50. In passages 33 in recuperator 90, heat is exchanged from walls 98 of recuperator 90 to compressed gas 22C. As shown in FIG. 1E, heated compressed gas 22H flows out of recuperator 90 to space 35 between cylindrical inner surface 82 of turbine exhaust 80 and cylindrical outer wall 54 of combustor 50. Heated compressed gas 22H may flow into combustor 54 through sidewall ports 55 or main inlet 57. Fuel (not shown) may be reacted in combustor 50, converting chemically stored energy to heat. Hot compressed gas 51 in combustor 50 flows through turbine 70 forcing turbine wheel 72 to rotate. Movement of surfaces of turbine wheel 72 away from gas molecules partially cools and decompresses gas 51D moving through turbine 70. Turbine 70 is designed so that exhaust gas 107 flowing from combustor 50 through turbine 70 enters cylindrical passage 59. Partially cooled and decompressed gas in cylindrical passage 59 flows axially in a direction away from permanent magnet motor/generator section 10, and then radially outward, and then axially in a direction toward permanent magnet motor/generator section 10 to passages 98 of recuperator 90, as indicated by gas flow arrows 108 and 109 respectively

[0031] In an alternate embodiment, low pressure catalytic reactor **80A** may be included between fuel injector inlets **58** and recuperator **90**. Low pressure catalytic reactor **80A** may include internal surfaces (not shown) having catalytic material (e.g., Pd or Pt, not shown) disposed on them. Low pressure catalytic reactor **80A** may have a generally annular shape defined by cylindrical inner surface **82** and cylindrical low pressure outer surface **84**. Unreacted and incompletely reacted hydrocarbons in gas in low pressure catalytic reactor **80A** react to convert chemically stored energy into additional heat, and to lower concentrations of partial reaction products, such as harmful emissions including nitrous oxides (NOx).

[0032] Gas **110** flows through passages **97** in recuperator **90** connecting from turbine exhaust **80** or catalytic reactor **80A** to turbogenerator exhaust output **2**, as indicated by gas flow arrow **112**, and then exhausts from turbogenerator **1**, as indicated by gas flow arrow **113**. Gas flowing through passages **97** in recuperator **90** connecting from turbine exhaust **80** to outside of turbogenerator **1** exchanges heat to walls **98** of recuperator **90**. Walls **98** of recuperator **90** heated by gas flowing from turbine exhaust **80** exchange heat to gas **22C** flowing in recuperator **90** from compressor **40** to combustor **50**.

[0033] Turbogenerator **1** may also include various electrical sensor and control lines for providing feedback to power controller **201** and for receiving and implementing control signals as shown in **FIG. 2**.

[0034] Alternative Mechanical Structural Embodiments of the Integrated Turbogenerator

[0035] The integrated turbogenerator disclosed above is exemplary. Several alternative structural embodiments are known

[0036] In one alternative embodiment, air **22** may be replaced by a gaseous fuel mixture. In this embodiment, fuel injectors may not be necessary. This embodiment may include an air and fuel mixer upstream of compressor **40**.

[0037] In another alternative embodiment, fuel may be conducted directly to compressor **40**, for example by a fuel conduit connecting to compressor impeller housing **44**. Fuel and air may be mixed by action of the compressor impeller **42**. In this embodiment, fuel injectors may not be necessary.

[0038] In another alternative embodiment, combustor **50** may be a catalytic combustor.

[0039] In another alternative embodiment, geometric relationships and structures of components may differ from those shown in **FIG. 1A**. Permanent magnet motor/generator section **10** and compressor/combustor section **30** may have low pressure catalytic reactor **80A** outside of annular recuperator **90**, and may have recuperator **90** outside of low pressure catalytic reactor **80A**. Low pressure catalytic reactor **80A** may be disposed at least partially in cylindrical passage **59**, or in a passage of any shape confined by an inner wall of combustor **50**. Combustor **50** and low pressure catalytic reactor **80A** may be substantially or completely enclosed with an interior space formed by a generally annularly shaped recuperator **90**, or a recuperator **90** shaped to substantially enclose both combustor **50** and low pressure catalytic reactor **80A** on all but one face.

[0040] Alternative uses other than in Integrated Turbogenerators

[0041] An integrated turbogenerator is a turbogenerator in which the turbine, compressor, and generator are all constrained to rotate based upon rotation of the shaft to which the turbine is connected. The concepts disclosed herein are preferably but not necessarily used in connection with a turbogenerator, and preferably but not necessarily used in connection with an integrated turbogenerator.

[0042] Turbogenerator System Including Controls

[0043] Referring now to **FIG. 2**, a preferred embodiment is shown in which a turbogenerator system **200** includes power controller **201** which has three substantially decoupled control loops for controlling (1) rotary speed, (2) temperature, and (3) DC bus voltage. A more detailed description of an appropriate power controller is disclosed in U.S. patent application Ser. No. 09/207,817, filed Dec. 8, 1998 in the names of Gilbreth, Wacknov and Wall, and assigned to the assignee of the present application which is incorporated herein in its entirety by this reference.

[0044] Referring still to **FIG. 2**, turbogenerator system **200** includes integrated turbogenerator **1** and power controller **201**. Power controller **201** includes three decoupled or independent control loops.

[0045] A first control loop, temperature control loop **228**, regulates a temperature related to the desired operating temperature of primary combustor **50** to a set point, by varying fuel flow from fuel control element **50P** to primary combustor **50**. Temperature controller **228C** receives a temperature set point, T^* , from temperature set point source **232**, and receives a measured temperature from temperature sensor **226S** connected to measured temperature line **226**. Temperature controller **228C** generates and transmits over fuel control signal line **230** to fuel pump **50P** a fuel control signal for controlling the amount of fuel supplied by fuel pump **50P** to primary combustor **50** to an amount intended to result in a desired operating temperature in primary combustor **50**. Temperature sensor **226S** may directly measure the temperature in primary combustor **50** or may measure a temperature of an element or area from which the temperature in the primary combustor **50** may be inferred.

[0046] A second control loop, speed control loop **216**, controls speed of the shaft common to the turbine **70**, compressor **40**, and motor/generator **10**, hereafter referred to as the common shaft, by varying torque applied by the motor generator to the common shaft. Torque applied by the motor generator to the common shaft depends upon power or current drawn from or pumped into windings of motor/generator **10**. Bi-directional generator power converter **202** is controlled by rotor speed controller **216C** to transmit power or current in or out of motor/generator **10**, as indicated by bi-directional arrow **242**. A sensor in turbogenerator **1** senses the rotary speed on the common shaft and transmits that rotary speed signal over measured speed line **220**. Rotor speed controller **216** receives the rotary speed signal from measured speed line **220** and a rotary speed set point signal from a rotary speed set point source **218**. Rotary speed controller **216C** generates and transmits to generator power converter **202** a power conversion control signal on line **222** controlling generator power converter **202**'s transfer of power or current between AC lines **203** (i.e., from

motor/generator **10**) and DC bus **204**. Rotary speed set point source **218** may convert to the rotary speed set point a power set point P^* received from power set point source **224**.

[0047] A third control loop, voltage control loop **234**, controls bus voltage on DC bus **204** to a set point by transferring power or voltage between DC bus **204** and any of (1) Load/Grid **208** and/or (2) energy storage device **210**, and/or (3) by transferring power or voltage from DC bus **204** to dynamic brake resistor **214**. A sensor measures voltage DC bus **204** and transmits a measured voltage signal over measured voltage line **236**. Bus voltage controller **234C** receives the measured voltage signal from voltage line **236** and a voltage set point signal V^* from voltage set point source **238**. Bus voltage controller **234C** generates and transmits signals to bi-directional load power converter **206** and bi-directional battery power converter **212** controlling their transmission of power or voltage between DC bus **204**, load/grid **208**, and energy storage device **210**, respectively. In addition, bus voltage controller **234** transmits a control signal to control connection of dynamic brake resistor **214** to DC bus **204**.

[0048] Power controller **201** regulates temperature to a set point by varying fuel flow, adds or removes power or current to motor/generator **10** under control of generator power converter **202** to control rotor speed to a set point as indicated by bi-directional arrow **242**, and controls bus voltage to a set point by (1) applying or removing power from DC bus **204** under the control of load power converter **206** as indicated by bi-directional arrow **244**, (2) applying or removing power from energy storage device **210** under the control of battery power converter **212**, and (3) by removing power from DC bus **204** by modulating the connection of dynamic brake resistor **214** to DC bus **204**.

[0049] Mounting Multiple Compressors using an Articulated Shaft

[0050] Rotary compressors typically place an axial load, in a direction opposite to the gas flow out of the compressor, on the housing to which they are mounted. Mechanical tolerances are therefore required to account for movement of such compressors, during operation, relative to the surrounding components of the system in which they are mounted. Where multiple compressors are mechanically connected, independent tolerances are required for each compressor, resulting in a net tolerance approaching the sum of each of the individual tolerances required for each compressor. Multi-compressor systems accordingly can have considerable tolerance requirements, resulting in system operation that is less than optimally efficient. The need for additive tolerances in multi-compressor systems can be alleviated in some instances through the use of back-to-back compressor mounting.

[0051] Referring now to FIG. 3, a side view of a cross section of an embodiment having four compressors **350**, **352**, **354** and **356** mounted on an air bearing articulated shaft is illustrated. Each of these compressors are preferably one of four stages of a multistage compression system designed to compress gas. Impeller wheels **300**, **302**, **304**, **306** of each of the four compressors rotate within cylindrical recesses **334**, **340**, **342** and **344**, respectively. The lateral movement of impeller wheel **300**, for example, is bounded on the right-hand side by housing face **338** and is bounded on the right hand side by housing face **336**.

[0052] Compressor **350** expels its compressed gas stream in a leftward direction, imparting a rightward force on impeller wheel **300** relative to the surrounding housing. To facilitate the rotation of impeller wheel **300**, and to prevent it from grinding against housing face **336**, the system is equipped with thrust air bearings **326**, such as a foil thrust bearings constructed with a thin, compliant aerofoil member. The compliant foil member of the foil thrust bearing may include an underspring member mounted on the thrust bearing surface and disposed between the thrust bearing surface and compliant foil member. The underspring member may have variable spring stiffness in both the circumferential and radial directions. The aerofoil may be clamped to the housing face **336**, or could be clamped to and rotate with the right-hand side of impeller wheel **300**. Each of the other impeller wheels **302**, **304** and **306** may similarly be equipped with thrust air bearings, preferably on the side of the impeller wheel on which the compressor is pressed against the housing by the forces generated by its operation. As illustrated in FIG. 3, impeller wheels **302**, **304** and **306** are supported in part by thrust air bearings **328**, **330** and **332**, respectively. Further description of thrust air bearings that may be used with this implementation is set forth in U.S. patent application Ser. No. 09/714,349, filed Nov. 15, 2000 and assigned to the assignee of the present application, and U.S. Pat. Nos. 5,529,398, 5,791,868, 5,827,040, 5,918,985, and 6,158,892, which are hereby incorporated by reference.

[0053] To partially offset the forces imparted by impeller wheels **300** and **302** on the surrounding housing, including the forces imparted by impeller wheel **300** on housing faces **336** and **338**, compressors **350** and **352** may be mounted back-to-back. In this orientation, the rightward force of impeller wheel **300** offsets to some extent the leftward force of impeller wheel **302**. Similarly, compressors **354** and **356** may be mounted in a back-to-back orientation so that they work against each other. Although such back-to-back mounting reduces the net forces of the compressors on their surrounding housing, it usually does not alleviate these forces altogether, particularly where each of the compressors is a single stage of a multi-stage compression arrangement because the axial load imparted by a rotary compressor is dependent upon the compression level of the gas it processes.

[0054] Optimally each compressor **350**, **352**, **354** and **356** in multi-stage compression arrangement **301** is independently floated as illustrated in FIG. 3. Independent axial suspension of each compressor may be accomplished using an articulated shaft such as shaft **303** to drive the compressors. An articulated shaft is a shaft having multiple pieces and a common axis, the pieces of which can move relative to one another. The multiple pieces comprising multi-piece shaft **303** include rotating connector **314**, articulated connector **316** and rotating connector **318**. More specifically, impeller wheel **300** is attached to rotating connector **318** which is, in turn, connected in splined engagement with articulated connector **316**. Impeller wheel **302** is attached to rotating connector **314** which is, in turn, connected to motor shaft **310** on one end and to articulated connector **316** on the other end. Rotating connectors **314** and **318** rotationally couple impeller wheels **300** and **302**, respectively, to motor shaft **310**, while permitting axial movement of impeller wheels **300** and **302** relative to each other, to motor **308** and to motor shaft **310**. The components coupled by articulated shaft **303**, comprised on the right-hand side **346** of motor

308 by articulated connector **316** and rotating connectors **314** and **318**, are coupled rotationally but not axially.

[0055] Analogous components on the left-hand side **348** of motor **308** may be similarly connected. In one preferred embodiment, impeller wheel **306** is attached to rotating connector **324** which is, in turn, connected in splined or other suitable engagement with articulated connector **322**. For example, the surface of rotating connector **324** that interfaces with articulated connector **322** may contain a plurality of teeth, each of which intermeshes with complimentary slots on a hub of the articulated connector **322** continuously during operation. The teeth are shaped and oriented so that the toothed components can move axially, but not rotationally, with respect to each other. A similar interconnection may be used between articulated connector **322** and rotating connector **320**, and between rotating connector **320** and motor shaft **312**, as well as between the analogous components on the right-hand side of motor **308**. Impeller wheel **304** is attached to rotating connector **320** which is, in turn, connected to motor shaft **312** on one end and to articulated connector **322** on the other end. Rotating connectors **320** and **324** thereby rotationally couple impeller wheels **304** and **306**, respectively, to motor shaft **312**, while permitting axial movement of impeller wheels **304** and **306** relative to each other, to motor **308** and to motor shaft **312**.

[0056] The use of a splined interconnection in some implementations may necessitate the use of lubricants or coatings to facilitate axial translation. The above-described rotating and articulated connectors may be interlinked through couplings other than a splined interface. For example, these components may be interlinked by gears or by mating pairs of complementary geometric shapes other than teeth, such as triangles or squares. The engagement between rotating connector **314** and motor shaft **310**, between rotating connector **314** and articulated connector **316**, and between articulated connector **316** and rotating connector **318** may, by way of further example, be multifaceted or engaged in any suitable fashion providing secure rotational attachment and permitting independent axial translation. Alternative suitable interconnection techniques, including a double diaphragm coupling, are described in further detail in U.S. Pat. Nos. 5,964,663, 6,037,687 and 6,094,799, which are assigned to the assignee of the present invention and are incorporated by reference herein.

[0057] The above-described articulated shafts are preferably supported by radial air bearings **358** and **360**. In some embodiments the radial air bearings **358** and **360** support some, but not all, of the components of the articulated shafts. The motor shafts **310** and/or **312** may also be supported by radial air bearings. In some embodiments, the motor shafts are supported by a splined coupling on each end that engages the inside diameter of the air bearings. These bearings are generally comprised of a bushing, a rotating element such as a rotor or shaft adapted to rotate within the bushing, non-rotating compliant fluid foil members mounted within the bushing and enclosing the rotating element, and non-rotating compliant spring foil members mounted within the bushing underneath the non-rotating compliant fluid foil members. The space between the rotating element and the bushing is filled with fluid, such as air or other suitable fluids, which envelops the foils. The motion of the rotating element applies viscous drag forces to the fluid in converging wedge channels. This results in increases in fluid pressure, especially near the trailing end of the wedge channels. If the rotating element moves toward the non-rotating element, the convergence angle of the wedge channel increases, causing

the fluid pressure rise along the channel to increase. Conversely, if the rotating element moves away, the pressure rise along the wedge channel decreases. Thus, the fluid in the wedge channels exerts restoring forces on the rotating element that vary with and stabilize running clearances and prevent contact between the rotating and non-rotating elements of the bearing. Exemplary air bearing apparatus, and related matter, is further described in U.S. Pat. Nos. 6,190,048 and 6,158,892, which are incorporated herein by this reference.

[0058] The above-described arrangement of components permits multiple compressor modules to self-align and float, thereby minimizing their interference with the associated stationary parts of the system into which they are incorporated. The foregoing techniques may be suitably applied to any rotary compound machine.

[0059] Having now described the invention in accordance with the requirements of the patent statutes, those skilled in this art will understand how to make changes and modifications in the present invention to meet their specific requirements or conditions. Such changes and modifications may be made without departing from the scope and spirit of the invention as set forth in the following claims.

What is claimed is:

1. An apparatus comprising:

a plurality of rotary compressors, each compressor having at least one impeller wheel; and

an articulated shaft that rotationally couples and axially decouples at least one impeller wheel from each of said plurality of rotary compressors.

2. The apparatus of claim 1 wherein said plurality of rotary compressors are mounted in back-to-back orientation.

3. The apparatus of claim 2 further comprising a motor coupled to said articulated shaft.

4. The apparatus of claim 1 wherein a splined coupling connects at least two segments of said articulated shaft.

5. The apparatus of claim 3 wherein a splined coupling connects said articulated shaft with at least one shaft of said motor.

6. The apparatus of claim 1 wherein said articulated shaft comprises at least three independent pieces.

7. The apparatus of claim 1 further comprising:

an air bearing supporting each of said impeller wheels.

8. The apparatus of claim 1 further comprising:

at least one foil thrust air bearing supporting at least one of said impeller wheels.

9. The apparatus of claim 8 wherein said foil thrust bearing further comprises:

an underspring member mounted between a thrust bearing surface and a compliant foil member.

10. The apparatus of claim 1 further comprising:

a radial air bearing supporting the articulated shaft.

11. The apparatus of claim 10 further comprising:

a motor shaft; and

a coupling on the inside diameter of said radial air bearing that engages a complimentary coupling on said motor shaft and connects said articulated shaft to said motor shaft.

12. The apparatus of claim 1 further comprising:
a plurality of articulated shafts that rotationally couple and axially decouple at least two back-to-back mounted rotary compressor impeller wheels.
13. The apparatus of claim 12 further comprising:
radial air bearings supporting said articulated shafts; and
air bearings supporting said impeller wheels.
14. The apparatus of claim 12 wherein each of said rotary compressors comprises one stage of a multi-stage compression system.
15. A system comprising:
a plurality of rotary compressors, each having at least one impeller wheel; and
a multi-piece shaft that rotationally couples an impeller wheel from each of said compressors and permits relative axial movement of said impeller wheels.
16. The system of claim 15 further comprising:
splined couplings connecting a plurality of segments of said multi-piece shaft.
17. The system of claim 16 further comprising:
radial air bearings supporting said multi-piece shaft; and
foil thrust air bearings supporting said impeller wheels.
18. The system of claim 15 wherein said system is a device that generates electricity.
19. The system of claim 15 wherein said system is an integrated turbogenerator.
20. A method for rotationally driving a compound machine comprising the steps of:

rotationally coupling two or more rotating elements of the compound machine to permit relative axial translation between said rotating elements; and

rotationally coupling said rotating elements to a driving shaft of the compound machine.
21. The method of claim 20 wherein said rotating elements are impeller wheels of rotary compressors.
22. The method of claim 20 wherein said step of rotationally coupling two or more rotating elements of the compound machine comprises coupling said elements with an articulated shaft.
23. The method of claim 22 further comprising coupling said articulated shaft to a motor.
24. The method of claim 22 further comprising connecting at least two segments of said articulated shaft through a splined coupling.
25. The method of claim 22 further comprising connecting said articulated shaft with a motor shaft via a splined coupling.
26. The method of claim 20 wherein said step of rotationally coupling two or more rotating elements of the compound machine comprises coupling said at least two rotating connectors through an articulated connector.
27. The method of claim 21 further comprising mounting said rotary compressors in back-to-back orientation.
28. The method of claim 27 further comprising supporting said impeller wheels with an air bearing.
29. The method of claim 21 further comprising supporting said impeller wheels with a foil thrust air bearing.
30. The method of claim 29 further comprising mounting an underspring member between a thrust bearing surface and an aerofoil portion of said foil thrust bearing.
31. The method of claim 22 further comprising supporting said articulated shaft by a radial air bearing.
32. The method of claim 31 further comprising connecting said articulated shaft to a motor shaft by engaging a coupling on the inside diameter of said radial air bearing with a complimentary coupling on said motor shaft.
33. The method of claim 20 wherein a the step of rotationally coupling two or more rotating elements of the compound machine comprises coupling at least two pairs of impeller wheels from back-to-back mounted rotary compressors using a plurality of articulated shafts.
34. The method of claim 22 further comprising the steps of:

supporting said articulated shaft by radial air bearings; and

supporting impeller wheels from a plurality of rotary compressors on air bearings.
35. The method of claim 34 wherein each of said rotary compressors comprises one stage of a multi-stage compression system.
36. The method of claim 21 further comprising mounting said rotary compressors within a device that generates electricity.
37. The method of claim 21 further comprising mounting said rotary compressors for use with a turbogenerator.
38. A turbogenerator comprising:

a plurality of rotary compressors; and

means for rotationally coupling and axially decoupling at least one impeller wheel from each of said plurality of rotary compressors.
39. The turbogenerator of claim 36 wherein said means for rotationally coupling also couples said impeller wheels to a motor shaft.
40. The turbogenerator of claim 36 further comprising:

means for mounting said impeller wheels.
41. The turbogenerator of claim 36 further comprising:

means for supporting said means for rotationally coupling.
42. The turbogenerator of claim 36 wherein each of said rotary compressors comprises one stage of a multi-stage compression system.
43. An apparatus comprising:

a rotating shaft;

a first rotating element;

a first coupling rotationally securing the first rotating element to the rotating shaft while permitting relative axial movement between the first rotating element and the rotating shaft;

a second rotating element; and

a second coupling rotationally securing the second rotating element to the rotating shaft while permitting relative axial movement between the first rotating element and the rotating shaft.
44. The apparatus of claim 43 wherein at least one of said first or second rotating elements is an impeller wheel from a rotary compressor and said apparatus is an integrated turbogenerator.
45. The apparatus of claim 43 wherein both the first and second rotating elements are rotating elements of rotary compressors.
46. The apparatus of claim 45 wherein the rotary compressors are mounted in back-to-back orientation.
47. The apparatus of claim 43 further comprising a motor coupled to the rotating shaft.

48. The apparatus of claim 43 further comprising a turbine coupled to the rotating shaft.

49. The apparatus of claim 43 wherein the first coupling is a multifaceted coupling.

50. The apparatus of claim 43 wherein the first coupling is a splined coupling.

51. The apparatus of claim 43 further comprising an air bearing supporting the first rotating element.

52. The apparatus of claim 43 further comprising foil thrust air bearings supporting the first and second rotating elements.

53. The apparatus of claim 52 wherein said foil thrust air bearings each comprise an underspring member mounted between a thrust bearing surface and compliant foil member.

54. The apparatus of claim 43 further comprising a radial air bearing supporting said rotating shaft.

55. The apparatus of claim 54 wherein said rotating shaft is connected to a motor shaft through a coupling on the inside diameter of said radial air bearing that engages a complimentary coupling on said motor shaft.

56. The apparatus of claim 43 wherein the first and second rotating elements are components of two back-to-back mounted rotary compressors.

57. The apparatus of claim 43 wherein the apparatus is a turbogenerator.

58. The apparatus of claim 57 wherein the first and second rotating elements are components of rotary compressors in a multi-stage compression system.

59. A method for mounting components in a compound machine comprising:

rotationally coupling a rotating shaft to a first rotating element using a coupling that permits relative axial movement between the first rotating element and the rotating shaft; and

rotationally coupling a second rotating element to the rotating shaft using a coupling that permits relative axial movement between the second rotating element and the rotating shaft.

60. The method of claim 59 wherein at least one of the first or second rotating elements is an impeller wheel from a rotary compressor.

61. The method of claim 59 wherein both the first and second rotating elements are components of rotary compressors that are mounted in opposite directions.

62. The method of claim 59 further comprising coupling the rotating shaft to a motor.

63. The method of claim 59 further comprising mating a splined surface of the rotating shaft with a complimentary surface of a motor shaft.

64. The method of claim 59 further comprising mounting said first and second rotating elements on air bearings.

65. The method of claim 59 further comprising supporting said rotating shaft by a radial air bearing.

66. A compound machine comprising:

a rotating shaft;

a first rotating component;

a second rotating component;

a first coupling rotationally securing the first rotating component to an intermediate coupling while permit-

ting axial translation of the first rotating component relative to the intermediate coupling; and

a second coupling rotationally securing the second rotating component to the intermediate coupling while permitting axial translation of the second rotating component relative to the intermediate coupling.

67. The compound machine of claim 66 wherein said first and second rotating elements are impeller wheels of rotary compressors.

68. The compound machine of claim 66 further comprising:

a motor shaft rotationally coupled to, and axially decoupled from, said second rotating component by said second coupling.

69. The compound machine of claim 68 wherein said second coupling is a splined coupling.

70. The compound machine of claim 68 wherein said second coupling has a multifaceted interface.

71. The compound machine of claim 66 wherein said compound machine is a turbomachine.

72. The compound machine of claim 68 further comprising radial air bearings and foil thrust air bearings.

73. The compound machine of claim 68 wherein said compound machine is an integrated turbogenerator.

74. A turbogenerator having a motor generator driven by a turbine wheel, the improvement comprising:

a multi-stage rotary compressor comprising a plurality of rotating components and a structure that rotationally couples but does not axially couple said plurality of rotating components.

75. The turbogenerator of claim 74 wherein each of said plurality of rotating components are compressor impeller wheels.

76. The turbogenerator of claim 74 wherein said structure is an articulated shaft.

77. The turbogenerator of claim 74 wherein each of said plurality of rotating components are supported by foil thrust air bearings and said structure is supported by radial air bearings.

78. The turbogenerator of claim 74 wherein at least two stages of said multi-stage rotary compressor are mounted back-to-back.

79. The turbogenerator of claim 74 wherein said multi-stage rotary compressor has at least four stages mounted in back-to-back pairs.

80. A rotationally-driven compound machine comprising:

means for coupling two or more rotating elements of the compound machine to permit relative axial translation between said rotating elements; and

means for rotationally coupling said rotating elements to a driving shaft of the compound machine.

81. The rotationally-driven compound machine of claim 80, wherein said rotating elements are impeller wheels, further comprising means for supporting said impeller wheels.

82. The rotationally-driven compound machine of claim 80, further comprising means for supporting said means for coupling two or more rotating elements.

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