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(54) **FIBEROPTIC CLEARANCE DETECTION METHOD AND OPTICAL FIBER PROBE USED THEREIN**

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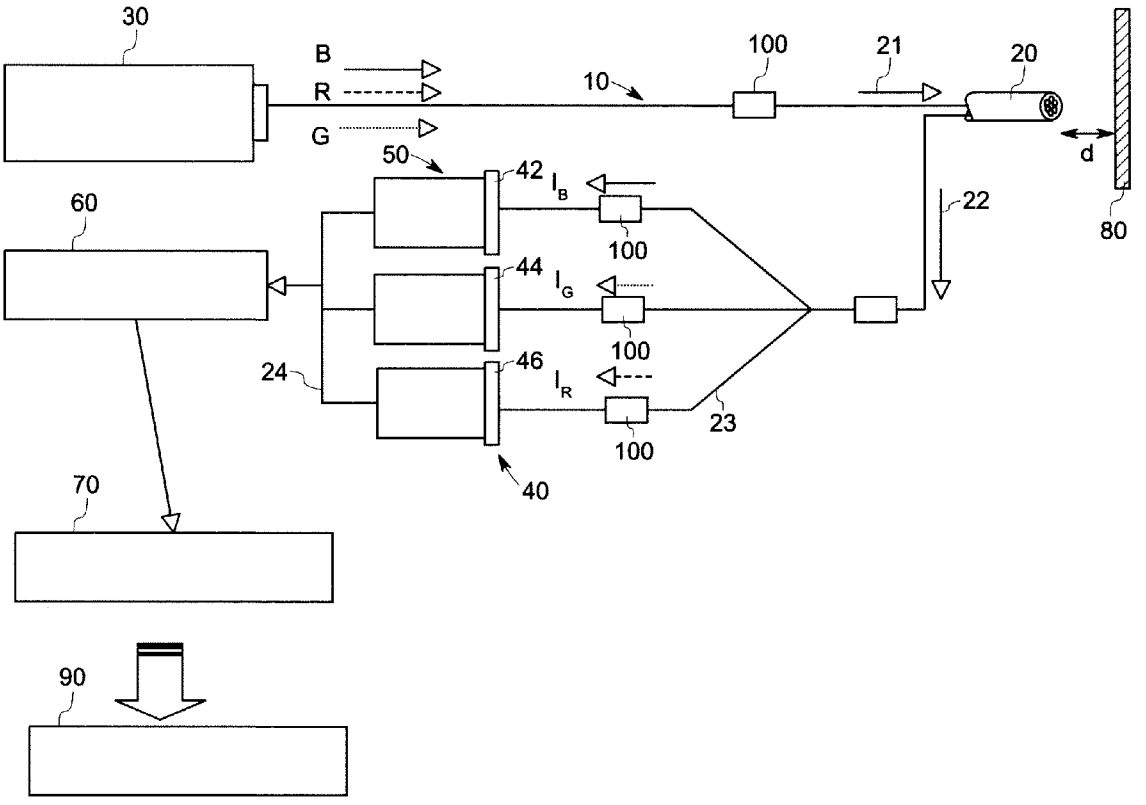
(57) **ABSTRACT**

A method includes transmitting light through at least one transmission optical fiber towards a target, receiving light reflected from the target through at least one signal optical fiber, filtering the received light at least two different wavelengths, and using the filtered light to detect a clearance variation. An optical fiber probe includes a plurality of optical fibers, a moisture-resistant enclosure enclosing the optical fibers, a hydrophobic layer situated over an end of the optical fiber probe for preventing moisture from reaching the optical fibers, and a broadband transmission layer between ends of the optical fibers and the hydrophobic layer.



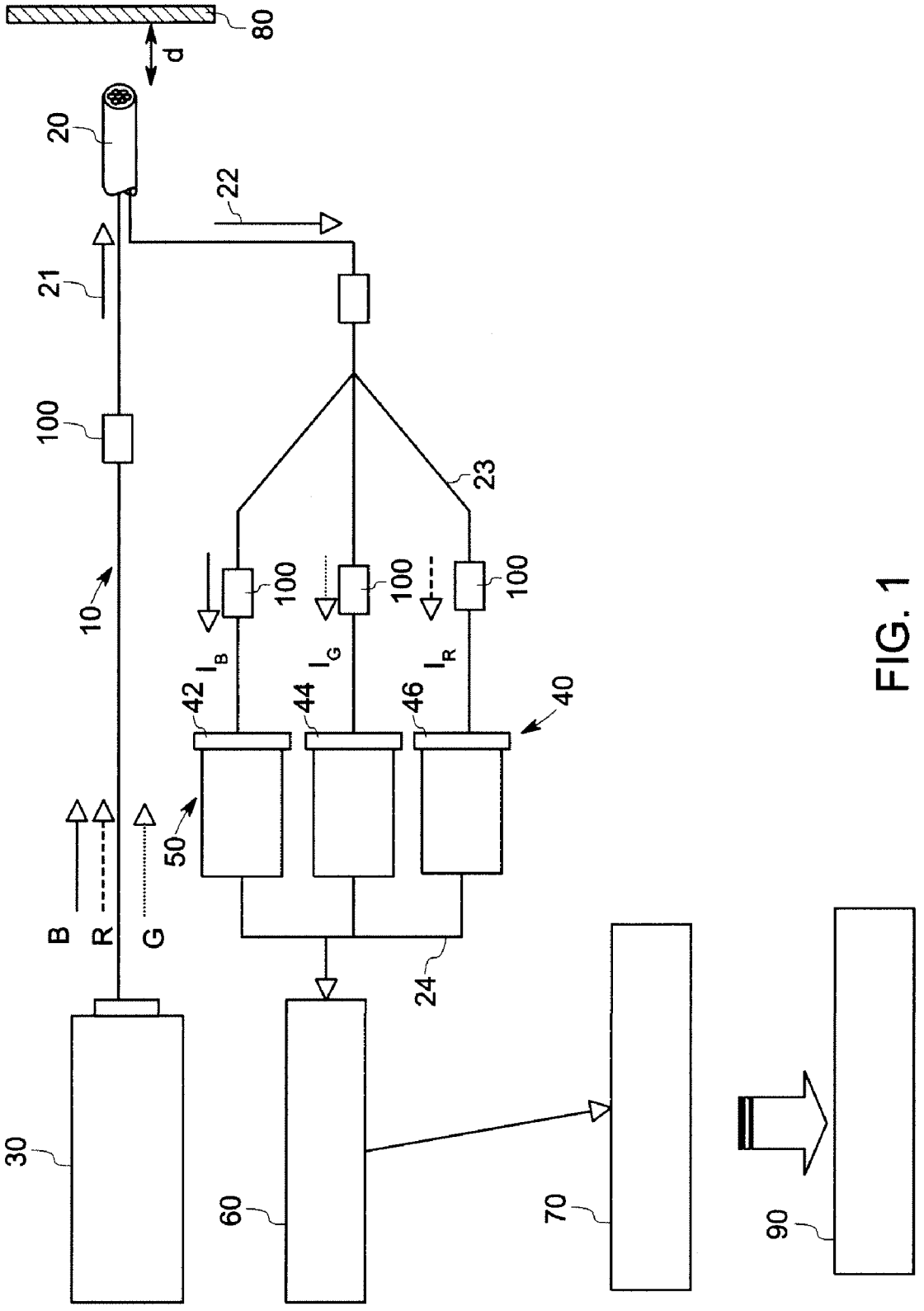

80
d
20
22
21
100
23
10
100
100
100
I_B
I_G
I_R
42
44
46
40
50
B
R
G
24
30
60
70
90

FIG. 1

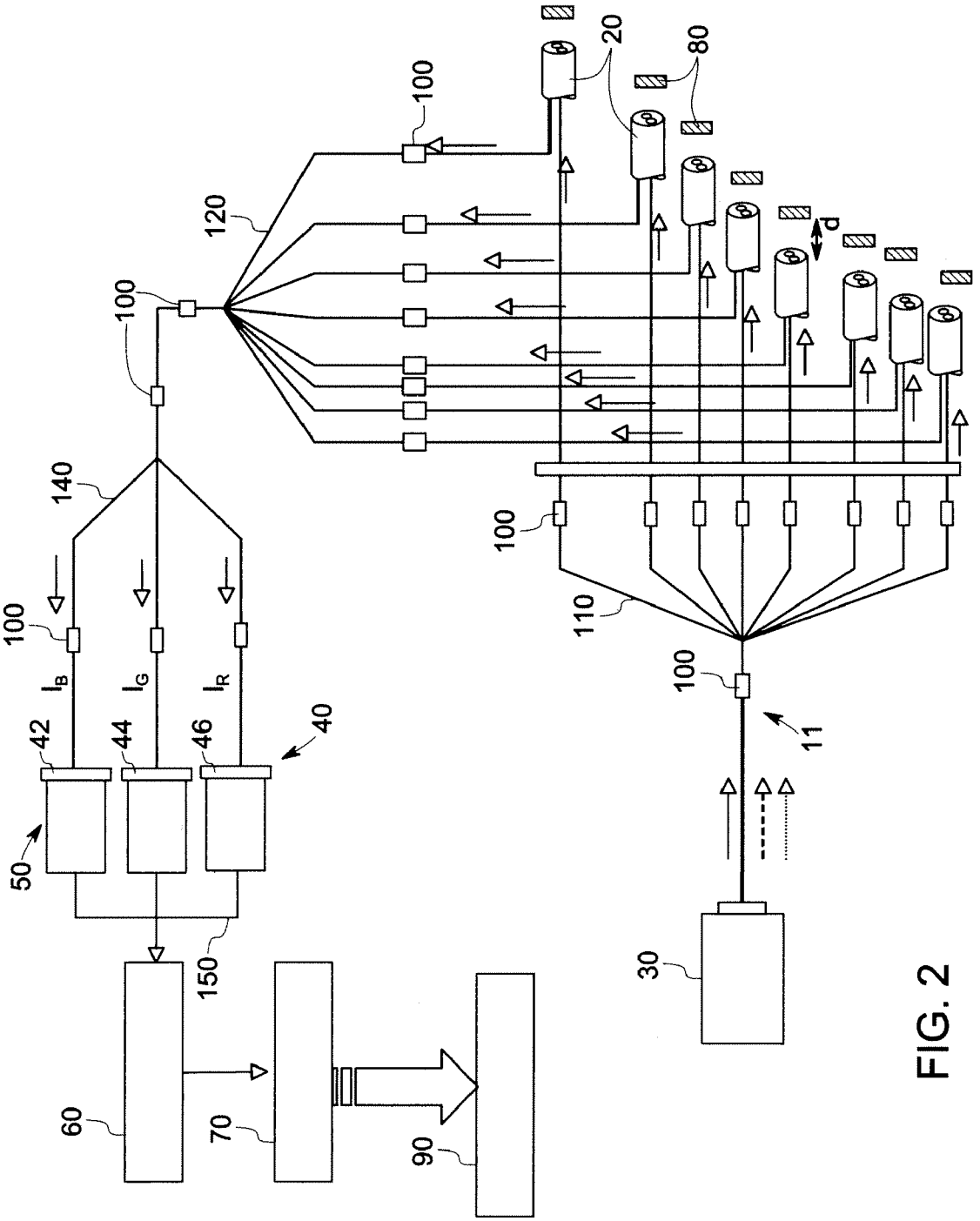


FIG. 2

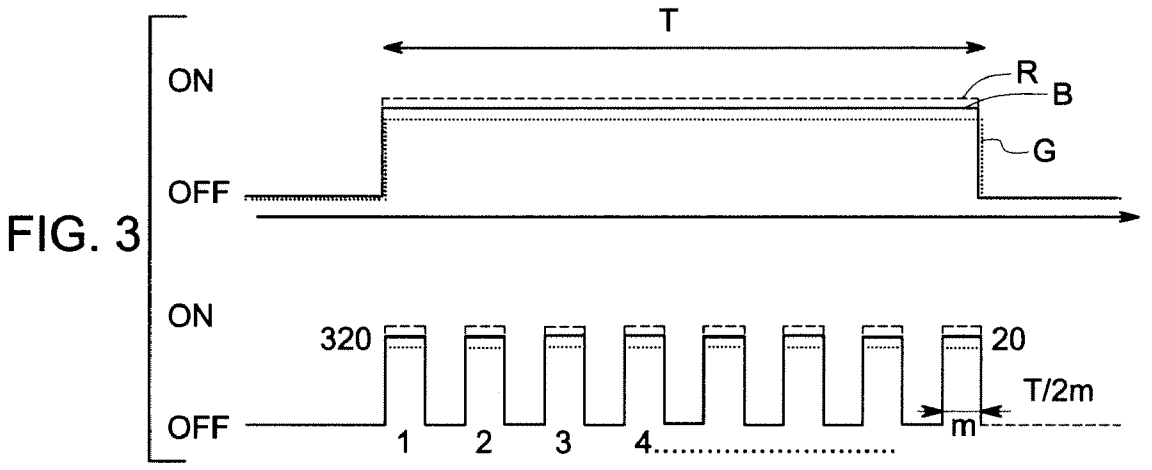


FIG. 3

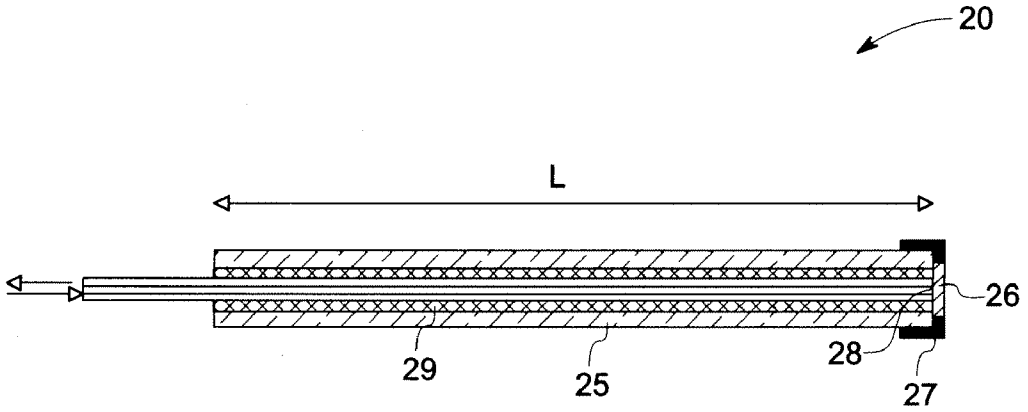


FIG. 4

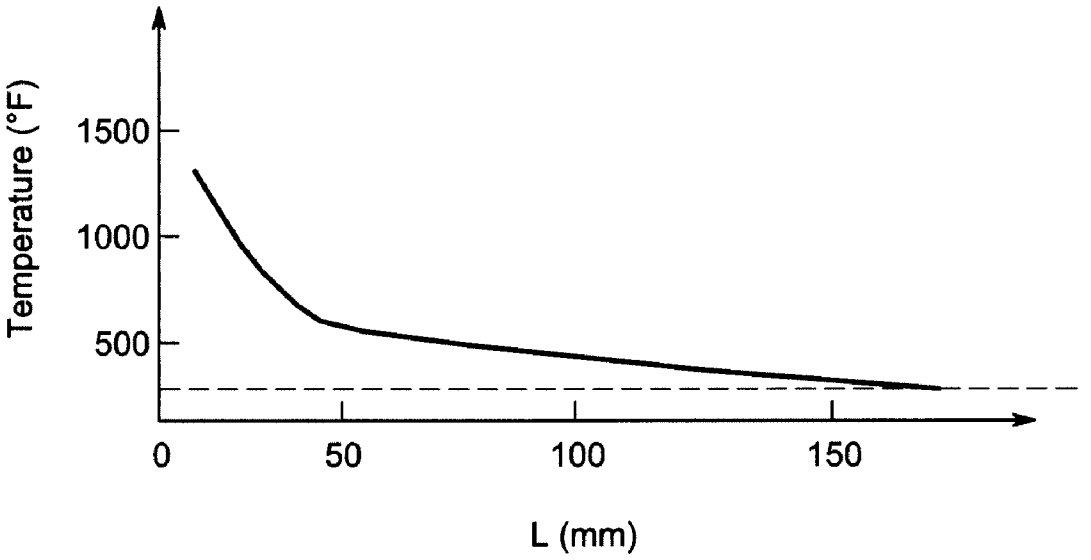

Temperature (°F)
1500
1000
500
0
50
100
150
L (mm)

FIG. 5

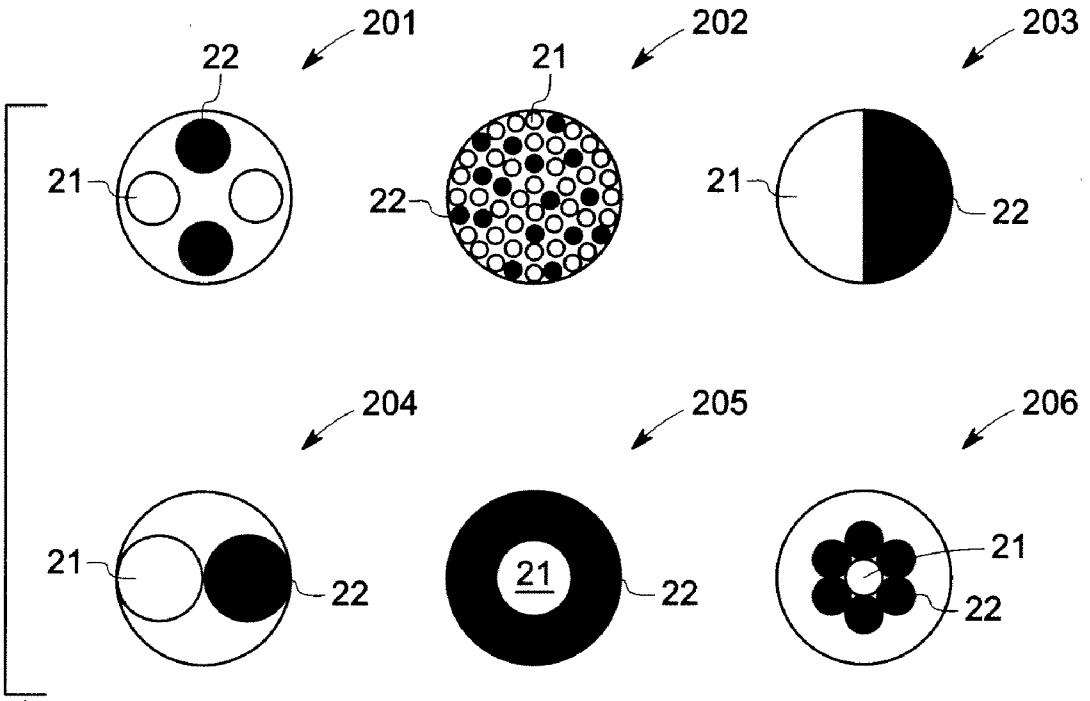

201
202
203
22
21
21
21
22
22
204
205
206
21
22
21
22
21
22

FIG. 6

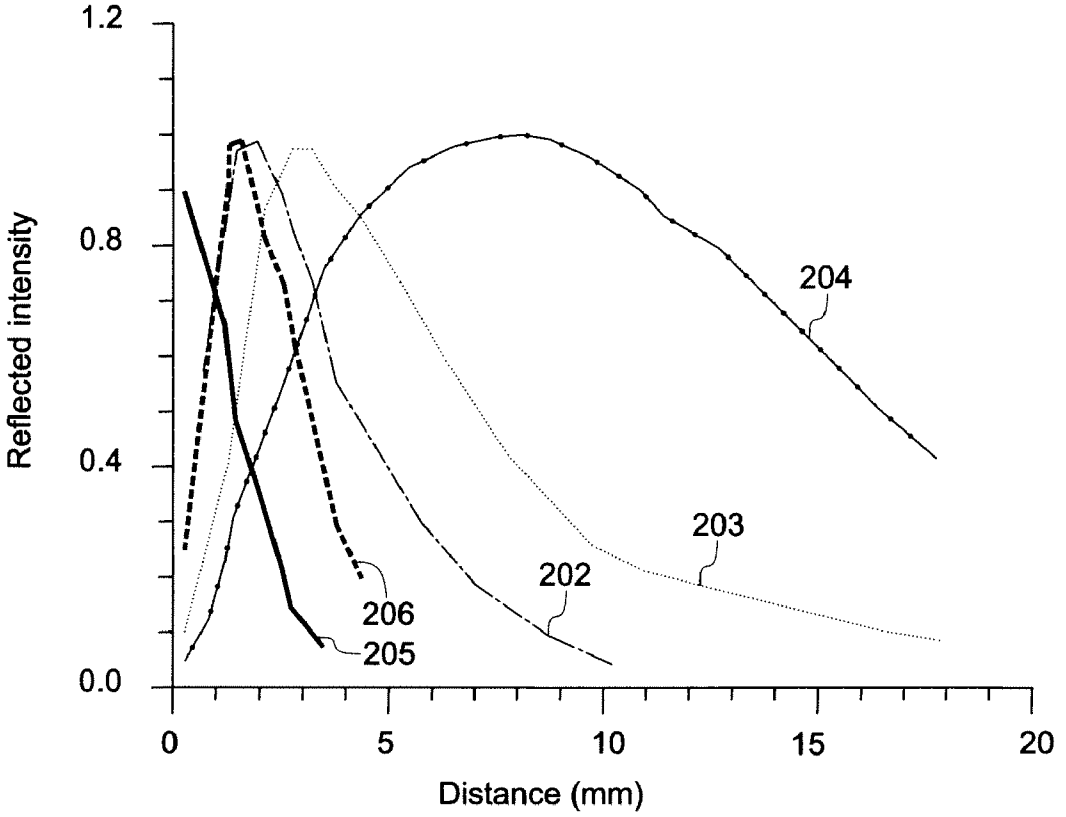

1.2
0.8
0.4
0.0
Reflected intensity
0
5
10
15
20
Distance (mm)
204
203
202
206
205

FIG. 7

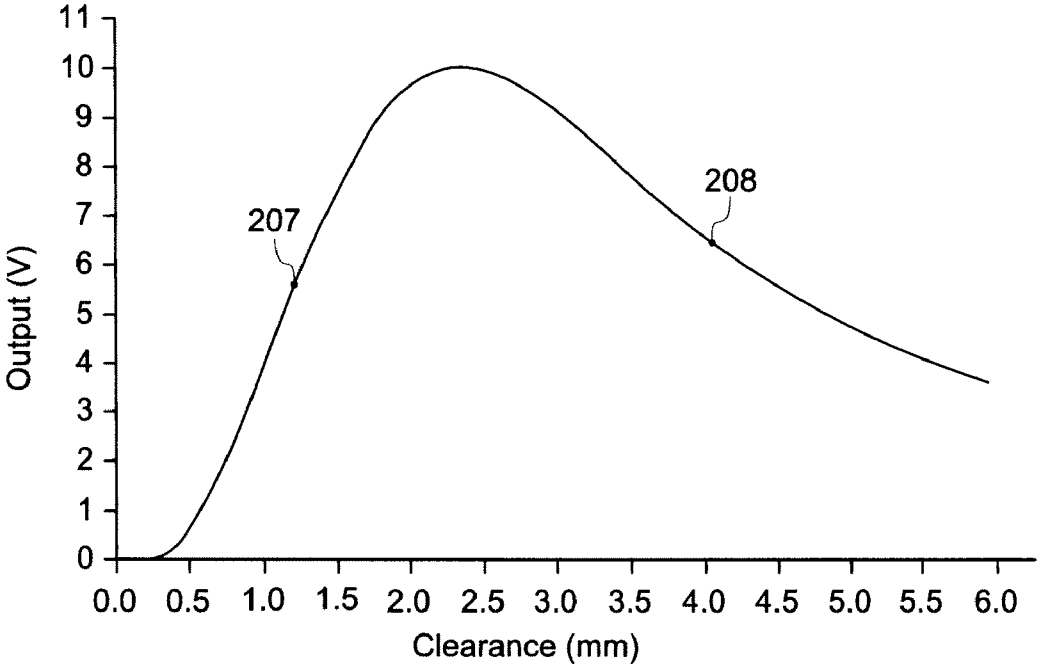

11
10
9
8
7
6
5
4
3
2
1
0
Output (V)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
Clearance (mm)
207
208

FIG. 8

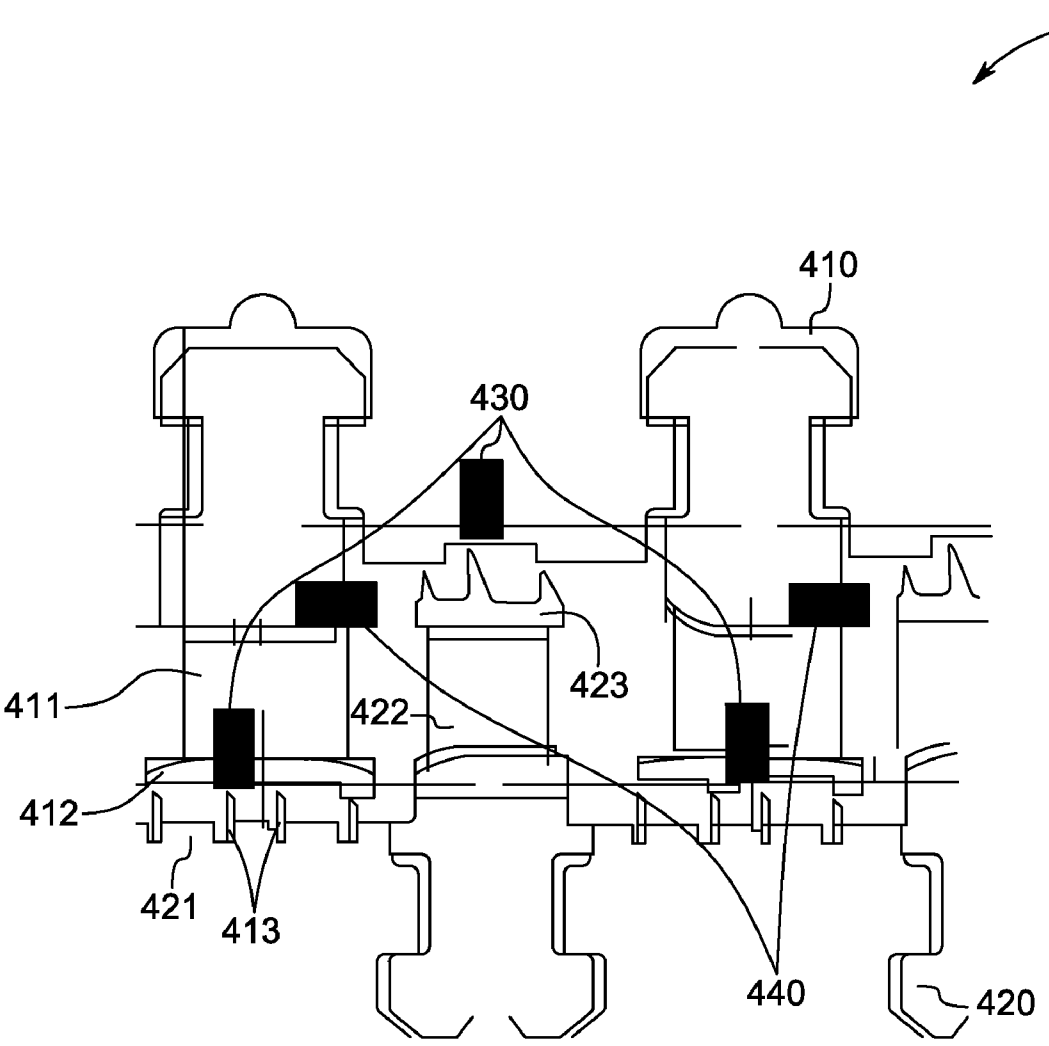


FIG. 9

FIBEROPTIC CLEARANCE DETECTION METHOD AND OPTICAL FIBER PROBE USED THEREIN

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. patent application Ser. No. 12/241,527, entitled "FIBEROPTIC CLEARANCE DETECTION SYSTEM AND METHOD," filed Sep. 30, 2008, which is herein incorporated by reference.

BACKGROUND

[0002] The subject matter disclosed herein relates generally to clearance detection.

[0003] Clearances between rotor blade tips and casings in turbomachinery such as steam turbine engines change during and following transient events and affect turbomachinery/engine performance. In a more specific example, axial and radial clearances inside steam turbines between rotors and stators have been limiting factors on size, start-up, loading, and shutdown of steam turbines. Currently, conservative clearances and transition times are used to minimize contact between steam turbine stators and rotors.

[0004] It would be desirable for a clearance sensing system to have high mechanical strength to tolerate various vibration, temperature, and pressure conditions in turbomachinery installation and maintenance and to have thermal properties that are insensitive to the environment. In addition, turbine clearances are sometimes asymmetric, so it is desirable that a clearance sensing system measure clearances at multiple locations. It would also be desirable to have a durable system and technique to provide a more compact steam turbine with faster start-up capabilities.

BRIEF DESCRIPTION

[0005] Briefly, in one embodiment disclosed herein, a system for measuring clearance comprises an optical fiber probe comprising a plurality of optical fibers, at least one of the optical fibers comprising a transmission fiber and at least one of the optical fibers comprising a signal fiber; a light source for providing light through the transmission fiber towards a target; filters for discriminating light from the signal fibers, at least two of the filters for filtering different wavelengths; and at least one photodetector for receiving filtered light from the filters.

[0006] In another embodiment disclosed herein, a method comprises transmitting light through at least one transmission optical fiber towards a target; receiving light reflected from the target through at least one signal optical fiber; filtering the received light at least two different wavelengths; and using the filtered light to detect a clearance variation.

[0007] In another embodiment disclosed herein, an optical fiber probe comprises a plurality of optical fibers, a moisture-resistant enclosure enclosing distal ends of the optical fibers, and a hydrophobic layer situated over an end of the probe for preventing moisture from reaching the optical fibers.

[0008] In yet another embodiment disclosed herein, a system comprises a steam turbine comprising a rotor and a stator, a moisture resistant optical fiber probe comprising a plurality of optical fibers, at least one of the optical fibers comprising a transmission fiber and at least three of the optical fibers comprising signal fibers, a light source for providing light through the transmission fiber towards the steam turbine rotor; filters for discriminating light from the signal fibers and for filtering out unwanted light; at least one photodetector for receiving filtered light from the filters; and a processor for receiving signals from the at least one photodetector and detecting a variation in distance between the steam turbine rotor and the steam turbine stator.

DRAWINGS

[0009] These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0010] FIG. **1** is a schematic view of a single-point fiberoptic clearance detection system in accordance with one aspect of the invention;

[0011] FIG. **2** is a schematic view of a multi-point fiberoptic clearance detection system in accordance with another aspect of the invention;

[0012] FIG. **3** is a schematic representation of optical switch time gating method to measure each clearance from an optical fiber probe with multiple laser wavelength modulation in accordance with one aspect of the invention;

[0013] FIG. **4** is a sectional view which illustrates an optical fiber probe according to one embodiment of the invention;

[0014] FIG. **5** is a graph illustrating temperatures in the optical fiber probe vs distance from the target;

[0015] FIG. **6** is several sectional views illustrating various arrangements of transmission fibers and signal fibers in accordance with embodiments of the invention;

[0016] FIG. **7** is a graph illustrating reflected intensities of lights vs transmitted distances through several of the arrangements of FIG. **4**;

[0017] FIG. **8** is a graph illustrating two clearance sensing points from the high-sensitive reflectance signal ranges; and

[0018] FIG. **9** is a side view showing a schematic steam turbine component incorporating the optical fiber probes.

DETAILED DESCRIPTION

[0019] As discussed in detail below, embodiments of the invention include a system and a method for detecting clearance. In one more specific example, the clearance detection is within a steam turbine. Embodiments described herein are also applicable and beneficial for other types of turbomachinery, for example, such as gas turbines, compressors, and generators.

[0020] FIG. **1** illustrates a schematic view of a clearance detection system **10** in accordance with one embodiment of the present invention wherein an optical fiber probe **20** comprises a plurality of optical fibers **21** and **22**, at least one of the optical fibers **21** comprising a transmission fiber and at least one of the optical fibers **22** comprising a signal fiber; a light source **30** for providing light through the transmission fiber **21** towards a target **80**; filters **40** for receiving light from the signal fiber **22**, at least two of the filters **40** for filtering different wavelengths; and at least one photodetector **50** for receiving filtered light from the filters **40**. As used herein, singular forms such as "a," "an," and "the" include plural referents unless the context clearly dictates otherwise.

[0021] In one embodiment, the light source **30** comprises a multi-wavelength light source such as an RGB emitting laser which is optionally tunable. In this embodiment, the emitted lights are of wavelengths of 405 nm to 471 nm, 515 nm to 555

nm, and 635 nm to 780 nm. In this embodiment, the filters **40** may include a narrow band interference filter **42** for transmitting light in the range of 405 nm to 471 nm, a red filter **44** for transmitting light in the range of 635 nm to 780 nm, and a green filter **46** for transmitting light in the range of 515 nm to 555 nm. The above described wavelength ranges of the light source and filters are for purposes of example only, however it is recommended that the ranges of the light source and filters be coordinated.

[0022] One or more photodetectors **50** may be present. In one embodiment, a plurality of photodetectors **50** are located behind corresponding filters **40** for receiving the filtered light. In another embodiment (not shown) one photodetector is used with a rotating wheel and different filters. In one embodiment, the photodetectors comprise silicon avalanche photodiodes. In another embodiment, wherein a selected laser wavelength range of a light source or filter is longer than 1.0 micrometer, an InGaAs-based photodetector or photodetector array is recommended.

[0023] A processor may be used for receiving signals from the at least one photodetector and detecting a variation in distance between the steam turbine rotor and the steam turbine stator. In one embodiment, the processor comprises a signal processor **60** for receiving and processing the signals, a data processor **70** for processing data from signal processor **60**. Signals from the processor may then be used by a controller **90** for steam turbine operation condition control.

[0024] The optical fiber probe **20** comprises a reflection based fiber bundle, which comprises at least two fibers, at least one fiber **21** (the transmission fiber) being designated for light delivering and at least one other fiber (the signal fiber) **22** being designated for reflectance receiving as indicated in the FIG. **1**. The received signal light is sent to the filters **40** and the photodetectors **50**. In one embodiment, the light is sent through an optical splitter **23**. In another embodiment, signal fiber **22** comprises a plurality of signal fibers (such as shown in FIG. **6**) that transmit light directly to the filters without the need of a splitter. The transmission fiber **21** transmits light from the light source **30** towards a target **80**. The signal fiber **22** transmits signals reflected from the target **80** to the filters **40**. Lights from the photodetectors **50** may be sent to the signal processor **60** by way of an optical combiner **24**.

[0025] For effective transmission of visible to near infrared light, in one embodiment the fibers **21**, **22** inside the optical fiber probe **20** comprise UV-grade quartz fiber having a doped fiber clad, a pure silica fiber core, a fiber core refractive index n_{core}, and a fiber clad refractive index n_{clad}, where $n_{core}>n_{clad}$. Doping ions for the fiber clad may comprise, for example, fluorine, chlorine, boron, or any combination thereof. In one embodiment, the fiber comprises a pure silica core with a fluorine-doped clad. In another embodiment, the fiber comprises a sapphire core with a metalized or polymerized clad. The fiber core diameter is typically in the range of 50 microns to 62.5 microns for quartz fibers and 70 microns to 250 microns for sapphire fibers. Optical fiber connectors **100** may be used to connect the light source **30**, the probe **20**, the optical splitter **23**, and the filters **40**, respectively.

[0026] Multiple probes may optionally share a common light source **30** through use of a splitter **110** as shown in FIG. **2** for example. Additionally, each of the filters **40** can also receive light from one or more than one signal fiber. FIG. **2** illustrates a system **11** for multi-point clearance detection in accordance with an embodiment of the present invention, in which the optical fiber probes **20** are distributed to different locations inside a steam turbine through an optical splitter **110**. In one embodiment, the reflectance signals from all probes **20** are recombined with an optical combiner **120**. Light from the optical combiner **120** is sent to the filters **40** and the photodetectors **50** by way of an optical splitter **140**. Such multiplexing and distribution embodiments may include an optical switch **130** to gate times for sequentially monitoring static and dynamic clearance at different steam turbine locations **80**. Lights from photodetectors **50** may be sent to the signal processor **60** by way of an optical combiner **150** and are then sent to the data processor **70**.

[0027] Referring to FIG. **3**, the optical switch **130** in FIG. **2** controls detection of clearance from each optical fiber probe **20** by a time sequence **320** for each of m optical fiber probes **20**. During each pulsed laser light exposure time T, a time period of T/2m is used for clearance detection from each optical fiber probe **20**. During each time gating period T, only one optical fiber probe is measuring clearance.

[0028] FIG. **4** is a diagrammatic representation of an optical fiber probe **20** as implemented in the systems **10** and **11** of FIG. **1** and FIG. **2**. The optical fiber probe **20** has an enclosure **25** (or "ferrule") enclosing the transmission and the signal fibers, a hydrophobic layer **26** situated over an end of the probe for preventing moisture from reaching and corroding the optical fibers, and a seal **27** sealing the fibers, the enclosure and the hydrophobic layer. The ferrule **25** may comprise an iron alloy such as stainless steel, an austenitic nickel-based superalloy such as Inconel™625 alloy (melting point: 2450° F.), or a nickel steel alloy such as Invar 36 alloy (melting point; 2600° F.). The hydrophobic layer **26** may comprise a sapphire plate or alumina (Al_2O_3) coating layer and act as a window for transmitting light from and to the optical fibers. A broadband transmission layer **28** may be disposed at the distal end of the fibers on either side of the hydrophobic layer and may comprise MgO, for example. The seal **27** may be made of Pt or Au. In one embodiment, between the fibers and the enclosure **25**, there is a gap filled with ceramic bonding material **29**. In a more specific embodiment, the gap is 25 micrometers, and the bonding material **29** is high-temperature ceramic adhesive comprising alumina/silicate material.

[0029] The selection of the adhesive material **29** may be based on the mitigation of the thermal stress between the fibers and the metal enclosure at high temperatures. In one example, when Inconel™ 625 (coefficient of thermal expansion (CTE): about 6.4 in/in/° F.) is used as the enclosure material, the adhesive material comprises an alumina based adhesive having CTEs that are in the range of 4.4 in/in/° F. In another example where Titanium (CTE: about 3.9 in/in/° F.) is used as the enclosure material, the adhesive material comprises either boron carbide based adhesive with a CTE of 2.6 in/in/° F.) or silicon carbide based adhesive with a CTE of 2.9 in/in/° F. It is useful for the selected adhesive materials to survive temperatures in excess of 1000° F. temperature. Such adhesives are commercially available with two example suppliers being Aramco Products, Inc. and Cotronics Corporation. Even when lower temperature limits are involved, adhesive materials may still be used for providing a stress buffer.

[0030] For steam turbine applications, the packaging is designed to enable the optical fiber probe **20** to operate in moist, corrosive, and high temperature environments and to resist damage during turbomachinery installation and maintenance. A packaging length L (FIG. **4**) may be selected to be of sufficient length so that package temperature that is experienced in the vicinity of the target is sufficiently reduced

across the length of package **25** so as to not damage equipment at the other (remote) end of package **25**. A sufficient temperature gradient may be designed based on package length and materials. In one example, if the rotor temperature inside the steam turbine, i.e., the target **80**, is about 1500° F., the packaging length L of the probe **20** is longer than the thickness of the stator core. In another example, the optical fiber probe is long enough so that the temperature around the end of the package **25** is decreased to be below 200° F. FIG. **5** is a simulated graph wherein the temperature at the target is about 1500° F., the package length L is along the X axis, and the resulting temperature at the remote end of the package is along the Y axis.

[0031] The optical probe **20** may comprise many fibers, one or more of which are transmission fibers used for light delivering and one or more of which are signal fibers for reflectance receiving. FIG. **6** shows arrangements **201-206** of transmission fibers **21** and signal fibers **22** in accordance with embodiments of the invention. Referring to FIG. **6**, the transmission fibers **21** and the signal fibers **22** according to the arrangements **201-206** may be arranged in multiple pairs **201**, in a random manner **202**, in a half/half arrangement **203**, in one pair **204**, or coaxially **205** or **206**, for example. In a specific embodiment, every two of the six signal fibers **22** of the arrangement **206** goes to one of the filters **40** of FIG. **1** and no splitter is needed. FIG. **7** is a graph showing measured clearance responses from different fiber bundle arrangements **202-206** of FIG. **6**. Each type of fiber configuration has a unique standoff distance and associated sensitivity.

[0032] Static and dynamic clearance measurements are improved when the optical fiber probe is set at an optimal distance from the target surface. Such a distance is defined as a "working point". The distance or working point may vary depending upon the fiber configuration inside the optical fiber probe **20**. FIG. **8** shows two "working points" for an exemplar probe, defined as front and rear clearance sensing points 207 (1.2 mm) and 208 (4.1 mm). The clearance can be measured by setting the probe distance either at front clearance sensing point **207** which is of higher sensitivity with a shorter standoff (distance) from the target, or at rear clearance sensing point **208** which is of a relative lower sensitivity but with a longer standoff (distance) from the target. When the clearance sensing point is chosen, the static and dynamic clearances can be measured by the signal intensity or power level. When using different wavelengths, the signal processing will be used to obtain a differential of each wavelength signal and the relative change of different wavelengths.

[0033] The standoff distance of an optical fiber probe may be selected at least in part based upon the fiber arrangement or configuration. For example, as can be seen from the graph of FIG. **7**, a fiber bundle with short standoff may have a higher sensitivity because of its steep front response curve feature. From clearance probe response curves in FIG. **7** and FIG. **8**, there are two points that could provide proper sensitivities. One is defined as front working point, which is first position for setting the optical fiber probe for clearance measurement. The other is defined as the rear working point.

[0034] If desired, for clearance sensing at a specific location, two probes can be used with one at the front working point and the other at the rear working point with the differentiation between two sensing signals being used for precise static clearance determination. However, one probe either at front or at rear working point could be used for dynamic clearance sensing. The selection of a fiber bundle type and working point depends upon the maximum clearance that needs to be measured at a specific steam turbine location.

[0035] In one detection example, intensities of lights in signal fibers are I_R, I_G, I_B, an initial distance between the probe **20** and the target **80** is d_0, and the clearance variation Δd between earlier time t_1 and later time t_2 is determined respectively by

$$\Delta d = \frac{I_G(d_2, t_2) - I_B(d_2, t_2)}{I_G(d_1, t_1) - I_B(d_1, t_1)} d_o,$$

$$\Delta d = \frac{I_R(d_2, t_2) - I_B(d_2, t_2)}{I_R(d_1, t_1) - I_B(d_1, t_1)} d_o$$

and

$$\Delta d = \frac{I_R(d_2, t_2) - I_G(d_2, t_2)}{I_R(d_1, t_1) - I_G(d_1, t_1)} d_o.$$

Differential signal processing is useful to mitigate laser light fluctuation and some specious events, such as steam absorption induced error. Fault diagnostics in such embodiments may include voting methods. For example, if two results match, the third unmatching result is likely an error.

[0036] FIG. **9** is a schematic drawing of a steam turbine component **400** comprising a stator **410**, a rotor **420** and optical fiber probes **430** and **440**. The stator **410** includes a fixed blade (or nozzle) **411**, a fixed blade shroud **412** and/or labyrinth seals. The rotor **420**, in one embodiment, includes a shaft **421**, rotating blade (or bucket) **422**, a shroud, labyrinth tip seals **423**, and labyrinth seals **413**. Two of the three probes **430** are located at left and right sides of FIG. **9** and are arranged radially to detect radial clearances between the fixed blade shrouds **412** of the stator **410** and the labyrinth seals **413** on the shaft **421** of the rotor **420**. The probe **430** in the middle is arranged radially to detect radial clearances between the inner wall of the stator **410** and the blade shroud and/or tip seals **423** of the rotor **420**. The probes **440** are arranged axially to detect axial clearances between trailing edges of the stator **410** and blade shroud leading edges of the rotor **420**.

[0037] While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

1. A method comprising:

transmitting light through at least one transmission optical fiber towards a target;

receiving light reflected from the target through at least one signal optical fiber;

filtering the received light at least two different wavelengths; and

using the filtered light to detect a clearance variation.

2. The method of claim **1**, wherein the at least one signal optical fiber comprises at least three signal optical fibers and wherein filtering the received light at at least two different wavelengths comprises filtering at least three different wavelengths.

3. The method of claim **2**, wherein using the filtered light to detect a clearance variation comprises determining a variation estimate at each of the at least three different wavelengths.

4. The method of claim **3**, wherein using the filtered light to detect a clearance variation comprises comparing the variation estimates.

5. The method of claim **1** wherein transmitting light through the at least one optical fiber towards a target comprises transmitting light at least two different wavelengths.

6. The method of claim **1**, wherein using the filtered light to detect a clearance variation comprises converting the filtered light to a signal using at least one photodetector.

7. The method of claim **6**, further comprising using the signal for steam turbine operation control.

8. A method comprising:

transmitting light through at least two optical fiber probes towards a target with a first one of the optical fiber probes situated at a different distance from the target than a second one of the optical fiber probes;

receiving light reflected from the target through the at least two optical fiber probes; and

determining a clearance variation using a differentiation between the light received from the at least two optical fiber probes.

9. The method of claim **8**, wherein transmitting light through each optical fiber probe comprises transmitting light at least three different transmission wavelengths.

10. The method of claim **9**, further comprising filtering the received light at least three different filter wavelengths prior to determining the clearance variation.

11. The method of claim **9**, wherein determining the clearance variation comprises determining a variation estimate at each of the at least three different filter wavelengths of each optical fiber probe.

12. The method of claim **11**, wherein detecting the clearance variation comprises comparing the variation estimates.

13. The method of claim **8**, further comprising situating the first one of the optical fiber probes at a front working point and the second one of the optical fiber probes at a rear working point while transmitting the light towards the target.

14. An optical fiber probe, comprising:

a plurality of optical fibers and a moisture-resistant enclosure enclosing the optical fibers;

a hydrophobic layer situated over an end of the optical fiber probe for preventing moisture from reaching the optical fibers; and

a broadband transmission layer between ends of the optical fibers and the hydrophobic layer.

15. The probe of claim **14**, wherein the hydrophobic layer comprises a plate comprising sapphire.

16. The probe of claim **14**, wherein the hydrophobic layer comprises a coating comprising aluminum oxide.

* * * * *