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(54) **SYSTEM FOR SUPPRESSING VIBRATION IN TURBOMACHINE COMPONENTS**

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(51) **Int. Cl.**

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G05B 15/00	(2006.01)
G05D 23/00	(2006.01)
F03D 11/00	(2006.01)
F04D 27/02	(2006.01)

(52) **U.S. Cl.**
USPC **700/275**; 415/119; 415/27; 60/39.281; 60/794

(58) **Field of Classification Search**
USPC 700/275; 415/119, 27; 60/39.281, 794
See application file for complete search history.

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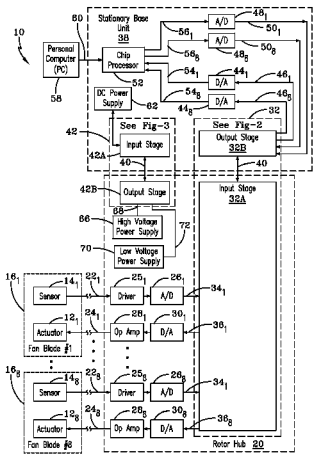
(57) **ABSTRACT**

Disclosed is a system for suppressing vibration and noise mitigation in structures such as blades in turbomachinery. The system includes flexible piezoelectric patches which are secured on or imbedded in turbomachinery blades which, in one embodiment, comprises eight (8) fan blades. The system further includes a capacitor plate coupler and a power transfer apparatus, which may both be arranged into one assembly, that respectively transfer data and power. Each of the capacitive plate coupler and power transfer apparatus is configured so that one part is attached to a fixed member while another part is attached to a rotatable member with an air gap therebetween. The system still further includes a processor that has 16 channels, eight of which serve as sensor channels, and the remaining eight, serving as actuation channels. The processor collects and analyzes the sensor signals and, in turn, outputs corrective signals for vibration/noise suppression of the turbine blades.

14 Claims, 4 Drawing Sheets



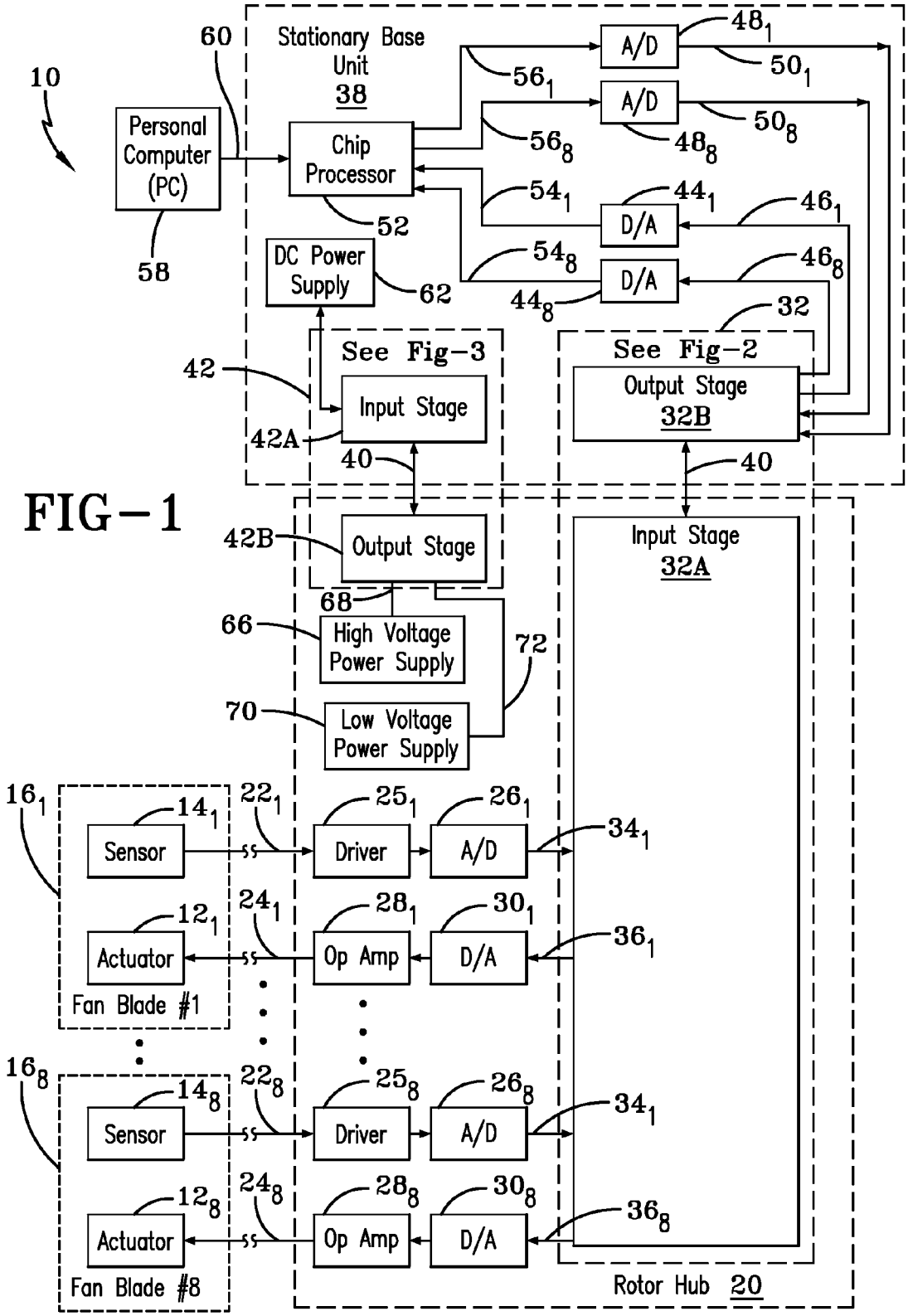

10
Personal Computer (PC)
60
58
Stationary Base Unit 38
Chip Processor
52
DC Power Supply
62
A/D
A/D
D/A
D/A
48_1
50_1
56_1
56_8
50_8
48_8
54_1
44_1
46_1
54_8
46_8
44_8
32
See Fig-3
See Fig-2
42
Input Stage
42A
40
Output Stage 32B
40
42B
Output Stage
Input Stage 32A
68
66
High Voltage Power Supply
72
70
Low Voltage Power Supply
16_1
14_1
22_1
25_1
26_1
34_1
Sensor
Driver
A/D
12_1
24_1
28_1
30_1
36_1
Actuator
Op Amp
D/A
Fan Blade #1
16_8
14_8
22_8
25_8
26_8
34_1
Sensor
Driver
A/D
12_8
24_8
28_8
30_8
36_8
Actuator
Op Amp
D/A
Fan Blade #8
Rotor Hub 20

FIG-1

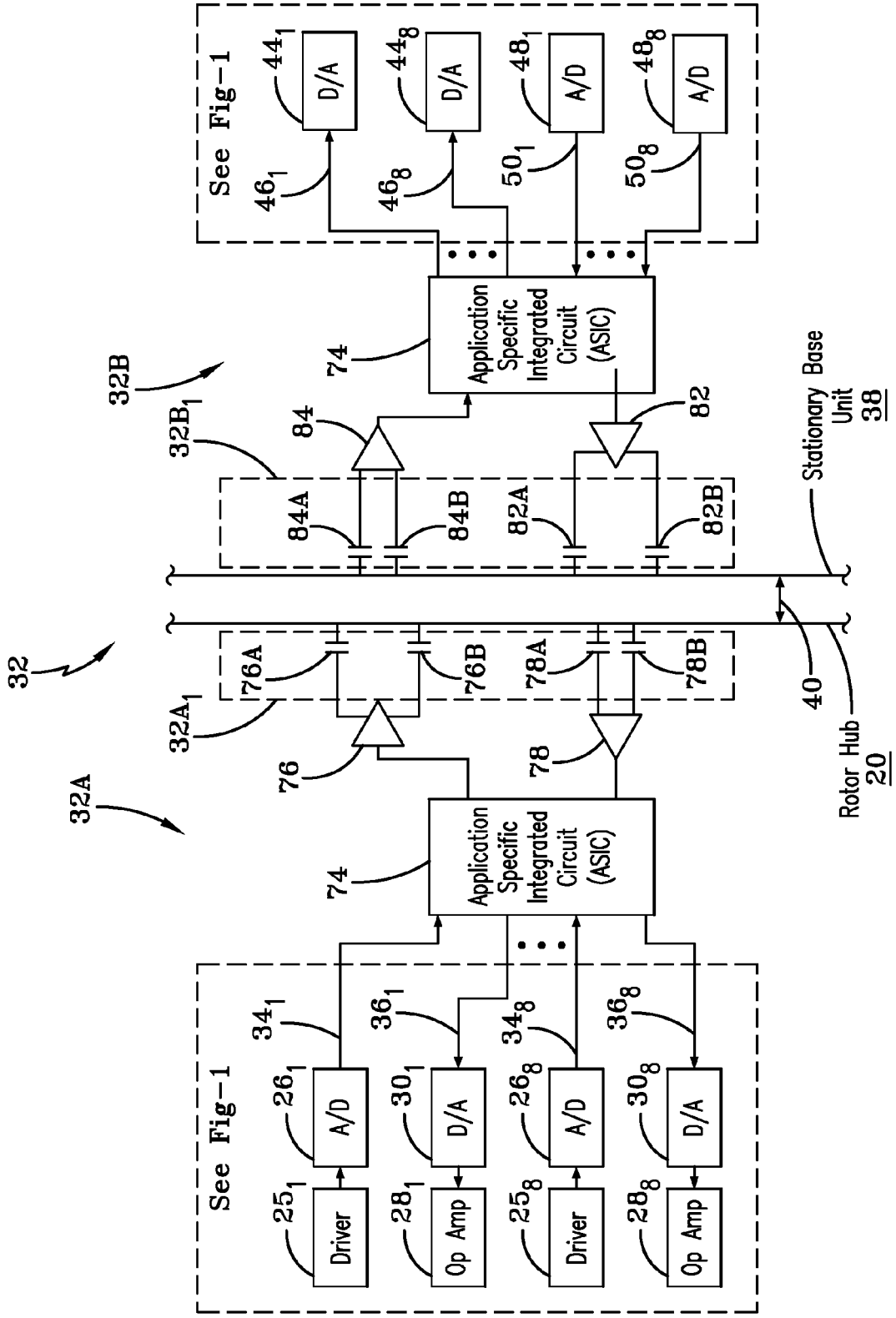

See Fig-1
D/A
D/A
A/D
A/D
Application Specific Integrated Circuit (ASIC)
Stationary Base Unit 38
Rotor Hub 20
Driver
Op Amp
Driver
Op Amp
A/D
D/A
A/D
D/A
Application Specific Integrated Circuit (ASIC)
See Fig-1

FIG-2

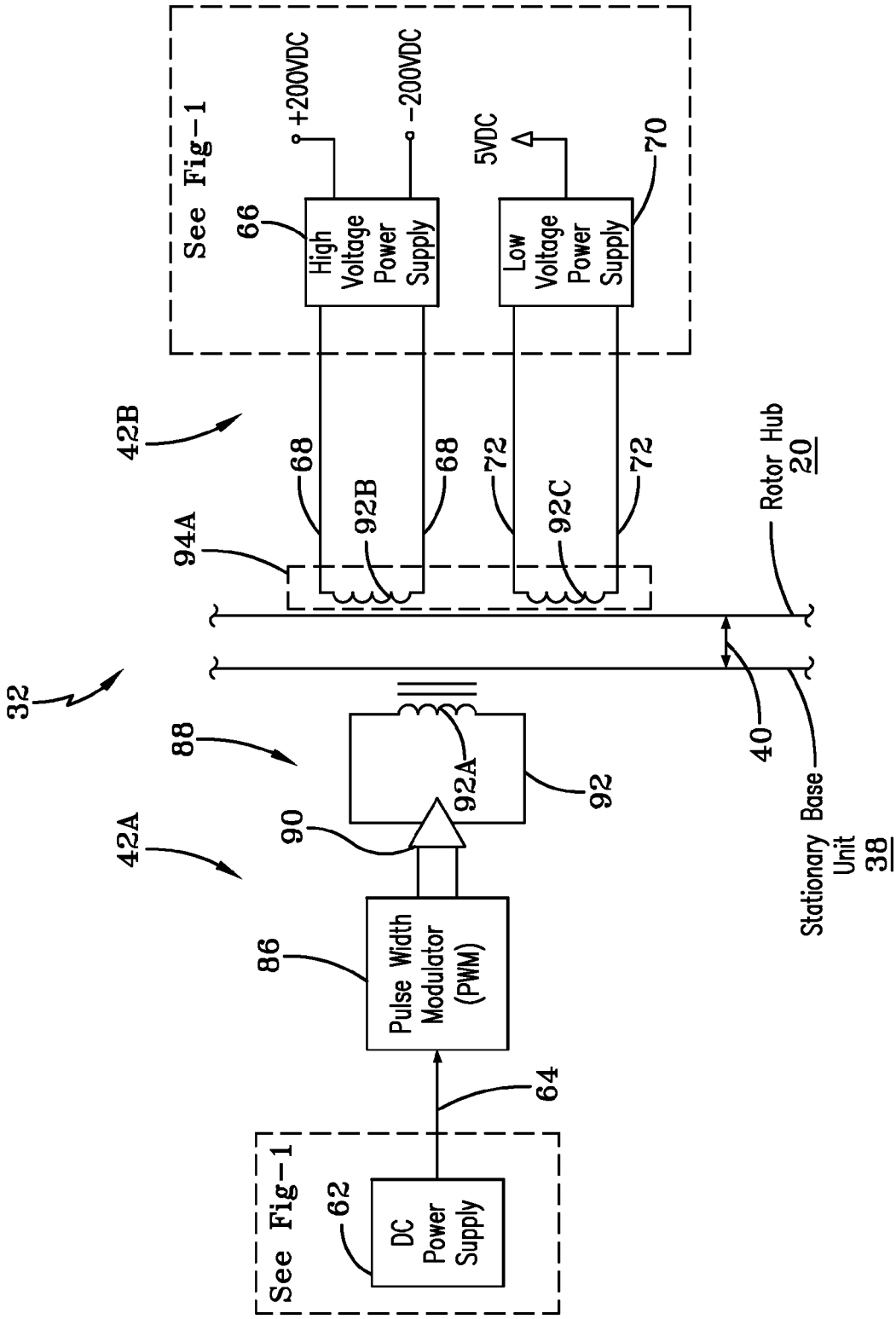

See Fig-1
+200VDC
-200VDC
5VDC
66
High Voltage Power Supply
Low Voltage Power Supply
70
42B
68
68
72
72
94A
92B
92C
Rotor Hub
20
32
88
92A
92
40
Stationary Base Unit
38
42A
90
86
Pulse Width Modulator (PWM)
64
See Fig-1
62
DC Power Supply

FIG-3

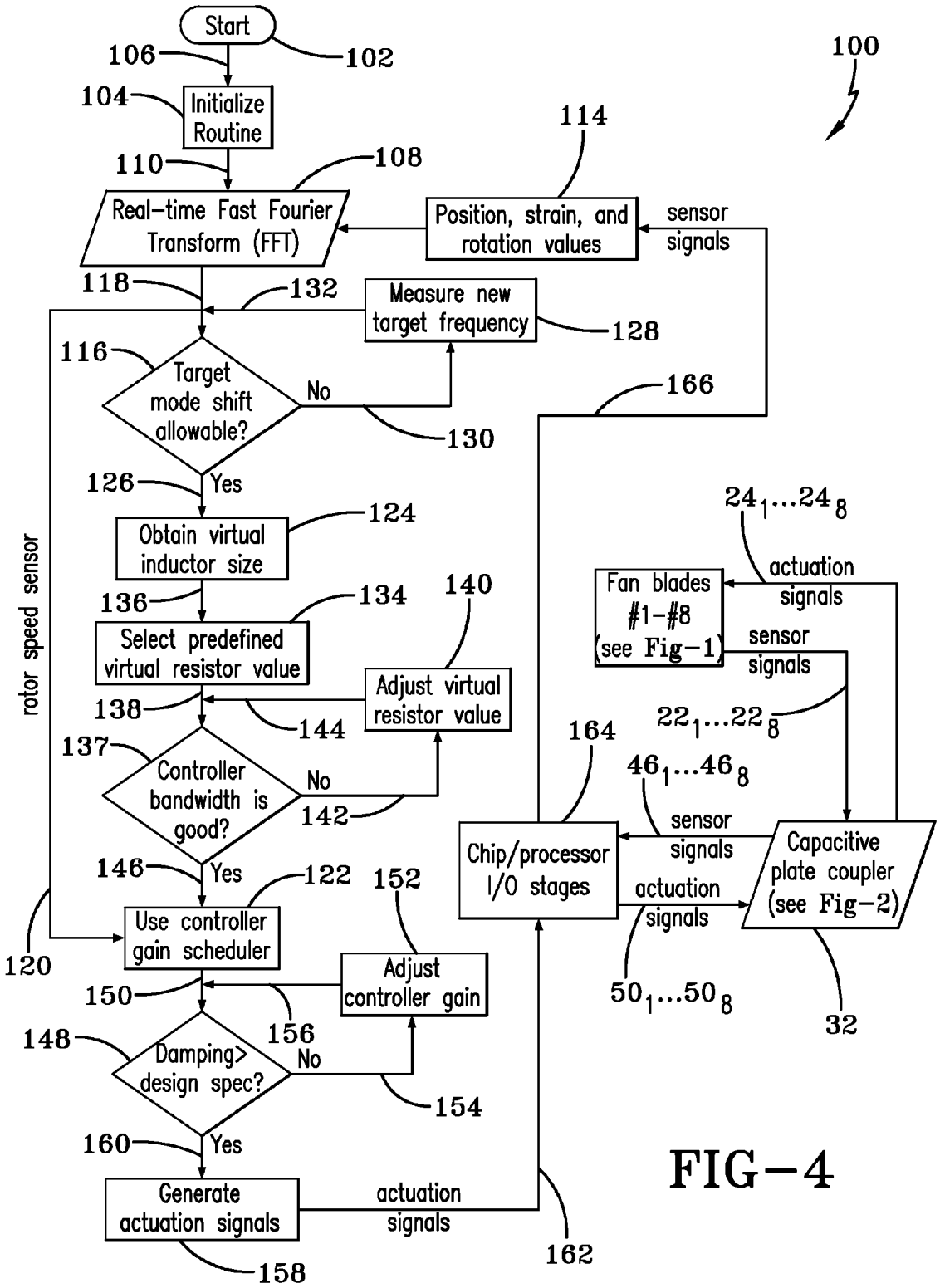

Start
102
106
104
Initialize Routine
110
108
Real-time Fast Fourier Transform (FFT)
114
Position, strain, and rotation values
sensor signals
100
118
132
Measure new target frequency
128
116
Target mode shift allowable?
No
130
166
126
Yes
Obtain virtual inductor size
124
rotor speed sensor
136
134
140
Select predefined virtual resistor value
Adjust virtual resistor value
138
144
137
Controller bandwidth is good?
No
142
146
Yes
122
152
Use controller gain scheduler
Adjust controller gain
120
150
156
148
Damping> design spec?
No
154
160
Yes
Generate actuation signals
actuation signals
158
162
$24_1 \ldots 24_8$
actuation signals
Fan blades #1-#8 (see Fig-1)
sensor signals
$22_1 \ldots 22_8$
164
$46_1 \ldots 46_8$
sensor signals
Chip/processor I/O stages
actuation signals
Capacitive plate coupler (see Fig-2)
$50_1 \ldots 50_8$
32

FIG-4

SYSTEM FOR SUPPRESSING VIBRATION IN TURBOMACHINE COMPONENTS

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C.2457).

CROSS-REFERENCE TO RELATED APPLICATIONS

None

FIELD OF THE INVENTION

The present invention relates to a system for suppressing vibrations in structures of turbomachinery and, more particularly, to a system for suppressing vibrations in turbomachinery blades by utilizing piezoelectric elements that are mounted on or in the blades and are activated and monitored by wireless devices including inductive and capacitive couplers that are attached to the rotor hub of the turbomachinery.

Blade vibration in turbomachinery is a nettlesome problem that demands an effective solution. Vibration in turbomachinery can cause blade failures and leads to the use of heavier, thicker blades that result in lower aerodynamic efficiency and increased noise of turbomachinery, Efficient engine operation necessitates minimal disturbance to the gas flowing across the turbine blades in any effort to mitigate blade vibration. The problem of turbomachinery blade vibration represents a serious safety issue. Prolonged, excessive vibration can cause blade failure, sometimes resulting in accidents. Past attempts at an effective solution to this vibration problem have limitations, due largely to issues of hardware impracticality.

One previous approach, called passive damping, may require heavy electronics incorporating a large coil and the use of unreliable, bulky slip ring technology having brushes serving as connecting means to a rotating element and which requires cooling and may prove unreliable and problematic over time. Another approach uses special mechanical devices or damping materials to dampen specific vibration frequencies in the blades, but even this approach has drawbacks due to the condition wherein the material adds weight to the turbomachinery blades. Further approaches utilize sensing and activating elements, such as piezoelectric devices, mounted in or on turbomachinery rotating blades, but the monitoring of these sensing and activating elements requires relatively complex circuit arrangements, sometimes referred to as wireless systems, of transmitter and receivers that are limited to providing excitation to the activating elements from a power source that is free from rotation. It is desired to provide a system for suppressing vibrations in a turbomachinery blade that is not plagued by the prior art drawbacks.

OBJECTS OF THE INVENTION

It is a primary object of the present invention to provide a system for detecting and suppressing vibrations in a turbomachine component, such as a fan compressor or turbine blade, that is free of slip ring technology.

It is another object of the present invention to provide a system for detecting and suppressing deleterious vibrations in fan blades that are free of relatively heavy electronics incorporating large coils or other bulky devices that unnecessary add weight to the fan blades, while undesirably interfering with air flowing across the turbine blade.

Further, it is still another object of the present invention to provide a system for detecting and suppressing deleterious vibrations in a fan compressor or turbine blades that supply excitation to sensing elements to measure vibrations by way of a rotating element of a wireless arrangement, so as to be free of the requirement of receiving the excitation for activating elements by way of stationary elements.

SUMMARY OF THE INVENTION

The present invention provides a system for suppressing vibrations in at least one fan blade of a turbomachine having a rotor hub and being located near a stationary unit. The system comprises; a) at least one actuator having an input and located on the at least one fan blade, the input of the actuator receiving a signal which causes deformation of the actuator; b) at least one sensor having an input and an output and located on the at least one fan blade, the input of the sensor generating a signal representative of the vibrations occurring on the at least one fan blade, the output of the sensor providing a signal representative of the vibrations. The system further comprises; c) at least one analog to digital converter located on the rotor hub receiving the output of the at least one sensor and providing a digital output signal representative thereof; d) a capacitive plate coupler having first and second stages spaced apart by a first predetermined distance with the first stage being located on the rotor hub and the second stage being located on the stationary unit, the first stage having an input and an output and the second stage having an input and output, the capacitive plate coupler having its first stage input receiving the output of the at least one analog to digital converter and providing a representative signal thereof at its output of its first stage. The system further still comprises; at least one digital to analog converter located on the stationary unit and receiving the output of the first stage of the capacitor plate coupler; f) a processor having operating routines for suppressing vibrations in the at least one fan blade, the processor further having first and second inputs and an output, the first input of the processor receiving the output of the at least one digital to analog converter located on the stationary unit, the operating routines of the processor providing an output signal to suppress the vibrations of the at least one fan blade. The system further includes; g) at least one analog to digital converter located on the stationary unit and receiving the output signal of the processor and providing a representative output therefrom that is routed to the input of the second stage of the capacitive plate coupler and providing a representative signal thereof of its output of its second stage; h) at least one digital to analog converter located on the rotor hub and receiving the output at the second stage of the capacitive plate coupler and providing a representative output thereof; i) a power supply located on the stationary unit and having at least one output. The system still further comprises; j) an inductive power transfer apparatus having first and second stages with the first stage thereof located at the stationary unit and the second stage thereof located at the rotor hub, the first and second stages being spaced apart by the first predetermined distance, the first stage of the inductive power transfer element being connected to the output of the power supply and providing a representative output thereof at the second stage of the inductive power transfer apparatus, the second stage being connected to power supplies located on the rotor hub.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of the system of the present invention that suppresses deleterious vibrations of a fan blade of a turbomachine;

FIG. **2** is a schematic drawing of a capacitive plate coupler comprised of first and second stages;

FIG. **3** is a schematic drawing of an inductive power transfer apparatus comprised of first and second stages; and

FIG. **4** illustrates the sequence of operations of the processor of the present invention for collecting and analyzing input sensor signals and, in turn, for providing correcting actuating signals to suppress deleterious vibrations experienced by a fan blade of the turbomachine.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is directed to the field of turbomachineiy, such as jet engines or electric power generators, wherein the system of the present invention suppresses destructive vibrations in turbomachinery components, such as turbine or fan compressor blades.

The present invention preferably utilizes piezoelectric elements which deliver a voltage when deformed, or conversely, which changes in shape when a voltage is applied to them. The piezoelectric elements that deliver a voltage when deformed serve as a sensor of the present invention and, conversely, the piezoelectric elements which change in shape when a voltage is applied serves as an actuator of the present invention.

The present invention provides an integrated system for non-contact transmission between stationary and rotating components, wherein power is transferred by inductive linking and the data is coupled by capacitive coupling. The system provides a full-duplex serial communication link suitable for transporting bi-directional channel data in a serial digital form to and from an external computer and/or data processor.

In one embodiment, the system **10** of the present invention couples analog signal data, at a 20 KHz bandwidth, associated with sixteen channels with eight channels thereof associated with actuators and eight channels thereof associated with sensors, to and from eight fan blades of a turbomachine. The system **10** of the present invention may be further described with reference to the block diagram of FIG. **1**.

The system **10** includes actuators $\mathbf{12}_1 \ldots \mathbf{12}_N$ and sensors $\mathbf{14}_1 \ldots \mathbf{14}_N$ that are mounted on or embedded in the fan blades $\mathbf{16}_1 \ldots \mathbf{16}_N$. For the embodiment of FIG. **1**, there are eight (8) fan blades $\mathbf{16}_1 \ldots \mathbf{16}_8$, each of which respectively has an actuator $\mathbf{12}_1 \ldots \mathbf{12}_8$ and a sensor $\mathbf{14}_1 \ldots \mathbf{14}_8$.

As will be further described hereinafter, the actuators **12** operates upon the application of a voltage in the range of plus (+) to minus (−) 200 VDC which causes the deformation of the actuator **12** itself. The mounting of the actuators and the sensors on to the fan blade is accomplished by the use of high-strength adhesive, such as high temperature epoxy, known in the art. The embedding of the actuators and sensors into the respective fan blades is accomplished, for composite fan blades, by cutting out sections of composite plies, making up the composite fan blades, and replacing them with the actuator or sensor before curing the composite fan blade; or in the case of a metal fan blade, by machining a pocket, mounting the actuator or sensor within the pocket with high-strength adhesive, and then closing the pocket with a welded metal cover so as to restore the external blade shape.

Each of the sensors **14** has an input connected to the respective fan blade and an output which is connected to a rotor hub **20** by way of signal paths $\mathbf{22}_1 \ldots \mathbf{22}_8$, and, similarly, each of the actuators **12** is connected to the rotor hub of **20**, by way of signal path $\mathbf{24}_1 \ldots \mathbf{24}_8$. The signal paths $\mathbf{22}_1 \ldots \mathbf{22}_8$ are preferably and respectively connected to drivers $\mathbf{25}_1 \ldots \mathbf{25}_8$ which, in turn, are respectively connected to A/D converters $\mathbf{26}_1 \ldots \mathbf{26}_8$. The signal paths $\mathbf{24}_1 \ldots \mathbf{24}_8$ are preferably and respectively connected to OP AMPS $\mathbf{28}_1 \ldots \mathbf{28}_8$ which, in turn, are respectively connected to D/A converters $\mathbf{30}_1 \ldots \mathbf{30}_8$.

The drivers $\mathbf{25}_1 \ldots \mathbf{25}_8$ are the conditioning circuits for the eight channels of analog data received from sensors $\mathbf{14}_1 \ldots \mathbf{14}_N$. The eight channels of data provided by D/A converters $\mathbf{30}_1 \ldots \mathbf{30}_8$ and OP AMP $\mathbf{28}_1 \ldots \mathbf{28}_8$ are used to drive the actuators $\mathbf{12}_1 \ldots \mathbf{12}_8$.

The drivers $\mathbf{25}_1 \ldots \mathbf{25}_8$ are analog current amplifiers which allow for the current output of the sensors $\mathbf{14}_1 \ldots \mathbf{14}_8$ to be connected to an analog voltage compatible with A/D converters $\mathbf{26}_1 \ldots \mathbf{26}_8$ both in source impedance and in amplitude. The output D/A voltages of D/A converters $\mathbf{30}_1 \ldots \mathbf{30}_8$ are inputs to high power amplifiers of OP AMPS $\mathbf{28}_1 \ldots \mathbf{28}_8$ which are capable of translating the low voltage output of the D/A's converters $\mathbf{30}_1 \ldots \mathbf{30}_8$ into the high level (+−200V) DC signals needed to drive the actuators $\mathbf{12}_1 \ldots \mathbf{12}_8$.

The AD converters $\mathbf{26}_1 \ldots \mathbf{26}_8$ supply output signals, via signal paths $\mathbf{34}_1 \ldots \mathbf{34}_8$, to a capacitor plate coupler **32** having an input stage **32**A and an output stage **32**B and to be further described hereinafter with reference to FIG. **2**. Similarly, the D/A converters $\mathbf{30}_1 \ldots \mathbf{30}_8$ receive an output signal from the capacitor plate coupler **32** by way of signal paths $\mathbf{36}_1 \ldots \mathbf{36}_8$.

The input stage **32**A is located on the rotor hub **20** whereas the output stage **32**B is located on the stationary base unit **38**. The input stage **32**A and the output stage **32**B are spaced apart by the first predetermined distance **40** which provide an air gap therebetween. The air gap **40** is from about 0.025 to about 0.030 inches. Similarly, the predetermined air gap **40** separates the input stage **42**A and the output stage **42**B of the inductive power transfer apparatus **42**, to be further described hereinafter with reference to FIG. **3**.

The output stage **32**B of the capacitor plate coupler **32** provides output signals to D/A converters $\mathbf{44}_1 \ldots \mathbf{44}_8$, located on the stationary base unit **38**, via signal paths $\mathbf{46}_1 \ldots \mathbf{46}_8$, and, similarly, the output stage **32**B of the capacitor plate coupler **32** receives input signals from A/D converters $\mathbf{48}_1 \ldots \mathbf{48}_8$, also located on the stationary base unit **38**, via signal paths $\mathbf{50}_1 \ldots \mathbf{50}_8$. The D/A converters $\mathbf{44}_1 \ldots \mathbf{44}_8$ supply input signals to a chip/processor **52**, via signal paths $\mathbf{54}_1 \ldots \mathbf{54}_8$ and, similarly, the A/D converters $\mathbf{48}_1 \ldots \mathbf{48}_8$ receive output signals from chip/processor **52**, via signal paths $\mathbf{56}_1 \ldots \mathbf{56}_8$.

For the embodiment shown in FIG. **1**, the chip/processor **52** receives information from a personal computer (PC) **58**, via signal path **60**. However, in other embodiments, the PC **58** may directly receive information from the D/A converters $\mathbf{44}_1 \ldots \mathbf{44}_8$ and transmit information directly to the A/D converters $\mathbf{48}_1 \ldots \mathbf{48}_8$. In further embodiments, the chip/processor **52** may be pre-programmed and act as a stand-alone device and not require any information from PC **58**.

The stationary base unit **38** has located thereon a DC power supply **62** which supplies power, signal path **64** to the input stage **42**A of the inductive power transfer apparatus **42** to be further discussed with reference to FIG. **3**. The inductive power transfer apparatus **42**, in response to its received input signal, provides an output signal at its output stage **4213**, which is routed to a high voltage power supply **66**, via signal path **68** and to a low voltage power supply **70**, via signal path **72**.

Although not shown for the sake of clarity, the high voltage power supply **66** is routed to the OP AMPS $\mathbf{28}_1 \ldots \mathbf{28}_2$ located

on the rotor hub **20** and feeding the actuators $12_1 \ldots 12_8$, whereas the low voltage power supply **70** is routed, also not shown for the sake of clarity, to all of the electronics located on the rotor hub **20** including the capacitor plate coupler **32** which may be further described with reference to FIG. **2**.

FIG. **2** illustrates that the input stage **32**A is separated from the output stage **32**B by the predetermined distance **40** previously discussed with reference to FIG. **1**. The input stage **32**A is comprised of an Application Specific Integrated Circuit (ASIC) **74**, a capacitor differential driver **76** having associated capacitor element **76**A and **76**B, and a capacitor differential receiver **78** having associated capacitor elements **78**A and **78**B, all arranged as shown in FIG. **2**. The capacitive elements **76**A and **76**B are arranged to receive the output of differential driver **76** and are located on a first plate $32A_1$, whereas capacitive elements **78**A and **78**B are arranged to provide an input signal to differential receiver **78** and are also located on the first plate $32A_1$.

The elements **76**A, **76**B, and **76** receive the input to the first stage $32A_1$, and capacitive elements **84**A and **84**B, to be described, receive the output of the first stage $32A_1$. Conversely, capacitive elements **82**A and **82**B receive the input to the second stage $32B_1$ and capacitive elements **78**A and **78**B receive the output of the second stage $32B_1$.

The output stage **32**B is comprised of the Applications Specific Integrated Circuit (ASIC) **74** also serving the input stage **32**A; a capacitor differential driver **82** having capacitive elements **82**A and **82**B, and a capacitor differential receiver **84** having associated capacitive elements **84**A and **84**B all arranged as shown in FIG. **2**. The capacitive elements **82**A and **82**B are arranged to receive the output of differential driver **82** and are located on a second plate $32B_1$, whereas capacitive elements **84**A and **84**B are arranged to provide an input signal to differential receiver **84** and are also located on the second plate $32B_1$.

The first and second plates $32A_1$ and $32B_1$, respectively, located on the input stage $32A_1$ and output stage $32B_1$, separated by an air gap **40** from about 0.025 to about 0.030 inches, are arranged so as provide capacitive coupling therebetween and to transfer data, in a serial format, at a rate of about 50 KHz.

In operation, the capacitive plate coupler **32** essentially provides digital signal data paths which are minor images from each other. More particularly, the capacitive plate coupler **32** provides for eight (8) analog channels of data to be connected to high speed digital serial stream. The digital data stream is then capacitively driven across the air gap **40** of about 0.025 to about 0.030 inches, via capacitive differential driver **76** and differential receiver **84**. The serial steam is then decomposed into the eight (8) individual channel data by ASIC **74**, which is output through eight (8) each D/A converters $44_1 \ldots 44_8$ essentially "reconstructing" the input eight (8) analog channels received from A/D converters $26_1 \ldots 26_8$. This process is run in both directions including capacitive differential driver **82** and differential receiver **78**; hence you have sixteen (16) channels of digital signal data passed across the air gap **40** in both directions.

The process of collecting the data from the eight (8) A/D converters $48_1 \ldots 48_8$ converting the data into a single digital data stream and sending it, receiving the serial data stream across the gap **40**, deconstructing it back into eight (8) individual channels for transmission to D/A converters $30_1 \ldots 30_8$ is accomplished by the Application Specific Integrated Circuit, (ASIC) **74** shown on both sides of the air gap **40**. The programming of (ASIC) **74** to accomplish the collection and reconstruction of the related data streams is known in the art.

The capacitive elements **82**A and **82**B are arranged to receive the output of differential driver **82** and are located on the second plate $32B_1$, whereas capacitive elements **84**A and **84**B are arranged to provide an input signal to differential receiver **84** and are also located on the second plate $32B_1$.

The capacitor plate coupler **32** comprises a first plate $32A_1$ comprised of elements **76**A, **76**B, **78**A, and **78**B, attached to rotor hub **20** and a second plate $32B_1$ comprised of elements **82**A, **82**B, **84**A, and **84**B, attached to the stationary unit **38**, allows the first plate $32A_1$ to be rotatable relative to the second plate $32B_1$ at a speed of about 1500 rpm and the first plates $32A_1$ and $32B_1$ are arranged, so as to provide capacitive coupling therebetween. The power provided for the capacitive plate coupler **32**, as well as the other elements shown in FIG. **1** located on the rotor hub **20**, is delivered by the inductive power transfer apparatus **42**, which may be further described with reference to FIG. **3**.

FIG. **3** shows the input stage **42**A separated from the output stage **42**B by the air gap **40** previously discussed with reference to FIGS. **1** and **2**. The input stage **42**A is comprised of a pulse width modulator **86** and an inductive driver **88** comprised of a differential driver **90** and an inductive element **92** which, in turn, is comprised of three inductive elements **92**A, **928**, and **92**C. The inductive element **92**A receives the output signal from inductive driver **90** and is spaced apart by the air gap **40** from inductive elements **92**B and **92**C which respectively provide power, previously discussed with reference to FIG. **1**, to high voltage power supply **66**, via signal path **68**, and to low voltage power supply **70**, via signal path **72**. The first inductive element **92**A and the second (**92**B) and third (**92**C) transfer energy therebetween by inductive linking. The first, second and third inductive elements **92**A, **92**B and **92**C serve as a pot core pair.

The inductive power transfer apparatus **42** has an inductively coupled pot core pair shown in FIG. **3** as comprising a first pot core **92**A and a second pot core **94**A comprised of inductive elements **92**B and **92**C.

In operation, the first pot core **92**A is the driver transmitter (on the stationary base unit **32**) the second pot core **94**A is the power receiver (on the rotor hub **20**). The first core **92**A and second core **94**A are arranged so as to be loosely coupled across the air gap **40** of about 0.025 to about 0.030 inches.

The signal applied on the driver side, that is at the input stage **42**A at the input to the inductive driver **90**, is a square wave provided by the Pulse Width Modulator (PWM) **86**. In one embodiment, the duty cycle of the PWM **86** is set for 50%, however, if desired, the signal provided by the PWM **86** can be furthered pulse width modulated to reduce the power delivered by the inductive power transfer apparatus **42**. The capability to modify power delivered by the inductive power transfer apparatus **42** allows for other embodiment of the present invention to adapt power to the system operational needs thereof.

The PWM **86** drive signal applied to the input of the inductive driver **90** is generated within an Integrated Circuit (IC) of PWM **86**. The IC used is a combination Micro-controller with a PWM block, known in the art, as an element within this IC. The use of a Micro-controller allows the practice of the present invention to be able to program its operation (such as base operating frequency of the PWM), and take advantages of the other features of the IC, such as Analog to Digital converters. The Micro-controller PWM output from the PWM **86** is buffered by traditional power MOSFET gate current drivers. High gain low impedance MOSFETS are implemented so as to preferably form a traditional ½H driver, known in the art, for activation of the drive pot core primary winding shown in FIG. **3** as first core **92**A.

Although the capacitive plate coupler **32** and inductive power transfer apparatus **42** are desired in the practice of the present invention, there are other devices for capacitively coupling data and for inductively transferring power both known in the art. In some prior art devices the data may be inductively coupled either on the same or a second transformer, while in some applications only data is transmitted without power. In the practice of the present invention, the data rate across the gap is high enough, e.g. 50 KHz, to effectively capacitively couple the data directly using differential capacitive coupling. The present invention also contemplates the transfer of data by the use of high frequency carrier modulation, in a manner known in the art.

Further, although the hereinbefore discussions described the capacitive plate coupler **32** and the inductive power transfer apparatus **42** as being separate devices, if desired, the capacitive plate coupler **32** and the inductive power transfer apparatus **42** may be arranged in one assembly with the capacitive plate coupler **32** providing capacitive coupling between its first and second plates and the inductive power transfer apparatus **42** providing inductive coupling between its first and second pot cores.

The operation of the chip/processor **52** that suppresses the vibrations encountered by the blades of a turbomachine may be further described with reference to FIG. **4** which is a flow chart **100** illustrating the sequence of operations of the chip/processor **52**.

In general, the routines running in the chip/processor **52** provide an active method for damping the vibration frequencies of blades #1 to #8. The damping stabilizes the quantities under analysis by the routines of the present invention by eliminating unwanted or excessive oscillators thereof. The active method selects predetermined values of inductors, resistors and capacitors to provide for frequency damping. These predetermined values are arranged in damping circuits provided by the routines running in the chip/processor **52**. The targeted or controlled frequencies may include those associated with bending, torsion and chordwise modes, all known in the art. The routines running in the chip processor **52** take into account that the vibration blade frequencies vary with the speed of the rotor hub **20**.

The present invention provides routines running in the chip/processor **52** that embody a digital code that takes into account transfer functions of LRC (L: inductor, R: resistor, and C: capacitor) shunt circuits used in the damping circuits of the present invention and which are expressed in S-domain which, in turn, allows for real-time adaptive control to accommodate real-time changes in blade frequencies. The S-domain is known in the art and can be programmed in a digital code.

The routines provide pre-processing quantities found in look-up tables that include targeted or controlled blade vibration frequencies in the range of the rotor speed of the rotor hub **20** that is to be analyzed and controlled. Depending upon design goals and the specification of the rotor hub **20** under analysis, the blade vibration frequencies may encompass modes such as bending, torsion, and chordwise modes. The look-up tables for the pre-processing quantities further include corresponding inductor and capacitor values (calculated or virtual values, not real physical capacitor or inductor sizes) used for the damping circuits provided by the routines running in the chip/processor **52**, as well as resistor values used in the damping circuits, all related to the blade frequencies to be dampened and analyzed. Further, the pre-processing quantities include gain values and bandwidth values utilized by a controller that controls the activities included in the routines running in the chip/processor **52**. These gain values are selectable for each mode blade vibration frequency under analysis by the routines running in the chip/processor **52** versus the speed of the rotor hub **20**. The routines running in the chip/processor **52** have a start event that, upon completion, passes control to program segment **104**, via signal path **106** as seen in FIG. **4**.

The program segment **104** embodies the initialization routine which sets up input and output channels of the chip/processor **52**. Upon completion, the program segment **104** passes control to program segment **108**, via signal path **110**.

The program segment **108** performs real-time Fast Fourier Transform (FFT) analysis upon the quantities received on signal path **112** which is the output of program segment **114**. The program segment **114** receives sensor signals delivered from blades 1-8, to be further described hereinafter, and containing position, strain, and rotation values of the fan blades 1-8. Program segment **114** delivers its received signals to program segment **108**, via signal path **112**. Program segment **108** accesses all of the pre-processing quantities found in the look-up tables previously mentioned. Upon completion, program segment **108** passes control to program segment **116**, via signal path **118**. Further, upon completion, program segment **108** delivers the rotor speed sensor quantity, which represents the rotor speed in rpm (revolution per minutes) of blades 1-8 under analysis, via signal path **120**, to program segment **122**.

The program segment **116** also receives the rotor speed sensor quantity and checks to determine if the target mode shift is or is not allowable. This target mode shift, that is the mode being targeted or controlled by the routines being run in the chip/processor **52**, takes into account that the blade frequencies vary with time due to rotor dynamics, non-linear material properties making up blades 1-8, and the aging of blades 1-8 themselves. Thus, it is necessary to determine if the blade vibration frequencies under analysis are different from the blade vibration frequencies stored in the look-up tables for particular rotor speeds and if any differences thereof falls into an allowable or non-allowable tolerance. This determination signifies that the target mode related to the blade vibration frequency under analysis does or does not shift or change due to rotor dynamics and non-linear material properties making up blades 1-8. If the answer to this determination is no, that is, the target mode shift is not allowable, program segment **116** passes control to program segment **128**, via signal path **130**.

The program segment **128** measures a new target frequency, which signifies a newly adaptive target frequency replacing the non-allowable target mode measured program segment **108**. The newly adaptive target frequency occurring because of the re-measuring of the blade frequency also provides a new value of inductor and corresponding capacitor value both stored in the look-up tables previously mentioned for the damping circuits embodied in the routines running in the chip/processor **52**. Upon completion, program segment **128** passes control back to program segment **116** by way of signal paths **132** and **118**.

As previously mentioned, program segment **116** also determines if the target mode shift is allowable and if this determination yields and answer of yes, program segment **116** passes control to program segment **124**, via signal path **126**.

The program segment **124** obtains the virtual inductor size. The virtual inductor size signifies a digitally implemented inductor, not physical inductor. This virtual inductor size is utilized in the damping circuits running in the chip/processor **52** and may be the same as found in program segment **128**. Upon completion, program segment **124** passes control to program segment **134**, via signal path **136**.

The program segment **134** selects the predefining virtual resistor value which signifies a digitally implemented resistor, not physical resistor. This virtual resistor value is utilized in the damping circuits running in the chip/processor **52**. At this junction in the routines being run in the chip/processor **52**, values have been selected and, if needed, updated for the transfer functions of LRC shunt circuits of the damping circuit utilized for dampening the vibrations of the fan blade under analysis. Upon completion, program segment **134** passes control to program segment **137**, via signal path **138**.

The program segment **137** determines if the controller bandwidth, that is, the bandwidth of the controller embodied in the routines running in the chip/processor **52** that controls the activities of the routines thereof, is good which signifies a good coverage for the peaks of blade frequency vibrations under analysis. The good coverage is indicative that the width of coverage provided by controller, embodied in the routines being run in the chip/processor **52**, is wide enough to cover the peaks of the blade frequency vibrations under analysis. If the width is not wide enough the value of the virtual resistor, previously mentioned in program segment **134**, is increased so as to provide a wider bandwidth, which also means more power is required for the actuation signals applied to blades 1-8, to be further described hereinafter. Conversely, if the width of the controller bandwidth is too wide, a lower valued virtual resistor is selected yielding the need for less power to be required for the actuation signals for blades 1-8. Accordingly, the routines being run in the chip/processor **52** provide optimal virtual resistor values for the damping circuits. If the answer to the determination of the required bandwidth is no, program segment **137** passes control to program segment **140** by way of signal path **142**.

The program segment **140** adjusts the virtual resistor value so that the virtual resistor value is correct and the controller bandwidth is correct and passes control back to program segment **137**, by way of signal paths **144** and **138**.

As previously discussed, program segment **137** determines if the controller bandwidth is or is not good and if this determination yields and answer of good or yes, program segment **137** passes control to program segment **122**, via signal path **146**.

As previously discussed, program segment **122** receives the rotor speed sensor quantity present on signal path **120**. The program segment **122** then uses a controller gain scheduler, which performs the duty of using a family of linear controller gains. The controller gain scheduler is part of the controller embodied in the routines running in the chip/processor **52** that controls the activities of the routines thereof. The routines running in the chip/processor **52** select the controller gains from a look-up table, and the selected gain operates so as to reduce the peak of the vibration frequency of the fan blade under analysis. If not a sufficient amount of the peak of the vibration frequency is being reduced, the value of the controller gain is increased. If the gain of the controller is selected to be too high, then too much power is required for the actuation signals being applied to blades 1-8, which may result in instability related to the actuation signals. The practice of the present invention allows for selecting an optimal controller gain. Upon completion, program segment **122** passes control to program segment **148**, via signal path **150**.

Program segment **148** determines if the dampening, being performed by the damping circuits embodied in the routines running in the chip/processor **52**, has exceeded design specifications which is equivalent to the turbomachinery industry's damping standard known in the art. If the dampening design specifications have not been exceeded, and, thus, more damping provided by the routines running in the chip/processor **52** is desired, program segment **148** passes control to program segment **152**, by way of signal path **154**.

Program segment **152** adjusts the controller gain which allows for the routines running in the chip/processor **52** to provide enough damping to meet the design specifications. Upon completion, program segment **152** passes control back to program segment **148**, via signal paths **156** and **150**.

As previously discussed, program segment **148** determines if the dampening has or has not exceeded the design specifications, and if the answer to that determination is yes, that is, the required dampening has been met, program segment **148** passes control to program segment **158**, by way of signal path **160**.

Program segment **158** generates actuation signals and routes these signals, via signal path **162** to the chip, processor I/O stages **164**, which is part of the chip/processor **52** of FIG. **1**. The chip, processor I/O stages **164** also routes the sensor signals, previously described with reference to FIG. **1**, on signal path **166** to program segment **114**, also previously discussed.

The determination by program segment **158**, along with the determinations and analysis performed by program segments **108**, **116**, **122**, **124**, **128**, **134**, **137**, **140**, **148**, and **152**, is deterministic if actuation signals for fan blades 1-8 are generated, and if so, actuation signals are delivered, via signal path **162** to chip/processor I/O stages **164**.

Accordingly, the chip/processor I/O stages **164**, receives sensor signals on signal path $\mathbf{46}_1 \ldots \mathbf{46}_8$, and routes these sensor signals to the program segment **114**, via signal path **166**. The chip/processor **52**, under control of the program segments illustrated in the flow chart **100** of FIG. **4**, either generates or does not generate the actuation signals on signal path **162** that alter the response of fan blades 1-8. The chip/processor I/O stages **164** generates activation signals on signal path $\mathbf{50}_1 \ldots \mathbf{50}_8$ that are routed to the capacitive plate coupler **32**, previously discussed with reference to FIG. **2**. Further, as discussed with reference to FIG. **2**, the capacitive plate coupler **32** routes the actuation signals, via signal path $\mathbf{24}_1 \ldots \mathbf{24}_8$ to the fan blades $\mathbf{16}_1 \ldots \mathbf{16}_8$. Further, as previously discussed with reference to FIGS. **1** and **2**, the sensor signals, originating from fan blades $\mathbf{16}_j \ldots \mathbf{16}_8$, are routed on signal paths $\mathbf{22}_1 \ldots \mathbf{22}_8$ to the capacitive plate coupler **32**, which forwards the sensor signals to the chip/processor I/O stages **164** for processing.

It should now be appreciated that the chip/processor **52** in response to the program segments shown on flow chart **100** provides a sequence of operations for collecting and analyzing input sensors and, in turn, for providing actuating signals to suppress deleterious vibrations that may otherwise be experienced by fan blades $\mathbf{16}_1 \ldots \mathbf{16}_8$ of a turbomachine.

It will be understood that many additional changes in the details, materials, steps and arrangement of parts, which have been herein described and illustrated in order to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the expressed in the appended claims.

What we claim is:

1. A system for suppressing vibrations in at least one fan blade of a turbomachine also having a rotor hub, and being located near a stationary unit, said system comprising:

a) at least one actuator having an input and located on at least one fan blade, said input receiving a signal which causes deformation of said actuator;

b) at least one sensor having an input and an output and located on said at least one fan blade and generating a signal representative of the vibrations occurring on said

at least one fan blade, said output of said sensor providing a signal representative of said vibrations;

c) at least one analog to digital converter located on said rotor hub and receiving said output of said at least one sensor and providing a digital output signal representative thereof;

d) a capacitive plate coupler having first and second stages spaced apart by a first predetermined distance with the first stage being located on said rotor hub and the second stage being located on said stationary unit, said first stage having an input and an output and said second stage having an input and an output, said capacitive plate coupler having its first stage input receiving said output of said at least one analog to digital converter and providing a representative signal thereof at its output of its first stage;

e) at least one digital to analog converter located on said stationary unit and receiving said output of said first stage of said capacitive plate coupler;

f) a processor having operating routines for suppressing vibrations in said at least one fan blade, said processor further having an input and an output, said input of said processor receiving said output of said at least one digital to analog converter located on said stationary unit, said operating routines of said processor providing an output signal to suppress the vibrations of said at least one fan blade;

g) at least one analog to digital converter located on said stationary unit and receiving said output signal of said processor and providing a representative output therefrom that is routed to the input of said second stage of said capacitive plate coupler and providing a representative signal thereof at its output of its second stage;

h) at least one digital to analog converter located on said rotor hub and receiving said output at said second stage of said capacitive plate coupler and providing a representative output thereof that is routed to said input of said at least one actuator located on said fan blade and causing said deformation of said actuator;

i) a power supply located on said stationary unit and having at least one output; and

j) an inductive power transfer apparatus having first and second stages with the first stage thereof located at said stationary unit and the second stage thereof located at said rotor hub, said first and second stages being spaced apart by said first predetermined distance, said first stage of said inductive power transfer element being connected to said output of said power supply and providing a representative output thereof at the second stage of said inductive power transfer element, said second stage being connected to power supplies located on said rotor hub.

2. The system according to claim **1**, further comprising at least one driver interposed between said at least one sensor and said at least one analog to digital converter located on said rotor hub and at least one operational amplifier (OP/AMP) interposed between said at least one digital to analog converter located on said rotor hub and said at least one actuator located on said at least one fan blade.

3. The system according to claim **2**, wherein said at least one fan blade comprises eight (8) fan blades and wherein;

a) said at least one actuator comprises eight (8) actuators one on each of said eight (8) fan blades;

b) said at least one sensor comprises eight sensors one on each of said eight (8) fan blades;

c) said at least one analog to digital converter located on said rotor hub comprises eight (8) said analog to digital converters;

d) said at least one digital to analog converter located on said rotor hub comprises eight (8) digital to analog converters;

e) said at least one operational amplifier (OP/AMP) located on said rotor hub comprises eight (8) operational amplifiers (OP/AMP);

f) said at least one driver located on said rotor hub comprises eight (8) drivers;

g) said at least one digital to analog converter located on said stationary unit comprises eight (8) receivers; and

h) said at least one analog to digital converter located on said stationary unit comprises eight (8) receivers.

4. The system according to claim **3**, wherein said eight (8) actuators and said eight (8) sensors are attached to their respective fan blade.

5. The system according to claim **3**, wherein said eight (8) actuators and said eight (8) sensors are embedded in their respective fan blades.

6. The system according to claim **3**, wherein said actuators operate with the application of voltages within the range of (+) to (−) 200 VDC.

7. The system according to claim **1**, wherein said processor is a chip/processor located on said stationary unit.

8. The system according to claim **1**, wherein said processor is a Personal Computer (PC).

9. The system according to claim **1**, wherein said capacitive plate coupler transfers data signals and said first predetermined distance is about 0.025 to about 0.030 inches, so as to provide a corresponding air gap and wherein said capacitive plate coupler comprises; a first plate and a second plate with the first plate serving as the input stage of said capacitive plate coupler and the second plate serving as the output stage of said capacitive plate coupler, said first plate being attached to said rotor hub and said second plate being attached to said stationary unit, said first plate being rotatable relative to said second plate, said first and second plates being arranged to provide capacitive coupling therebetween.

10. The system according to claim **9**, wherein said first plate is rotatable at a speed of about 1500 rpm.

11. The system according to claim **9**, wherein said capacitive plate coupler provides data transfer in a full-duplex serial communication link protocol.

12. The system according to claim **1**, wherein said inductive power transfer apparatus transfers power signals and comprises first, second, and third inductive elements with said first, inductive elements being spaced apart from said second and third inductive elements by said first predetermined distance of about 0.025 inches so as to provide a corresponding air gap therebetween, said first, said second, and said third elements transferring energy therebetween by means of a inductive linking.

13. The system according to claim **1**, wherein said capacitive plate coupler and said power transfer apparatus are arranged in one assembly with the capacitive plate coupler being further arranged to couple and transfer data signals and the power transfer apparatus being further arranged to transfer power signals.

14. The system according to claim **1**, wherein the routines for suppressing vibrations include transfer functions of LRC (L: inductor, R: resistor, and C: capacitor) employed in damping circuits and that are expressed in S-domain programmable in a digital code.

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