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(54) **FATIGUE TESTING A SAMPLE BY CYCLICAL APPLICATION OF UNIDIRECTIONAL STRESS**

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(57) **ABSTRACT**

A sample having a known mass and stiffness is rigidly secured to an axially elongated beam having a mass and a stiffness that are very large as compared to the mass and stiffness of the sample. The beam is then caused to resonate in the free-free mode. This subjects the sample to cyclical unidirectional stress. Advantageously, resonance of the beam occurs at an audio frequency, permitting severe fatigue tests requiring tens of millions of cycles to be completed in a relatively short time.

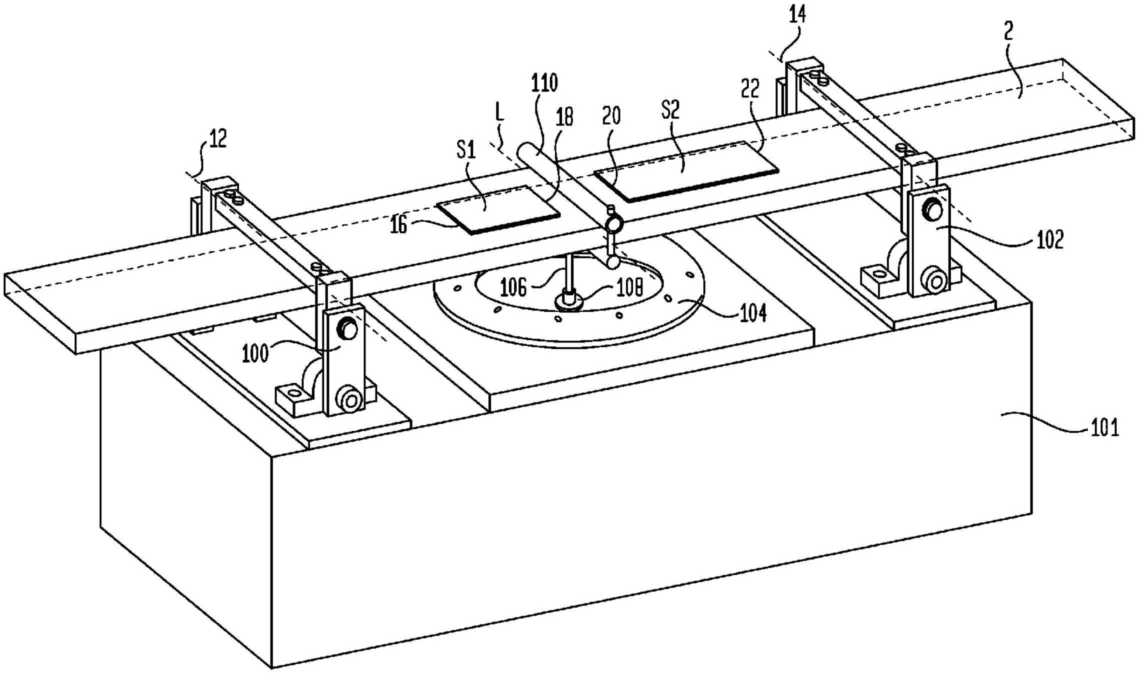


FIG. 1

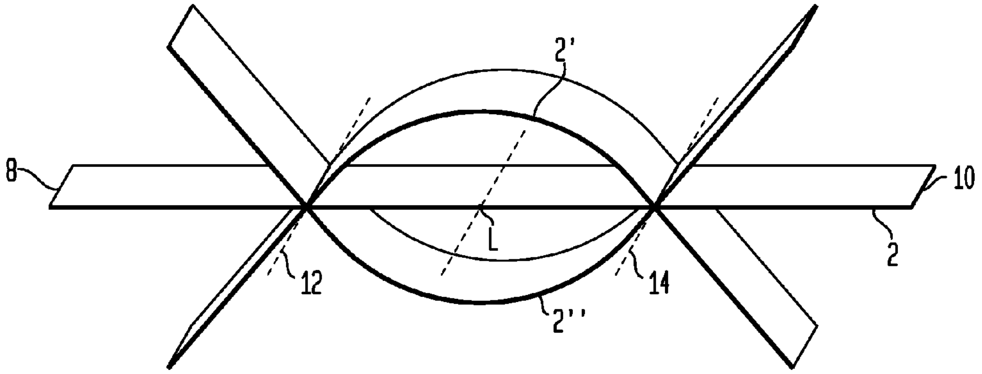


FIG. 2A

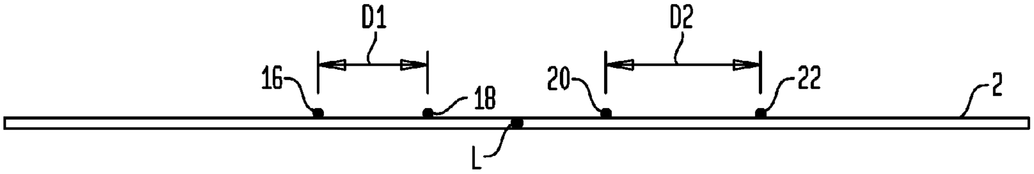
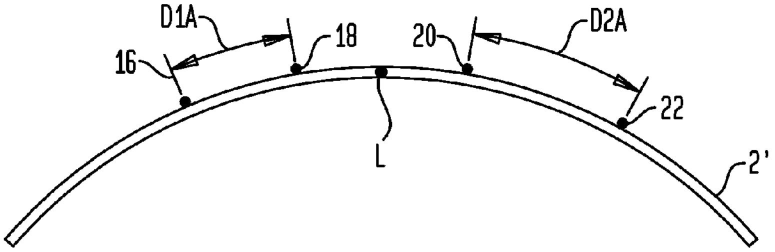


FIG. 2B



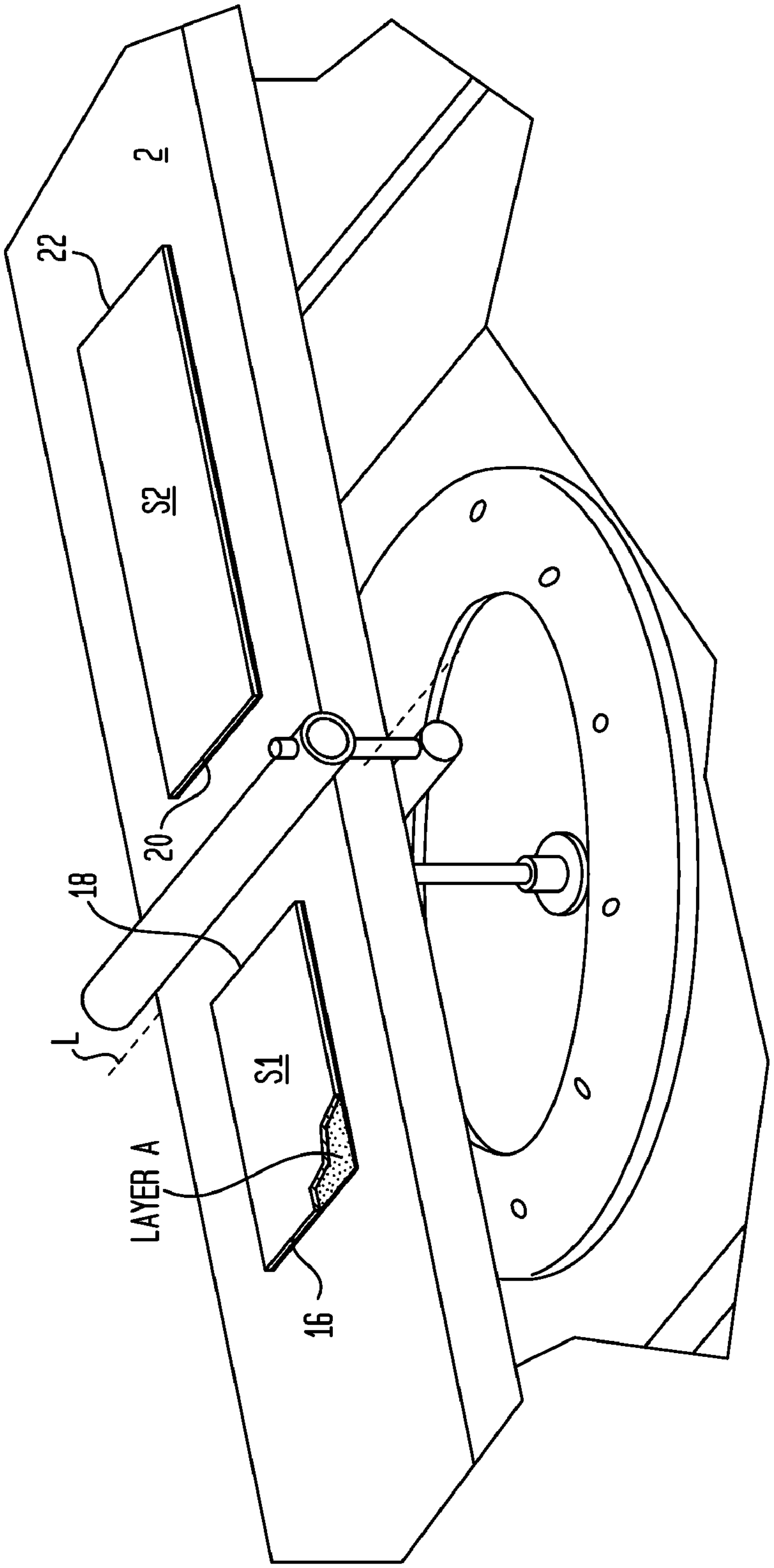


FIG. 3

FIG. 4

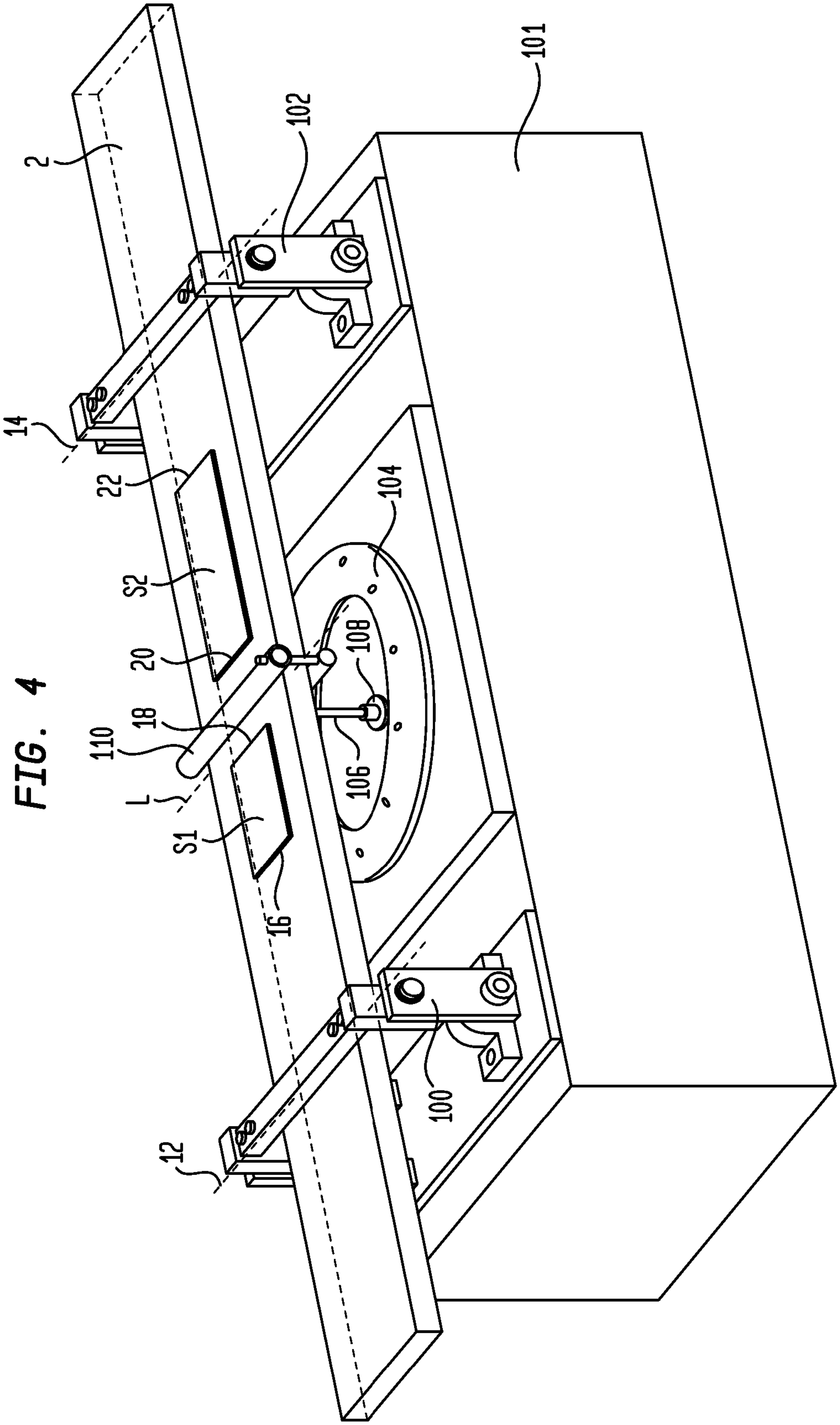


FIG. 5A

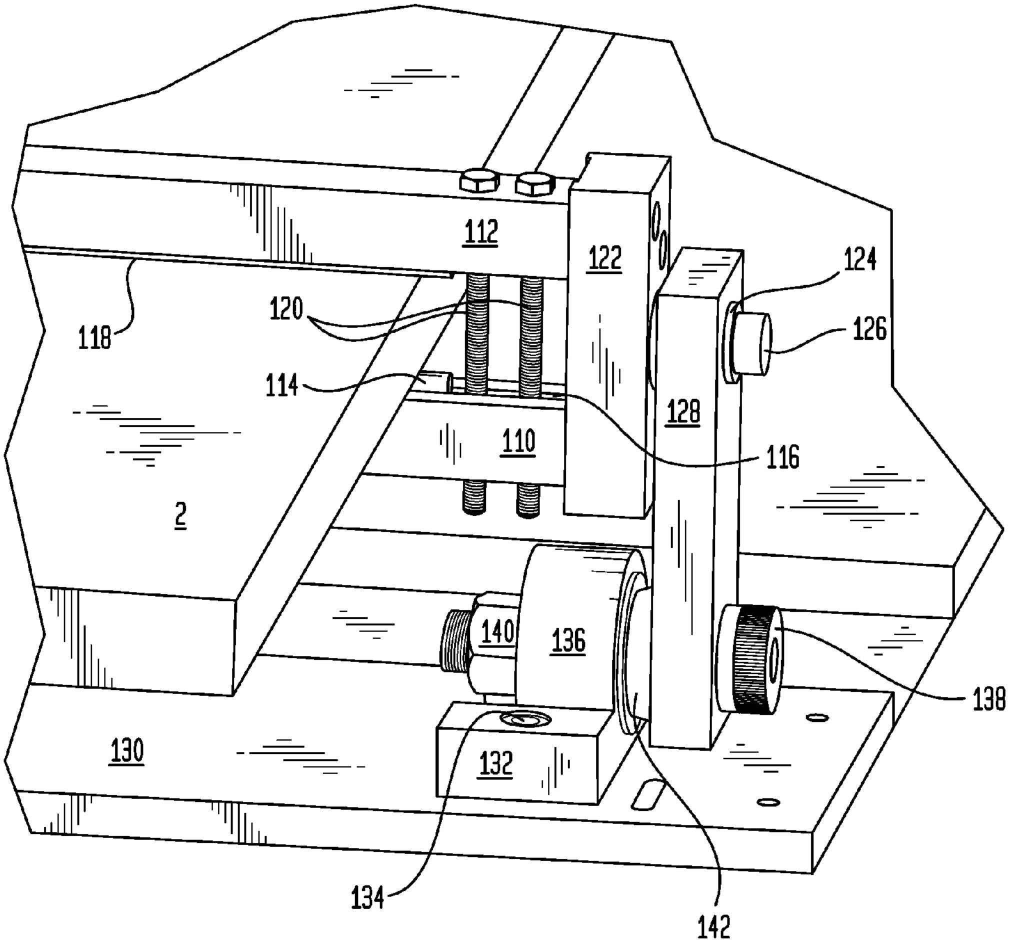
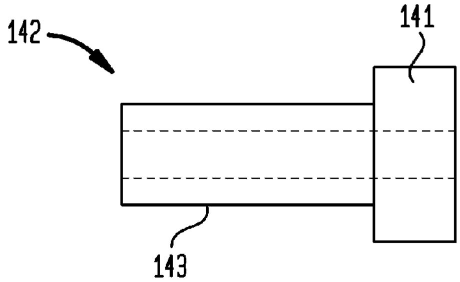

112
122
124
126
120
118
114
128
110
116
2
140
136
138
130
132
134
142

FIG. 5B


142
141
143

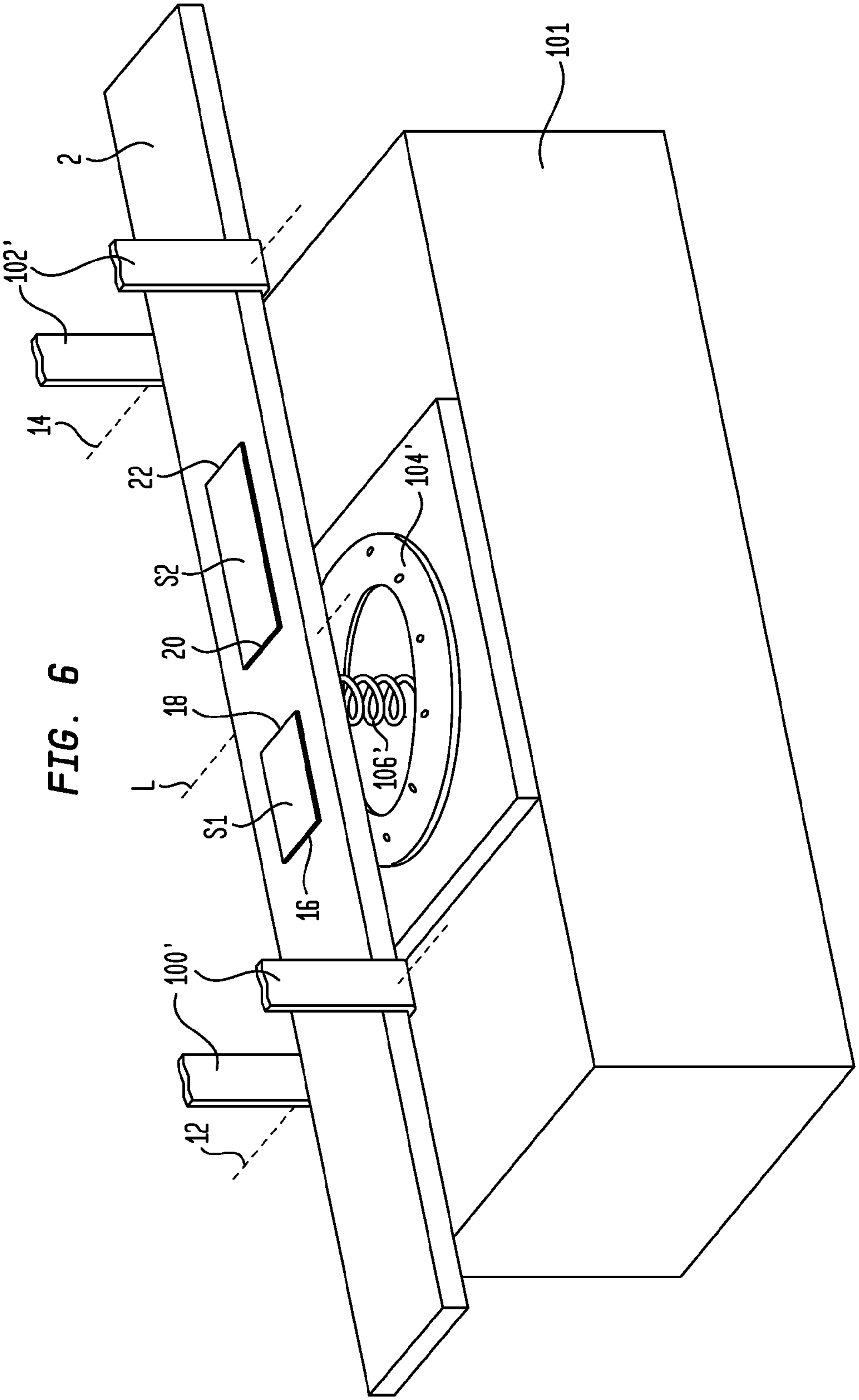


FIG. 6

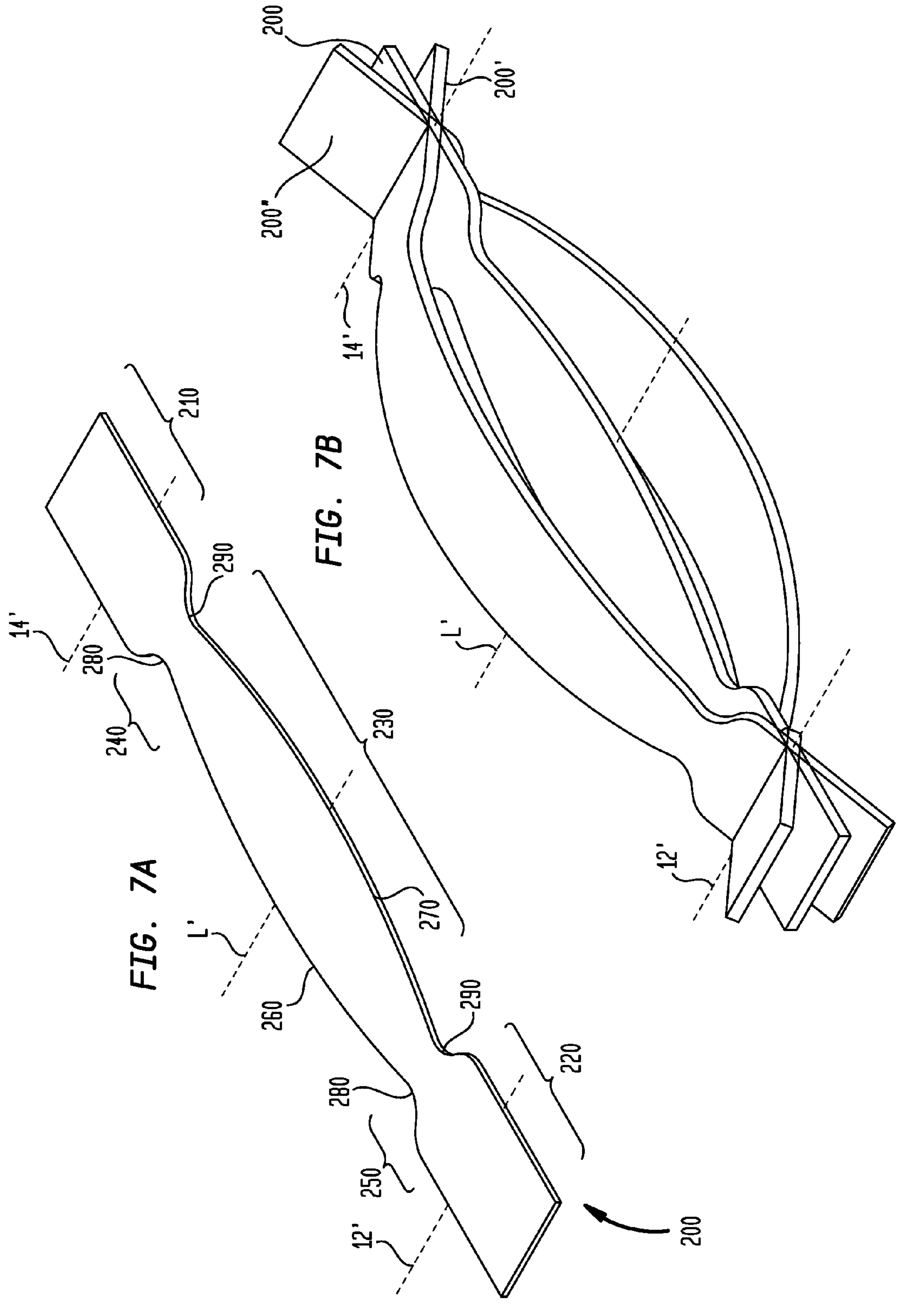

210
290
14'
280
240
230
L'
270
260
290
220
280
250
12'
200
200
200'
200"
14'
L'
12'

FIG. 7A

FIG. 7B

FIG. 8

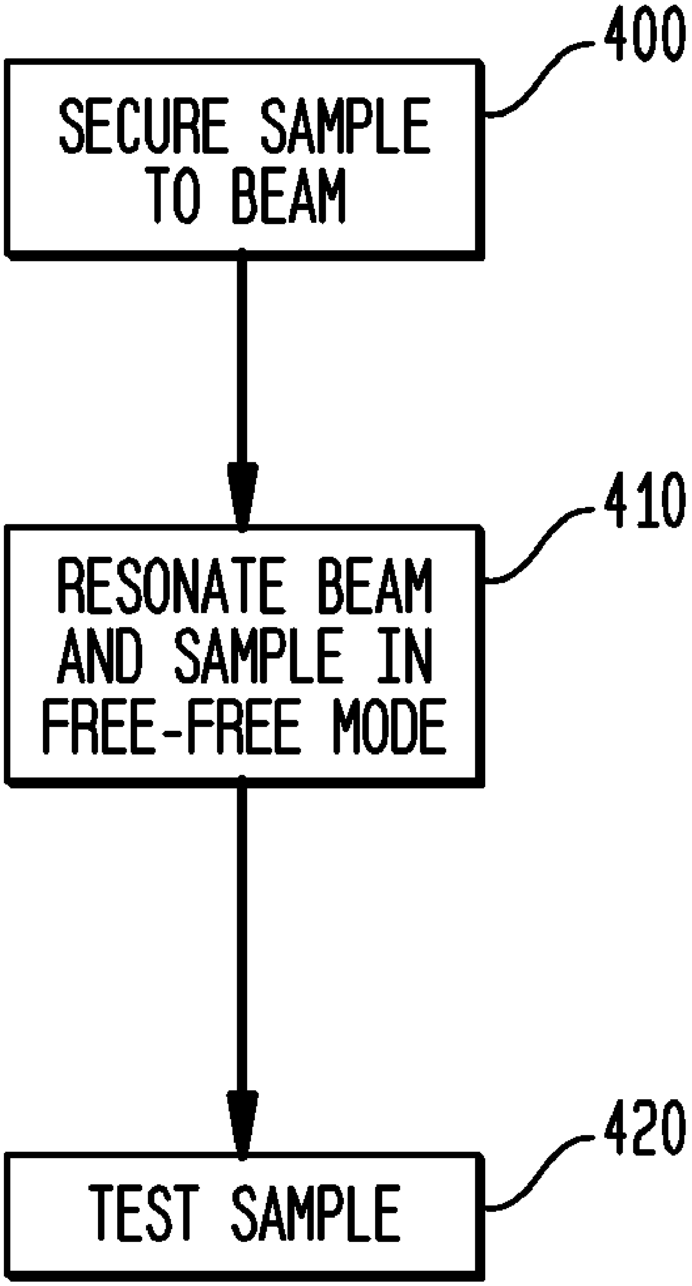

400
SECURE SAMPLE TO BEAM
410
RESONATE BEAM AND SAMPLE IN FREE-FREE MODE
420
TEST SAMPLE

FIG. 9

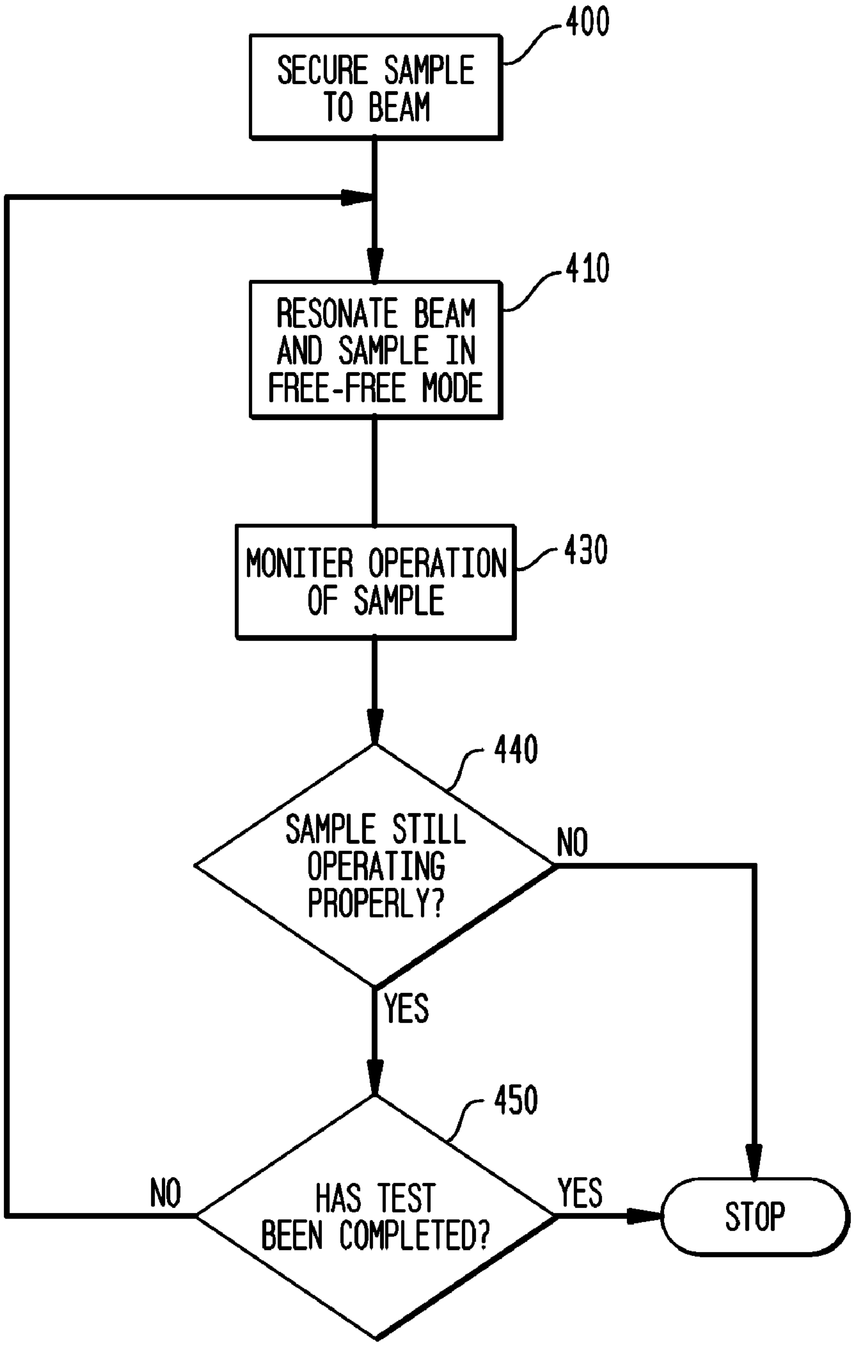

400
SECURE SAMPLE TO BEAM
410
RESONATE BEAM AND SAMPLE IN FREE-FREE MODE
430
MONITER OPERATION OF SAMPLE
440
SAMPLE STILL OPERATING PROPERLY?
NO
YES
450
HAS TEST BEEN COMPLETED?
NO
YES
STOP

FIG. 10A

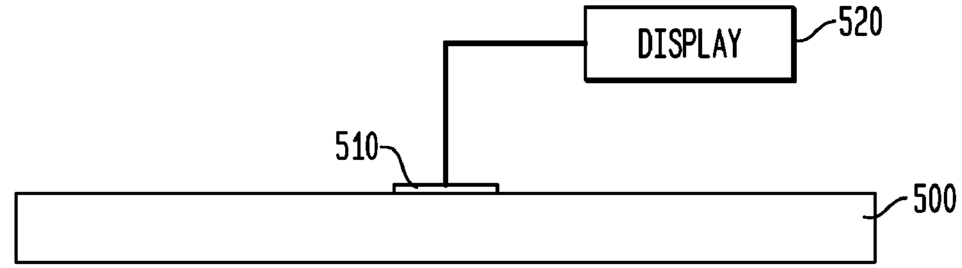


FIG. 10B

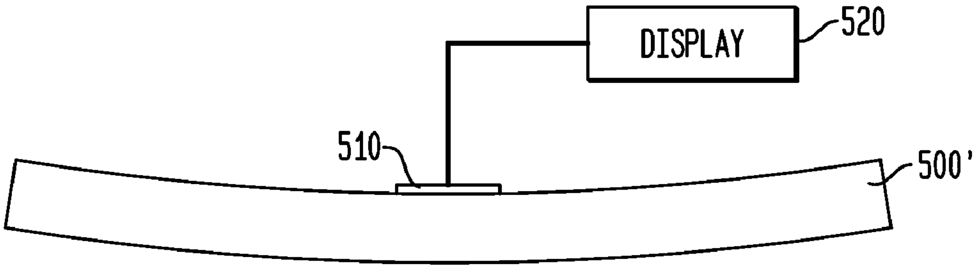


FIG. 10C

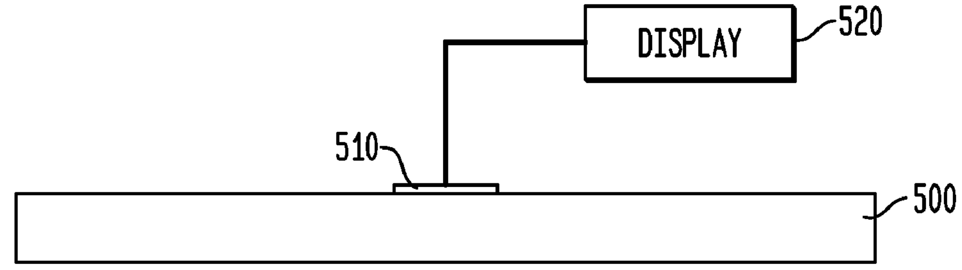


FIG. 11

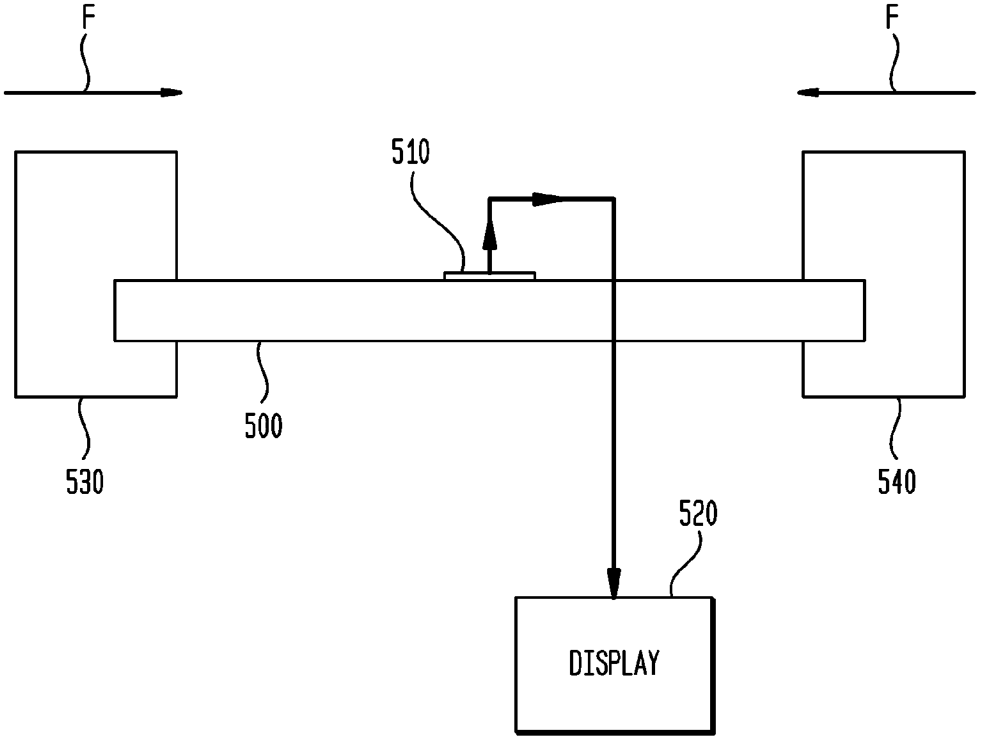


FIG. 12

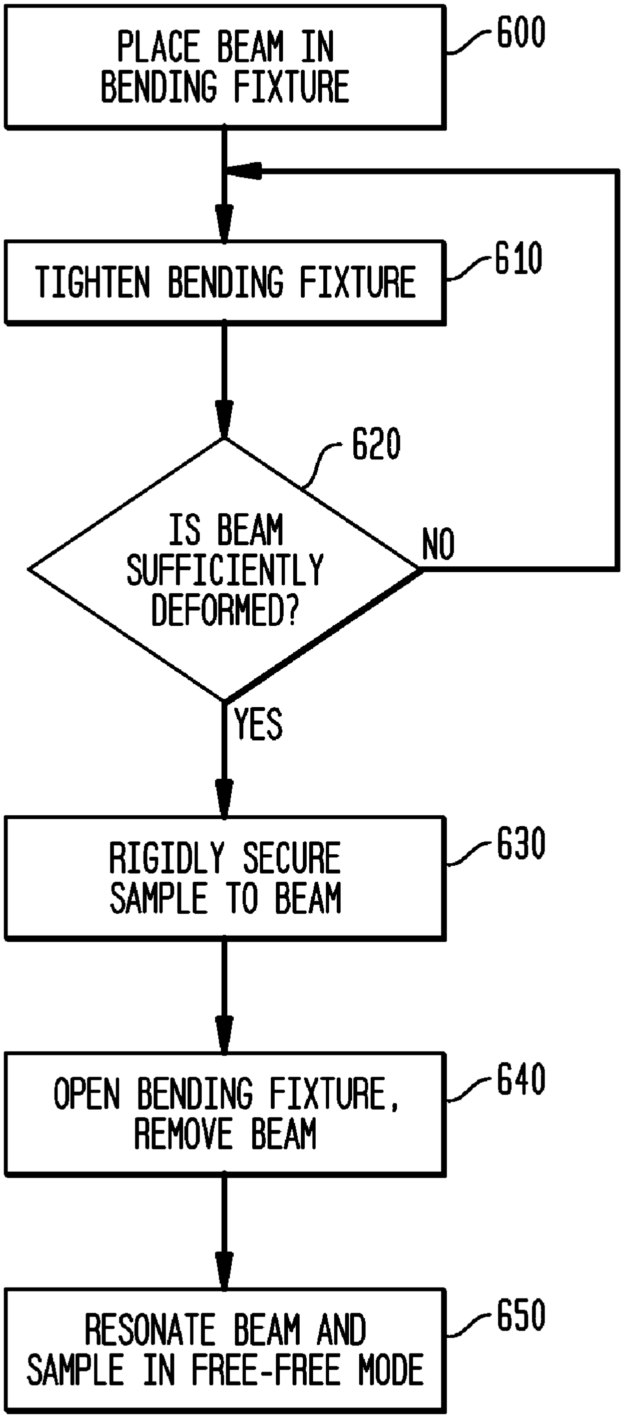
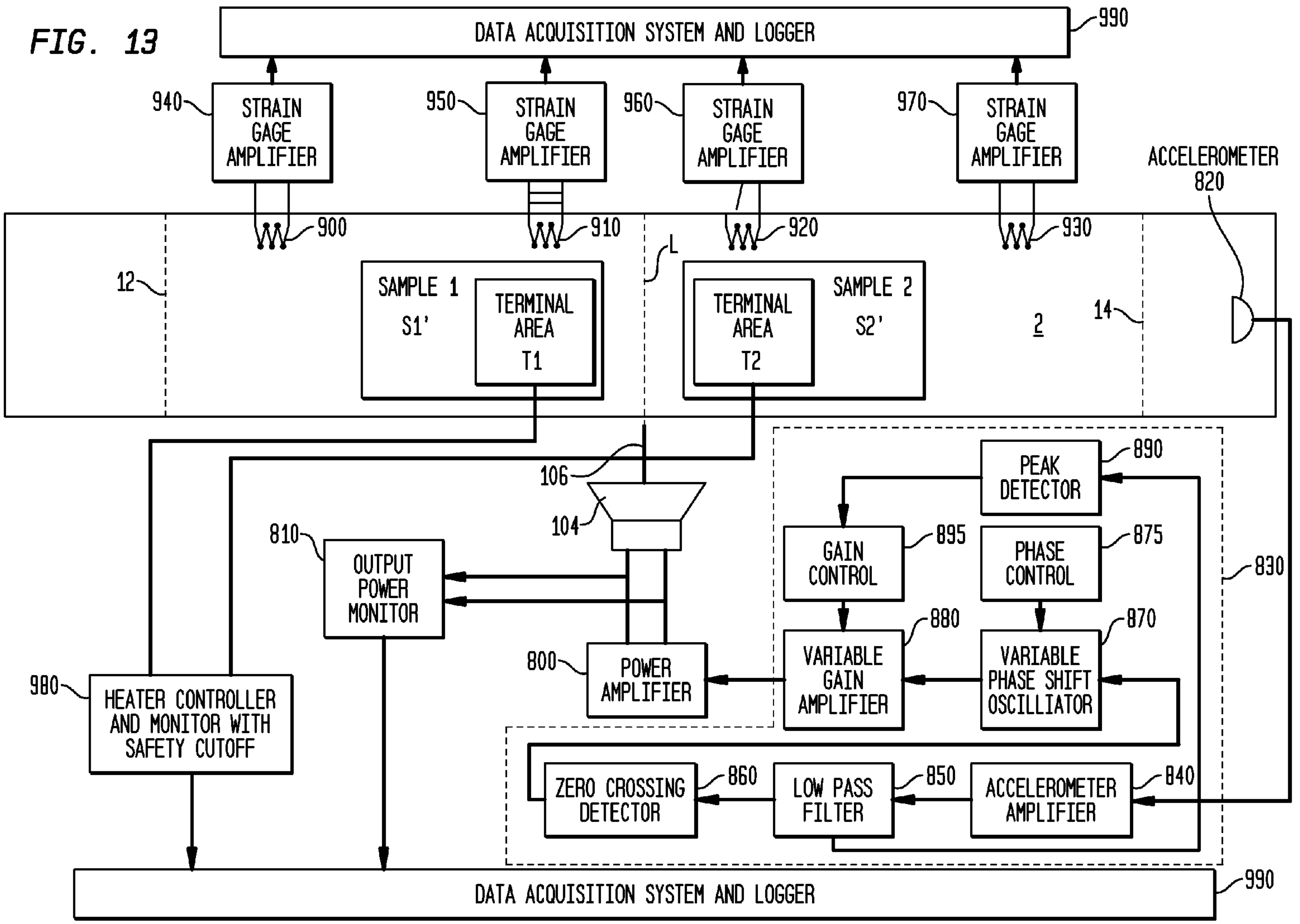

PLACE BEAM IN BENDING FIXTURE
600
TIGHTEN BENDING FIXTURE
610
620
IS BEAM SUFFICIENTLY DEFORMED?
NO
YES
RIGIDLY SECURE SAMPLE TO BEAM
630
OPEN BENDING FIXTURE, REMOVE BEAM
640
RESONATE BEAM AND SAMPLE IN FREE-FREE MODE
650

FIG. 13


DATA ACQUISITION SYSTEM AND LOGGER
990
940
STRAIN GAGE AMPLIFIER
950
STRAIN GAGE AMPLIFIER
960
STRAIN GAGE AMPLIFIER
970
STRAIN GAGE AMPLIFIER
ACCELEROMETER 820
900
910
920
930
12
L
14
SAMPLE 1
S1'
TERMINAL AREA T1
TERMINAL AREA T2
SAMPLE 2
S2'
2
106
104
810
OUTPUT POWER MONITOR
890
PEAK DETECTOR
895
GAIN CONTROL
875
PHASE CONTROL
830
880
VARIABLE GAIN AMPLIFIER
870
VARIABLE PHASE SHIFT OSCILLIATOR
800
POWER AMPLIFIER
980
HEATER CONTROLLER AND MONITOR WITH SAFETY CUTOFF
860
ZERO CROSSING DETECTOR
850
LOW PASS FILTER
840
ACCELEROMETER AMPLIFIER
DATA ACQUISITION SYSTEM AND LOGGER
990

FATIGUE TESTING A SAMPLE BY CYCLICAL APPLICATION OF UNIDIRECTIONAL STRESS

BACKGROUND OF THE INVENTION

[0001] The invention relates to testing apparatus, and more particularly relates to apparatus used to subject samples to fatigue tests. In its most immediate sense, the invention relates to apparatus for fatigue testing a sample by cyclical application of unidirectional stress, thereby causing the sample to undergo cyclical strain.

[0002] A heater for a helicopter rotor blade must be highly strain-resistant. As is set forth in U.S. Pat. No. 4,841,124, a helicopter rotor blade is subject primarily to centrifugal and bending forces. For one particular military helicopter rotor blade that is to be provided with a heater, centrifugal force on the blade (and therefore on the heater, which is fixed to the blade) is assumed to cause a maximum longitudinal strain on the order of 1300 microinches per inch (1300 microstrain). However, bending forces are not constant. Normally, a helicopter blade bends as it advances into the wind during one half of its rotation and as it retreats away from the wind during the other half. For this rotor blade and heater, stress from this bending is assumed to add a cyclic longitudinal strain component of about 1250 microstrain. This cyclic component will have a relatively constant frequency of about 5 Hz (corresponding to the approximately constant 300 rpm at which the helicopter rotor is driven). When these effects are combined, the net effect is an overall unidirectional (here, longitudinally extending) strain on the rotor blade and attached heater, which strain varies cyclically at a rate of approximately 5 Hz between 50 and 2550 microstrain.

[0003] For a mission-critical element such as a heated helicopter rotor blade, reliability is a prime consideration. For this application, the heater must have a proven ability to survive a fatigue test of 80 million cycles. Such a proof can only occur if samples of the heater remain working after they have been stressed (i.e. subjected to a force of deformation) 80 million times.

[0004] Fatigue testing is a well-known technique and equipment is presently manufactured to carry such testing out. However, existing equipment is unsuitable for carrying out such severe fatigue tests. Using conventional materials testing equipment, a fatigue test of 80 million cycles of 1300+/−1250 microstrain might require six months of steady operation. Such a prolonged test is impractical.

[0005] There is a need for method and apparatus for fatigue testing a sample by cyclical application of unidirectional stress.

SUMMARY OF THE INVENTION

[0006] The invention proceeds from the realization that existing fatigue testing is based on an inherently slow methodology. A conventional fatigue testing machine holds the sample between a fixed jaw and a moveable jaw and slowly stretches the sample through a precisely calibrated distance. For such an apparatus to complete 80 million cycles while maintaining appropriate dimensional control must necessarily take an impracticably long time.

[0007] In accordance with the invention, the sample to be tested is rigidly (advantageously but not necessarily, adhesively) secured to an elongated beam (advantageously but not necessarily, a rectangular beam) with a mass and a stiffness that are very large as compared with the mass and stiffness of the sample under test. Then, the beam is deformed. Advantageously, the beam is caused to resonate, and in the preferred embodiment the beam is caused to resonate in a free-free mode, i.e. in a mode wherein the beam is in resonance and supported only at its vibrational nodes.

[0008] Because the sample is rigidly secured to the beam, deformation (strain) of the beam stresses the sample and causes it to experience the same strain that the beam does. By locating the sample appropriately on the beam and selecting the degree to which the beam deforms, the stress applied to the sample, and therefore the degree to which the sample is strained, can be precisely controlled.

[0009] Furthermore, by selecting materials and dimensions appropriate for causing the beam to resonate in the free-free mode, resonance can be caused to occur at an audio frequency, advantageously on the order of 50 Hz. As a result, an 80 million cycle fatigue test can be carried out in less than 20 days instead of the six months required using conventional equipment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The invention will be better understood with reference to the following illustrative and non-limiting drawings, in which:

[0011] FIG. **1** schematically illustrates a thin beam resonating in a free-free mode;

[0012] FIG. **2** schematically illustrates deformation of the center of the beam;

[0013] FIG. **3** schematically illustrates application of unidirectional stress to two samples;

[0014] FIG. **4** schematically illustrates apparatus in accordance with a preferred embodiment of the invention;

[0015] FIG. **5** illustrates one half of a beam support in accordance with a preferred embodiment of the invention;

[0016] FIG. **6** schematically illustrates a second embodiment of the invention in which a spring connects a vibration source to the beam;

[0017] FIG. **7** schematically illustrates an alternate design for the beam and shows the effect of that design on the shape of the beam in resonance;

[0018] FIG. **8** is a flow chart showing a preferred embodiment of a method in accordance with the invention;

[0019] FIG. **9** is a flow chart showing a second preferred embodiment of a method in accordance with the invention;

[0020] FIG. **10** is a schematic illustration of preloading the beam to test a sample at a cyclically applied unidirectional stress having a nonzero average value;

[0021] FIG. **11** is a schematic illustration of apparatus for preloading the beam to test a sample at a cyclically applied unidirectional stress having a nonzero average value;

[0022] FIG. **12** is a flow chart showing a preferred embodiment of a method in accordance with the invention, wherein a sample is tested at a cyclically applied unidirectional stress having a nonzero average value; and

[0023] FIG. **13** is a block diagram of a control system used in accordance with a preferred embodiment of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0024] In the Figures, the same element is always indicated by the same reference numeral. The Figures are not to scale, and details may be enlarged or eliminated for clarity. Corresponding elements in different embodiments are indicated using primed reference numerals.

[0025] FIG. **1** shows an exemplary beam **2** that is long with respect to its width and thickness. In the preferred embodiment, the beam **2** is made of G10 type fiberglass/epoxy laminate and is 72 inches long, 8 inches wide, and 1.25 inches thick, but these features are not necessary; another material with a high strain fatigue limit, and different dimensions, could be used instead.

[0026] Mechanical energy in the form of vibration is supplied to the beam **2** along line L at the center of the beam **2** in order to cause the beam **2** to resonate in its free-free mode. In such resonance, the beam **2** vibrates between the position **2'** and the position **2"**. As can be seen in FIG. **1**, the ends **8** and **10** of the bar **2** are unconstrained, and the bar **2** is almost motionless at nodes **12** and **14**.

[0027] FIG. **2** shows the physical deformation of the beam **2** that occurs about line L when the beam **2** is in resonance in its free-free mode. When the beam **2** is flat (FIG. **2**A), points **16** and **18** are spaced apart from each other by distance D**1**, and points **20** and **22** are spaced apart from each other by distance D**2**. As is shown in FIG. **2**A, the points **16**, **18**, **20** and **22** are located on the upper surface of the beam **2**.

[0028] However, when the beam **2** has reached position **2'** (FIG. **2**B), the upper surface of beam **2** is slightly longer than it was when it was lying flat. With the beam **2** in position **2'**, the distance D**1**A between points **16** and **18** is slightly longer than the distance D**1**, and the same is true for the distance D**2**A between points **20** and **22** with respect to the distance D**2**. When the beam is in position **2"**, the distance D**1**A between points **16** and **18** is slightly shorter than the distance D**1**, and the same is true for the distance D**2**A between points **20** and **22** with respect to the distance D**2**.

[0029] Turning now to FIG. **3**, two samples S**1** and S**2** are rigidly secured to the surface of the beam **2**. (The samples S**1** and S**2** are shown as differently sized. This is because the invention can be used to test a plurality of samples, and the samples need not be identical. However, in practice, a plurality of identical samples will usually be tested simultaneously, since a fatigue test of a single sample may not be statistically sufficient to demonstrate the service life the sample is required to have.) In this example, the samples S**1**, S**2** are attached using a layer of adhesive A, but this is only preferred and other methods could be used instead. (In the preferred embodiment, Hysol EA 956 Epoxy Paste Adhesive was used to attach the samples to the beam, but this is not required and another adhesive could be used instead.) Because the samples S**1**, S**2** are rigidly secured to the beam **2**, the samples S**1** and S**2** are constrained to deform as the beam **2** does. As a result, when the beam **2** is urged from its flat state towards position **2'** by mechanical energy supplied along line L, the bar **2** applies a unidirectional force (stress) to the samples S**1** and S**2**, causing them to elongate (tensile strain). The same thing happens when the beam **2** is urged from its flat state towards position **2"**, producing a compressive strain.

[0030] It may now be understood that when the beam **2** is caused to resonate in its free-free mode with the samples S**1** and S**2** rigidly secured to it, unidirectional (longitudinally-extending) stress is cyclically applied to the samples S**1** and S**2**, causing them to cyclically undergo stretching and contraction.

[0031] While it is greatly preferred for the beam **2** to be brought to resonance, and for the resonance to be in the free-free mode, this is not absolutely essential. The beam **2** need only be deformed and not caused to resonate, and it would alternatively be possible for the beam **2** to a) be supported at one end and caused to vibrate in the manner of a diving board, or b) to be supported at both ends as mechanical energy is supplied to it. By using free-free mode resonance of the beam **2**, the service life of apparatus in accordance with the invention is very long and the apparatus itself becomes not only precisely controllable but also inexpensive.

[0032] Turning now to FIG. **4**, the beam **2** is supported by stands **100** and **102**, which are located at the nodes **12** and **14**. The stands **100** and **102** are themselves supported by a rigid frame **101**. To excite the beam **2** to a state in which it resonates in its free-free mode, mechanical energy in the form of vibration is supplied to it along line L. This occurs using a vibration source **104** (which advantageously but not necessarily is a conventional subwoofer loudspeaker) that is connected to the beam **2** by a rigid link generally indicated by reference numeral **106**. Link **106** advantageously but not necessarily has an enlarged end plate **108** at its lower end and a transversely-extending frame **110** at its upper end. The end plate **108** is bonded to the voice coil of the subwoofer loudspeaker **104** and the frame **110** is advantageously clamped to the beam **2** along the line L. It would alternatively (see below) be possible to use another vibration source such as a shaker head instead of a subwoofer loudspeaker, but the use of a subwoofer loudspeaker has proven to be an inexpensive and effective expedient.

[0033] As a practical matter, the mass and stiffness of the beam **2** should advantageously be very large as compared to the mass and stiffness of all samples (e.g. samples S**1** and S**2**) taken together. The beam **2** should be chosen to be so stiff and heavy that its free-free mode resonance is observed to be largely unaffected by the presence or absence of samples S**1**, S**2** upon it. As stated above, the beam **2** of the here-described preferred embodiment resonates at 52 Hz with no samples mounted upon it, and with samples mounted upon it the resonant frequency of the beam **2** changes by less than 1 Hz. As long as the ratio of mass and stiffness is sufficient, other methods of attaching the fatigue samples to the beam, such as bolting, can be used to conduct fatigue tests.

[0034] The resonant frequency of the beam **2** can be estimated theoretically and then determined more exactly by experiment (advantageously with the samples mounted to it). In this example, the resonant frequency of the beam **2** was approximated using finite element analysis. Then, the subwoofer loudspeaker **104** was driven using a sinusoidal audio signal having the thus-computed resonant frequency and observing the motion of the bar when the frequency of the signal was increased above, and decreased below, that computed frequency. The resonant frequency of the beam **2** is the frequency that produces the maximum amplitude at resonance with power input held constant. (In this example, the estimated resonant frequency of the beam **2** was 50 Hz and the actual resonant frequency of the beam **2** was 52 Hz, and each of the nodes **12** and **14** was located 16.5 inches inwardly of its end of the beam **2**.) Once the resonant frequency of the beam **2** has been determined, the stress applied to the specimens S**1** and S**2** can be adjusted by changing the power used to drive the subwoofer loudspeaker **104**. Increasing the power increases the strain on the beam **2** and thus the stress upon, and resulting strain of, the specimens S**1** and S**2**. Decreasing the power has the opposite effect.

[0035] G10 type fiberglass/epoxy laminate was chosen as the material for the beam **2** because this material has low internal friction and therefore low damping. The beam **2** is advantageously made of a low damping material because the input power required to keep the beam **2** resonating at a given amplitude is determined by the damping characteristics of the beam **2**. By using a material having low damping characteristics, high amplitude resonance of the beam **2** can be obtained with low power input. Additionally, this material has a fatigue-strain limit that is high as compared with the samples that will be tested.

[0036] In a preferred embodiment of apparatus in accordance with the invention, the stands **100** and **102** are identical and are symmetrical about the centerline of the beam **2**. As can be seen in FIG. **5**, each end of each stand **100**, **102** has a transversely extending lower jaw **110** and a transversely extending upper jaw **112**. A lower rod **114** rests in a mating recess **116** in the lower jaw **110**, and an upper rod **118** rests in a like recess (not visible in FIG. **5**) in the upper jaw **112**. Threaded fasteners **120** clamp the rods **114**, **118** tightly against the beam **2**, and the stands **100**, **102** are so located that the rods **114**, **116** are precisely aligned with a corresponding one of the nodes **12**, **14**.

[0037] The jaws **110**, **112** are supported by vertically extending elements **122**. The elements **122** themselves are fixed to centrally located axles **126** that are rotatably supported within bushings **124** in vertical supports **128**.

[0038] Each of the vertical supports **128** has a hole at the bottom. A bolt **138** passes through each such hole. Each bolt **138** passes through a resilient bushing **142**. Bushing **142** has an enlarged exterior head **141** and a cylindrical body **143**; the body is located in the central cavity of a flange **136** and the head **141** is located between the vertical support **128** and the flange **136**. The flange **136** is part of a unitary component that is bolted to a baseplate **130** by bolt **134**. A nut **140** is threaded to the end of the bolt **138**. The nut **140** bears tightly against the cylindrical body of the bushing **142** and the bolt **138** bears tightly against the vertical support **128**, whereby the vertical support **128** is held tightly against the bushing **142**. The baseplate **130** is attached to the frame **101**. It will be understood that by this mechanism, the stands **100** and **102** are fixed at their bottom ends to the frame **101** and at their top ends to the beam **2**.

[0039] The operation of each of the stands **100**, **102** will now be described. When in resonance, the beam **2** is not motionless at nodes **12** and **14**. The beam **2** rotates slightly about nodes **12** and **14** and that rotation is accommodated by the rotational support of the axles **126** within the bushings **124**. Furthermore, as the beam **2** oscillates in resonance between the positions **2'** and **2"**, the axles **126** at nodes **12** and **14** move slightly in the horizontal direction. To increase the service life of the beam **2**, this horizontal motion of the axles **126** should be accommodated; if such accommodation is lacking, the excessive constraint on motion of the beam **2** will accelerate the time in which it fails in fatigue.

[0040] This accommodation is accomplished by the bushings **142** of the stands **100**, **102**. No bolt **138** is directly attached to its corresponding flange **136**; each bolt **138** rather rests within, and is attached to, its corresponding bushing **142**. Because each bushing **142** is resilient, each bushing **142** absorbs the horizontal motion of the beam **2** by allowing vertical support **128** to rotate slightly.

[0041] In an overall sense, the function of the stands **100**, **102** is to support the beam **2** without exerting any significant resistance to its motion. An alternate structure for doing this is illustrated in FIG. **6**. Here, the vibration source **104'** is a vibration head, and vibration from the vibration head **104'** is transmitted to the beam **2** by a spring **106'**. Rubber straps **100'** and **102'** support the beam **2** from an overhead support structure (not shown). This structure is presently not preferred. This is because the spring **106'** is subject to fatigue failure whereas the link **106** is not, and the spring **106'** introduces additional undesirable resonances into the control system.

[0042] FIG. **7** schematically illustrates an alternate structure for the beam **2**. Beam **200** is rectangular as viewed from the side, but as viewed from the top it has two rectangular end regions **210** and **220**, a parabolically shaped central region **230**, and transition regions **240** and **250** that connect the ends of the central region **230** to the end regions **210** and **220** respectively.

[0043] The central region has sides **260** and **270** in the shape of parabolas (as viewed from the top of the beam **200**) and transition regions **240**, **250** have sides **280** and **290** in the shape of ellipses (likewise as viewed from the top of the beam **200**). The reasons for these shapes are discussed below.

[0044] In contrast to the beam **2**, which has a uniform stiffness along its length, the stiffness of the beam **200** is nonuniform. All else being equal, it is easier to deform a narrower component than a wider one. It may therefore be understood that the stiffness of the beam **200** at any point along its length is determined by its width at that point (the beam **200**, like the beam **2**, is of material(s) having an invariant stiffness). Wider regions of the beam **200** are stiffer than narrower regions.

[0045] The effect of the parabolic shape of the sides **260** and **270** on the behavior of the beam **200** may now be understood. When a vibration source (not shown) is linked to the beam **200** at line L' and causes the beam **200** to resonate in its free-free mode, narrower regions of the beam **200** deform more than wider regions. The parabolic shapes of the sides **260**, **270** are dimensioned such that strain (i.e. deformation) of the central region **230** is substantially the same at all points on its surface. Thus, when the beam **200** is induced to resonate in its free-free mode, many samples can be identically fatigue-tested simultaneously by adhesively securing them all over the central region **230**. This is different from the behavior of the beam **2**. In the beam **2**, strain of the surface varies with position; maximum strain (and therefore maximum stress on a test specimen) occurs in the center of the beam **2** at the line L because that is where minimum bend radius of the beam **2** occurs. As distance from the line L increases, surface strain diminishes.

[0046] The sides **280**, **290** of the transition regions **240**, **250** have elliptical shapes because this will increase the service life of the beam **200**. At the ends of the central region **230**, the strain of the beam **200** is nonzero. The elliptical shape of the sides **280**, **290** serves to smooth the transition to the rectangular sections **210** and **220**. Without such smoothing, abrupt variations in internal stress of the beam **200** would eventually cause the beam **200** to fail in fatigue.

[0047] Although the stiffness of the beam **200** is made to be nonuniform by suitably choosing the shape of the beam **200**, this is only for convenience and is not necessary. It would alternatively be possible to make the beam **200** nonuniformly stiff by varying its composition or its thickness.

[0048] A preferred embodiment of a method in accordance with the invention is shown in FIG. **8**. In step **400**, a sample having a known mass and a known stiffness is rigidly secured to an axially elongated beam having a mass and a stiffness that are very large as compared with the mass and stiffness of the sample. Then, in step **410**, the beam is caused to resonate in the free-free mode. This resonance is continued for the time required to subject the sample to the required number of unidirectional stress cycles, and in step **420** the sample is tested to see if it has failed in fatigue.

[0049] Alternatively, as shown in FIG. **9**, in step **430** operation of the sample is monitored while the beam is resonating. This is possible if the sample has an electrical characteristic (e.g. resistance) that can be measured, or if the characteristics of the sample can be otherwise ascertained (as by monitoring heat generated by the sample). (The method by which operation of the sample is monitored is not part of the invention.) In step **440**, it is determined whether the sample is continuing to operate as required. If not, the sample has failed in fatigue and the test is stopped. If the sample is continuing to operate as required, it is then determined in step **450** whether the test has continued for the required time. If so, the sample has passed the test and the test is stopped. If not, the test is continued.

[0050] The monitoring of the operation of the sample may be carried out continuously or at intervals; this is not a part of the invention.

[0051] The above-described method subjects the sample to an average stress of zero. This is because the beam is undeformed when the sample is attached to it, and each unidirectional stress cycle therefore starts from zero, reaches a maximum elongation, passes through zero to reach a maximum compression in the opposite direction, and then reaches zero at the end of the cycle. However, as stated above, a heater for a helicopter rotor blade is assumed to be subjected to a superposition of a) a constant strain caused by centrifugal force and b) a cyclical strain caused by bending forces. Thus, a fatigue test of a helicopter rotor blade heater carried out under conditions of zero average stress would not reflect the conditions under which the heater would actually be used. It would therefore be advantageous to be able to carry out a fatigue test under conditions wherein the average stress was nonzero.

[0052] To do this, a method schematically illustrated in FIGS. **10** and **12** is carried out. As is shown in FIG. **10**A, an initially flat beam **500** of an appropriate type has a strain gauge **510** attached at the center of its top surface. The beam **500** is subjected to forces that cause it to bow downward (FIG. **10**B) until the negative of the desired average strain is read out upon display **520**. (FIG. **10**B shows the beam **500** in a substantially bowed configuration **500'**; in practice, the beam **500** is usually so slightly bowed as to appear flat to the naked eye and FIG. **10**B is exaggerated for clarity.) Then, while the beam **500** is in the bowed state illustrated in FIG. **10**B, the sample (not shown) is rigidly secured to the top surface of the beam **500** (as by using adhesive that is then allowed to cure). Once this has been accomplished, the forces acting upon the beam **500** are released, allowing the beam **500** to return to its original unbowed state as shown in FIG. **10**C.

[0053] By attaching the sample to the beam **500** when the beam **500** is bowed in this manner, the sample will be subjected to tensile stress (and therefore strained in tension, i.e. stretched out) when the beam **500** flattens out. In this way, the sample is pre-stressed to the intended degree before testing begins. Thus, when the beam **500** is then caused to resonate in the free-free mode, a steady stress in the desired amount will be superimposed on the cyclical stress produced by resonance of the beam **500**.

[0054] The apparatus schematically shown in FIG. **11** may be used to accomplish the method schematically illustrated in FIG. **10**. The beam **500** is held between two jaws **530** and **540** of a bending fixture. The jaws **530**, **540** can be pushed toward each other by an appropriate mechanism (not shown), thereby exerting axially-directed forces of compression F, which squeeze the ends of the beam **500** toward each other and cause the beam **500** to bow downward. The strain gauge **510** is mounted to the beam **500**, and is connected to the display **520** on which the strain measured by the strain gauge **510** can be read out.

[0055] Turning now to FIG. **12**, after the beam **500** has been placed in the bending fixture (step **600**), the bending fixture is progressively tightened (step **610**). Tightening continues until the negative of the desired average strain is read out on display **520** (step **620**). Then, in step **630**, with the beam **500** bowed, the sample is rigidly secured to the beam **500** (as by adhesive). After step **630** has been accomplished, in step **640** the bending fixture is opened up, thereby releasing the axially directed forces of compression on the beam **500**. The beam **500** and attached sample may then be resonated in the free-free mode.

[0056] Turning now to FIG. **13**, identical samples **S1'** and **S2'** are adhesively secured to beam **2**, which is supported along nodes **12** and **14** by stands **100**, **102** (not shown in this Figure). A subwoofer loudspeaker **104** is attached to the beam **2** at line L by link **106** as has been described above.

[0057] The control system of apparatus in accordance with a preferred embodiment of the invention is set up to conduct a fatigue test of the samples S1' and S2' in such a way as to minimize fatigue of the beam **2**. This is done by resonating the beam **2** in the free-free mode at its resonant frequency and at an appropriate amplitude, but driving the subwoofer loudspeaker **104** at a minimum power output from power amplifier **800** as measured by the output power monitor **810**, thereby transferring minimum mechanical energy to the beam **2** via the link **106**.

[0058] To do this, an accelerometer **820** is mounted adjacent one end of the beam **2** and is connected to control circuitry **830**, which is used to control the power output from the power amplifier **800**. The output from the accelerometer **820** is amplified in amplifier **840** and the output of the amplifier **840** is routed to a low-pass filter **850**. As stated above, the resonant frequency of the beam **2** is 52 Hz and the low-pass filter **850** filters out higher harmonics (those with frequencies above approximately 60-70 Hz) to avoid improper triggering of subsequent circuitry. One output of the low-pass filter **850** is connected to a zero-crossing detector **860**, and another output of the low-pass filter **850** is connected to a peak detector **890**.

[0059] The zero-crossing detector **860** produces a signal when the acceleration of the end of the beam **2** is zero (as measured by the output of the accelerometer **820**) i.e. when the beam **2** is flat, and the peak detector **890** produces a signal representing the maximum acceleration of the beam **2** as measured by the accelerometer **820**. Thus, the signal from the zero-crossing detector **860** represents the phase of oscillation of the beam **2**, and the signal produced by the peak detector **890** represents the maximum acceleration of the end of the beam **2**, which is related to the maximum displacement of the end of the beam **2**.

[0060] The output of the zero-crossing detector **860** is input to a variable phase-shift oscillator **870**, which produces a sine wave in the audio range (in this example, in a frequency window that includes 52 Hz). The variable phase-shift oscillator **870** is also connected to a phase control **875**. The output of the peak detector **890** is then routed through a gain control **895** to be input to a variable gain amplifier **880**, which amplifies the output of the variable phase-shift oscillator **870** and directs the amplified output to the power amplifier **800**.

[0061] The operation of the control circuitry **830** will now be described. First, the circuitry is energized and the frequency of the variable phase-shift oscillator **870** is adjusted until the beam **2** is in resonance. The resonance of the beam **2** occurs at that frequency that maximizes the displacement of the end of the beam **2**, so as a practical matter the frequency of the audio sine wave from the variable phase-shift oscillator **870** is tuned to maximize the signal from the peak detector **890**. As stated above, in this example the resonant frequency of the beam **2** was initially computed to be 50 Hz but was actually determined to be 52 Hz with samples S**1**' and S**2**' mounted upon it.

[0062] Next, the phase of the audio sine wave from the variable phase-shift oscillator **870** is varied by adjusting the phase control **875**. It will be recalled that the signal from the zero-crossing detector **860** represents the phase of oscillation of the beam **2**. Adjustment of the phase control **875** causes the phase of the sine wave output from the variable phase-shift oscillator **870** to be advanced or retarded relative to the phase of oscillation of the beam **2**. It has been experimentally determined that by appropriately shifting the phase of the signal from the variable phase-shift oscillator **870** relative to the phase of oscillation of the beam **2**, the power produced by the power amplifier **800** can be minimized without reducing the amplitude of oscillation at the end of the beam **2**. Thus, once the beam **2** has been caused to resonate, the phase control **875** is adjusted to minimize the output from the power amplifier **800** as measured by the output power monitor **810**. As a result, resonance of the beam **2** is maintained even when only a minimum quantity of mechanical energy is transferred to the beam **2**. This produces the minimum possible wear on the beam **2** and prolongs its service life.

[0063] Once the beam **2** has been brought to resonance using minimum power from the power amplifier **800**, the amplitude of the oscillation of the beam **2** is adjusted to produce the desired cyclic stress on the samples S**1**' and S**2**'. This is done by adjusting the gain control **895**, which causes the output of the variable gain amplifier **880** (and thus the output from the power amplifier **800**) to increase (increasing the amplitude of oscillation of the beam **2**) or to decrease (decreasing the amplitude of oscillation of the beam **3**). Strain gauges **900**, **910**, **920**, and **930** are mounted to the beam **2** and are connected via strain gauge amplifiers **940**, **950**, **960**, and **970** to a data acquisition system **990**, and the gain control **895** is adjusted until the amplitude of the cyclic stress applied to samples S**1**' and S**2**' produces appropriate strain of the beam **2** as measured by the strain gauges **900**, **910**, **920**, and **930**.

[0064] In this example, the samples S**1**' and S**2**' are electrical heaters supplied with power at terminal areas T**1** and T**2** respectively. A controller **980** controls power to the samples S**1**' and S**2**' and the operation of the samples S**1**' and S**2**' is monitored by the data acquisition system **990**.

[0065] When either or both of the samples S**1**' and S**2**' fail in fatigue, it (or they) short-circuits and overheats. This can cause a fire. For this reason, infra-red detectors (not shown) are mounted on a frame (also not shown) above the samples S**1**' and S**2**' and are connected to the controller **990**. When a sample S**1**' or S**2** overheats as a result of a fatigue failure, the controller **980** shuts off the power to that sample to avoid causing a fire.

[0066] The controller **980** and above-described infra-red detectors are not part of the invention. They are provided only because the samples S**1**' and S**2**' are electrical heaters.

[0067] Although at least one preferred embodiment of the invention has been described above, this description is not limiting and is only exemplary. The scope of the invention is defined only by the claims, which follow:

1. An apparatus for fatigue testing a sample by cyclical application of unidirectional stress, the sample having a known mass and a known stiffness, the apparatus comprising:
an axially elongated beam having a mass and a stiffness that are very large as compared to the known mass and stiffness of the sample;
means for rigidly securing the sample to the beam; and
means for deforming the beam.

2. The apparatus of claim **1**, wherein the means for deforming the beam comprises means for causing the beam to resonate.

3. The apparatus of claim **2**, wherein the means for causing the beam to resonate comprises means for causing the beam to resonate in a free-free mode.

4. The apparatus of claim **1**, wherein the beam has a uniform stiffness.

5. The apparatus of claim **1**, wherein the beam has a non-uniform stiffness.

6. The apparatus of claim **1**, wherein the beam is rectangular.

7. The apparatus of claim **1**, wherein the beam has a central region having parabolically shaped sides.

8. The apparatus of claim **1**, wherein said means for rigidly securing is adhesive.

9. The apparatus of claim **1**, wherein said means for deforming the beam comprises a vibration source and a spring, the spring connecting the beam to the vibration source.

10. The apparatus of claim **1**, wherein said means for deforming the beam comprises a vibration source and a rigid element connecting the beam to the vibration source.

11. The apparatus of claim **10**, wherein the vibration source is a subwoofer loudspeaker.

12. The apparatus of claim **1**, wherein the means for deforming the beam comprises means for supporting the bar at its resonant nodes.

13. The apparatus of claim **10**, further comprising:
means for providing energy to the vibration source; and
means for minimizing energy consumed by the vibration source when the beam is resonating in a free-free mode.

14. The apparatus of claim **13**, wherein:
the vibration source is an electromechanical transducer;
the means for providing energy comprises an oscillator operating at an audio frequency; and
the means for minimizing energy comprises means for phase-shifting the output of the oscillator.

15. A method for fatigue testing a sample by cyclical application of unidirectional stress, the sample having a known mass and a known stiffness, the method comprising the following steps:
rigidly securing the sample to an axially elongated beam having a mass and a stiffness that are very large as compared to the known mass and stiffness of the sample; and
deforming the beam.

16. The method of claim **15**, wherein the step of deforming the beam comprises the step of causing the beam to resonate.

17. The method of claim **16**, wherein the step of causing the beam to resonate comprises the step of causing the beam to resonate in the free-free mode.

18. The method of claim **13**, further comprising the steps of:

deforming the beam before said rigidly securing step; and

allowing the beam to assume its undeformed state after said rigidly securing step and before the step of deforming the beam.

19. A method for fatigue testing a sample by cyclical application of unidirectional stress having a nonzero average value, the sample having a known mass and a known stiffness, comprising the following steps performed in order:

obtaining an axially elongated beam having a mass and a stiffness that are very large as compared to the known mass and stiffness of the sample;

applying deforming the beam;

rigidly securing the sample to the deformed beam;

allowing the beam to resume its undeformed state; and

causing the beam to resonate in a free-free mode.

20. The method of claim **19**, wherein the step of deforming the beam is carried out until the measured strain of the beam is the negative of the desired average strain.

21. An apparatus for fatigue testing a sample by cyclical application of unidirectional stress, the sample having a known mass and a known stiffness, the apparatus comprising:

an axially elongated beam having a mass and a stiffness that are very large as compared to the known mass and stiffness of the sample;

means for rigidly securing the sample to the beam; and

means for causing the beam to resonate in a free-free mode.

22. A method for fatigue testing a sample by cyclical application of unidirectional stress, the sample having a known mass and a known stiffness, the method comprising the following steps:

rigidly securing the sample to an axially elongated beam having a mass and a stiffness that are very large as compared to the known mass and stiffness of the sample; and

causing the beam to resonate in a free-free mode.

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