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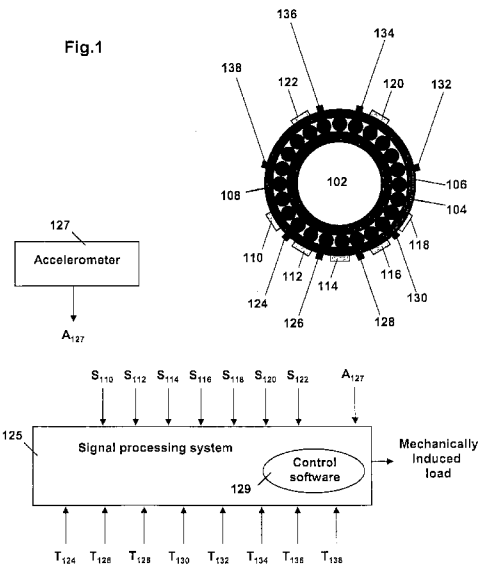
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(54) **Title**: LOAD ON OBJECT DERIVED FROM NATURAL-MODE SERIES MODELLING

Fig.1



(57) **Abstract**: The mechanical load on, for example, a rolling element bearing (102) is determined from the deformation sensed on a bearing ring (106) of the bearing. Computational efficiency is obtained by expressing the deformation as a first linear combination of natural-mode shapes of the bearing ring (106). A thermal load on the bearing ring is also expressed as a second linear combination of the same natural-mode shapes. Subtracting the second linear combination from the first linear combination enables to remove the thermally induced deformation from the sensed deformation.

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LOAD ON OBJECT DERIVED FROM NATURAL-MODE SERIES MODELLING

FIELD OF THE INVENTION

The invention relates to a method of determining a mechanical load on a physical object. The invention also relates to a load sensing system for determining a mechanical load on a physical object, to a signal processing system for use in the load sensing system, and to control software on a computer-readable medium for implementing the method on a computer.

BACKGROUND ART

US patent 5,952,587, incorporated herein by reference, discloses a system for sensing real-time rolling element loads in a rolling element bearing having a plurality of rolling elements disposed between an inner race and an outer race. A plurality of sensors is disposed about one of the inner race and the outer race of the bearing to output sensor data corresponding to detected loads. Before operation of the system in real-time, the sensors are calibrated to model a relationship of roller load and measured strain. The bearing is then rotated and sensor data is output from each the sensors. The sensor data is cyclical, and peaks and valleys are extracted from the sensor data to determine rolling element loads and measured bearing speed. Load components from a plurality of rolling elements are then summed to obtain total applied system load in real time.

The sensors in the known system are in the form of strain gauges. By measuring the resistance change in the gauge, the change in strain in the inner race or the outer race can be uniquely determined. However, the electrical resistance of the gauge will also change in response to a change in temperature. The system is adjusted for temperature by first recording the output of the strain gauges under a "no-load" condition while the temperature is varied. The output resistance of the strain gauge is then recorded for a plurality of pre-determined temperature intervals. The output resistance is referred to as "apparent strain" and the values are stored in a look-up table for later recall. During the operation of the known system under a load condition, the resistive component of temperature is measured along with the resistive component of strain. In other words, the strain that is output from the gauge includes the actual strain plus the apparent strain (due to temperature). At this juncture, the actual temperature of the bearing may be measured and the apparent strain which

corresponds to the measured temperature may be determined from a look-up table. Another form of temperature compensation may be employed by mounting a second strain gauge in a non-load-bearing, temperature-sensitive location. In this regard, the second strain gauge should be placed in such close proximity to the first strain gauge to vary correspondingly in temperature. The second strain gauge may be placed in a non-load-bearing location by simply rotating the gauge 90 degrees from the first strain gauge. The output of the second strain gauge is then connected in a bridge circuit to serve as a reference.

SUMMARY OF THE INVENTION

In the known system the deformation of a rolling element bearing is measured and the mechanical load is derived from the strain as measured by the electrical resistance of the strain gauges. As the electrical resistance is dependent on the temperature, the strain as measured is compensated to remove the contribution to the electrical resistance that arises from the temperature-dependence of the operation of the strain gauge. Therefore, the known system derives the mechanical load from the strain as measured by the strain gauges after compensation for the temperature-dependent operation of the strain gauges.

Accordingly, it is known that a deformation of a physical object, e.g., a ring of a rolling element bearing, can be caused by a mechanical load. However, a physical object can also be deformed as a result of a thermal load. A thermal load is present if spatial or temporal temperature differences occur within the physical object and/or between the physical object and an environment of the physical object. Therefore, an actual deformation of a physical object as sensed is generally a superposition of mechanically induced deformation as a result of an applied mechanical load, and of a thermally induced deformation as a result of a thermal load on the physical object. Note that mechanically deforming the physical object may give rise to the generation, or absorption, of heat as an adiabatic process within the physical object, which then also results in a thermal load.

For example, the physical object can be a component of a rolling element bearing installed in a piece of machinery. The rolling element bearing has an inner ring, an outer ring and a plurality of rolling elements accommodated between the inner ring and the outer ring. The rolling element bearing is configured for carrying a mechanical

load. For example, consider the piece of machinery to be an automobile and the rolling element bearing is accommodated in a wheel hub. The inner ring of the rolling element bearing is attached to a half shaft driving the wheel. The outer ring of the rolling element bearing is attached to e.g. a steering knuckle. The rolling element bearing and the half shaft are oriented coaxially. The weight of the automobile and the force exerted on the wheel by the road surface cause a mechanical load to be exerted on the rolling element bearing. Measuring the deformation of one or both of the inner ring and outer ring can give information about the mechanical load borne by the driven wheel in operational use of the automobile. An onboard computer receives as input a signal representative of the current mechanical load on the driven wheel and supplies an output signal to control, e.g., the amount of power supplied to the driven wheel or the stiffness of the suspension connecting the wheel to the chassis of the automobile. In that case, the load sensing mechanism could be physically integrated with the rolling element bearing. In operation, however, the rolling element bearing is subjected to both mechanically induced deformation and thermally induced deformation. Accordingly, the measured deformation is not unambiguously representative of the mechanical load. That is, if the mechanical load were determined based on the deformation sensed, there would be a discrepancy between the mechanical load as determined and the actual mechanical load. The discrepancy is due to the fact that the thermal effects contribute to the deformation of the physical object as sensed. In other words, the deformation as sensed is a superposition of a mechanically induced deformation and a thermally induced deformation of the physical object. The thermal load on a rolling element bearing is a result of, e.g., heat generated by the rolling friction of rolling elements of the bearing, especially when the rolling elements are subjected to a high mechanical load. Another example of a thermal load on the rolling element bearing is, e.g., the heat generated by sources in the vicinity of the bearing, such as the heat that results from dissipation losses in the rotor of an electric motor, the rotor being supported by the rolling element bearing, or such as the heat generated by a disc brake or drum brake in a wheel that is supported by the rolling element bearing.

Therefore, the inventors propose an improved method of determining a mechanical load on a physical object. The method comprises: sensing a deformation of the physical object at at least a particular location on the physical object; determining a first shape of the physical object corresponding to the deformation as sensed;

measuring at least one temperature gradient within the physical object by sensing a temperature of the physical object at at least a first location and a second location on the physical object; determining a second shape of the physical object corresponding to the temperature gradient as measured; determining a difference between the first shape and the second shape; and determining the mechanical load based on the difference.

If the mechanical load were to remain the same, but the thermal load were to increase the overall deformation of the physical object, as determined in the known system, would give rise to measuring an increased mechanical load. In the invention, a distinction is made between a mechanically induced deformation as a result of a mechanical load on the physical object, and a thermally induced deformation as a result of a thermal load on the physical object. The deformation of the physical object as sensed is corrected by means of removing the thermally induced deformation before determining the mechanical load.

In order to explain an embodiment of the method in the invention, first consider US patent 7,444,888 and US patent 7,389,701, both incorporated herein by reference. US patent 7,444,888 discloses a method and sensor arrangement for determining a contact force vector acting on a rolling element bearing in operation. Sensor signals are received from a plurality of sensors measuring performance characteristics of the rolling element bearing. The received sensor signals are processed to determine the contact force vector. The plurality of sensors are arranged to measure a bearing component deformation, and the step of processing comprises the step of determining the contact force vector using an inverse transformation of a finite element analysis model which describes the rolling element bearing. The finite element analysis model is simplified using at least one generalized-mode shape, the at least one generalized-mode shape being a mathematical description of a natural or elementary mode deformation of a component of the rolling element bearing, such as the inner or outer ring.

US patent 7,389,701 discloses a method and sensor arrangement for determining a load vector acting on a rolling element bearing in operation. The expression "load vector" refers to the complete load vector: three orthogonal force components and two moments. The rolling element bearing comprises an inner ring, an outer ring and

multiple rolling elements that are accommodated between the inner ring and the outer ring. A plurality of *N* sensors are provided, which measure displacement and/or strain for determining displacement and/or strain in, e.g., the inner ring or the outer ring. Furthermore, a mode-shape coefficients calculator is provided, connected to the plurality of *N* sensors, for determining a deformation of the inner ring or the outer ring by calculating amplitude and phase of *N/2* Fourier terms representing at least one radial mode shape of the inner ring or the outer ring.

A modelling technique used in US patent 7,444,888 and in US patent 7,389,701 is based on the Ritz method: a variational method used in mathematical physics, and named after the Swiss theoretical physicist Walther Ritz. For the Ritz method, see, e.g., "Methoden der Mathematischen Physik I", R.Courant and D.Hilbert, Dritte Auflage, Springer-Verlag 1968, Viertes Kapitel, §2. Applied to a physical object under a load in order to determine the deformation of the physical object, the deformation of the physical object is approximated by a series of natural-mode shapes (referred to in above US patents as generalized-mode shapes), each whereof is weighted by a particular weight factor. A particular one of the natural-mode shapes in the series describes a particular elementary shape of the physical object given the boundary conditions of the physical object, and given the shape of the physical object in the absence of the load. The deformation or vibration of a physical object can be thought of as being determined by the natural mode shapes and the natural frequencies associated with the natural mode shapes. If the supply of energy to the physical object is in phase with a natural vibration of a natural frequency, the energy absorbed by the physical object is larger than at frequencies not being natural frequencies. The Finite-Element Method, heuristics and/or symmetry considerations may help to determine the natural-mode shapes. In a linear approximation, any dynamic deformation or vibration of the physical object can be described by a linear combination of the natural-mode shapes of the physical object to a good approximation. By choosing suitable natural-mode shapes in the frequency range of interest, the size of the problem to be solved can be reduced significantly, as discussed in above patents. The weight factors in the series of natural-mode shapes are chosen such that the difference between the actually measured deformation and the series of natural-mode shapes is minimized. The minimizing is based on using the variational principle, e.g., the Ritz method.

If the physical object is divided into several components and the behaviour of each individual component is described by the Ritz method, then the method is referred to as component mode synthesis (CMS). Consider a deformation of the inner ring of the rolling element bearing, or a deformation of the outer ring of the rolling element bearing, as a result of an applied mechanical load. The deformation can be thought of as a linear combination of natural-mode shapes. See, e.g., J. A. Wensing, "On the dynamics of ball bearings", ISBN 90-36512298, incorporated herein by reference. These natural-mode shapes may be determined using, e.g., a finite-element analysis model. The natural-mode shapes allow transforming the finite-element analysis model with tens of thousands of surface elements to a model with a few hundred mode shape descriptions, which is much easier and faster to solve than the finite-element model. The natural-mode shapes are used in a linear combination for describing the actually sensed deformation to a good approximation. In this sense, the natural-mode shapes serve the same purpose as the sines and cosines do in Fourier analysis of a signal.

The inventors have recognized that the same basic set of natural-mode shapes, used in the series expansion of the deformation of the physical object as a result of a mechanical load, can be used to describe the deformation of the physical object as a result of a thermal load. Accordingly, the inventors propose to measure the actual deformation of the physical object by, e.g., strain gauges, and to approximate the measured actual deformation to any desired accuracy by a truncated first series of natural-mode shapes. The qualifier "truncated" is introduced here for clarity, as the concept "series" as used in mathematics refers to the result of adding an infinite sequence of terms. In practice, however, only a finite number of terms can be processed. The inventors propose to measure at least one temperature gradient by sensing temperature at one or more pairs of locations on the physical object and to calculate, or otherwise determine, a thermal deformation of the physical object that corresponds to the one or more temperature gradients as measured. The thermal deformation is expressed in a truncated second series of the natural-mode shapes. If the truncated second series is subtracted from the truncated first series, the result is a truncated third series. The truncated third series is then considered representative of the mechanically induced deformation. Note that the mechanically induced deformation thus obtained is, to a good approximation, the actual measured deformation but now compensated for the thermal effects. The truncated third series is

then used in turn to determine the actual mechanical load that corresponds to the deformation described by the truncated third series. In other words, the deformation as sensed is compensated for thermal effects so as to obtain the deformation of the physical object as if the deformation was entirely caused by a mechanical load, so as to enable reconstructing the mechanical load applied. As both the mechanically induced deformation and the thermally induced deformation are expressed as truncated series of natural-mode shapes, the calculations are much easier and faster to solve than with use of a conventional finite-element method.

Accordingly, an embodiment of the method of the invention for determining a mechanical load on a physical object comprises representing the first shape as a first truncated series of natural-mode shapes of the physical object; and representing the second shape as a second truncated series of the natural-mode shapes. The determining of the difference comprises subtracting the second truncated series of the natural-mode shapes from the first truncated series of the natural-mode shapes. The mechanical load is determined from the third truncated series using, e.g., the approach described in US patent 7,444,888 and/or US patent 7,389,701, referred to above.

A further embodiment of the method comprises: determining a rate of change of the temperature at at least a first location on the physical object; using the rate of change to determine a further temperature at a further location on the surface other than the first location; and using the temperature and the further temperature in the determination of the second shape.

The rate of change of the temperature at the first location enables to determine a further temperature at a further location in the neighbourhood of the specific location. The rate of change of the temperature is the time derivative of the temperature at the specific location as represented by, e.g., a difference quotient. As known, the thermal conduction in a solid can be modelled by the following partial differential equation: $\delta T/\delta t = \lambda \Delta T$, wherein "T" is the temperature field, depending on the time "t" and the location, wherein "λ" stand for the thermometric conductivity (a physical property of the solid), and wherein "Δ" is the Laplace operator, also defined as the divergence of the gradient. Measuring the time derivative of the temperature $\delta T/\delta t$ at the specific location at a particular moment enables to reconstruct the temperature distribution in

the neighbourhood of the specific location at that particular moment by using, e.g., the Green's function approach. See e.g. "Methoden der Mathematischen Physik I", R.Courant and D.Hilbert, Dritte Auflage, Springer-Verlag 1968, Fünftes Kapitel, §14. Monitoring the temperature as well as the time derivative of the temperature at the specific location enables to obtain information about the temperature at a further location in the physical object, thus emulating a further temperature sensor at the further location. This approach then saves additional temperature sensors, but enables to increase the number of temperature samples that are taken into account for determining the thermally induced deformation so as to increase the resolution of the temperature distribution.

A further embodiment of the method of the invention comprises determining an acceleration of the physical object for determining an inertial load on the physical object; and subtracting the inertial load from the mechanical load as determined.

Removal of the inertial load, as determined by, e.g., an accelerometer, from the mechanical load as determined above reveals the mechanical loads on the physical object from an origin different than from the acceleration of the physical object as a whole. The mechanical load minus the inertial load enables to retrieve information about the mechanical loads exerted on the physical component due to, e.g., vibrations or imbalance caused elsewhere in a mechanical structure or dynamic system, of which the physical object forms a part.

The invention also relates to a load sensing system for determining a mechanical load on a physical object. The load sensing system comprises at least one deformation sensor and at least two temperature sensors. The deformation sensor is configured for supplying a deformation sensor signal representative of a deformation of the physical object at at least a particular location at the physical object. The temperature sensor is configured for supplying a temperature sensor signal representative of one or more temperature gradients within the physical object, measured by sensing a temperature of the physical object at at least a first location and a second location on the physical object. Suitably, the first and second locations are selected so as to lie on regions of the object that are subject to different temperatures. The load sensing system further comprises a signal processing system. The signal processing system is configured for: receiving the deformation sensor signal and the temperature sensor

signal; determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed; determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients as sensed; determining a difference between the first shape and the second shape; and determining the mechanical load based on the difference.

The load sensing system of the invention carries out a method according to the invention as specified earlier. The deformation sensor comprises, e.g., one or more strain gauges. Strain gauges are well known in the art. Examples of a temperature sensor are, e.g., a silicon bandgap temperature sensor, a resistive thermal device (RTD) such as a PT100, a thermistor, an infrared thermometer, etc. Optionally, the deformation sensor and the temperature sensor are created close to one another and accommodated together on the same substrate. This configuration enables to adjust the deformation sensor signal if the operation of the deformation sensor itself has a dependence on temperature. The signal processing system comprises, for example, a general-purpose computer with dedicated software on a computer-readable medium for processing the deformation sensor signal. Examples of a computer-readable medium are: a storage device with a solid-state memory (e.g., an EEPROM such as flash memory; or an SRAM, or a DRAM), another storage device with an optical memory such as an optical disc, and yet another storage device with a magnetic memory such as a magnetic disk, etc. Alternatively, the signal processing system comprises one or more dedicated signal processors or dedicated electronic hardware for processing the deformation sensor signal. The signal processing system is functionally connected to the at least one deformation sensor and to the at least one temperature sensor via a wired connection or a wireless connection. The deformation sensor(s) and the temperature sensor(s) may also be coupled to the signal processing system via a data network via a suitable interface.

In a further embodiment of the load sensing system, the signal processing system is configured for: representing the first shape as a first truncated series of natural-mode shapes of the physical object; and representing the second shape as a second truncated series of the natural-mode shapes. The determining of the difference comprises subtracting the second truncated series of the natural-mode shapes from the first truncated series of the natural-mode shapes.

In a further embodiment of the load sensing system, the signal processing system is configured for: determining a rate of change of the temperature at at least the first location; determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and determining the second shape using the temperature and the further temperature.

Measuring the temperature as well as the rate of change of the temperature enables to determine a further temperature at a further location at the physical object in the vicinity of the temperature sensor, as explained above, thus emulating a further temperature sensor at the further location and increasing the resolution of the temperature field determined.

In a further embodiment of the load sensing system, the load sensing system determining system comprises an accelerometer for supplying an accelerometer sensor signal representative of an acceleration of the physical object. The signal processing system is configured for: receiving the accelerometer sensor signal; determining from the accelerometer sensor signal an inertial load on the physical object; and subtracting the inertial load from the mechanical load as determined.

The invention also relates to a signal processing system for use in a load sensing system for determining a mechanical load on a physical object. The load sensing system comprises at least one deformation sensor and two or more temperature sensors. The at least one deformation sensor is configured for supplying a deformation sensor signal representative of a deformation of the physical object at at least a particular location on the physical object. The two or more temperature sensors are configured for supplying a temperature sensor signal representative of one or more temperature gradients within the physical object, measured by sensing a temperature at at least a first location and a second location on the physical object. The signal processing system is configured for: receiving the deformation sensor signal and the temperature sensor signal; determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed; and determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients as measured.

An aspect of the invention resides in the processing of the deformation sensor signal and the temperature sensor signal for determining the first shape and the second shape. Accordingly, a signal processing system according to the invention can be marketed as a dedicated component for use in a load sensing system. For example, the processing of the deformation sensor signal and the temperature sensor signal can be tailored to the specific type of physical object on which the mechanical load is to be determined. That is, the processing carried out by each specific type of a signal processing system of the invention is tailored to a specific one of a plurality of types of physical objects. Different types of physical objects may be composed of different materials having different thermal properties (e.g., thermal conductivity) and different mechanical properties (e.g., stiffness, compressibility). Different types of different physical objects may have different sizes and different shapes. A signal processing system can therefore be tailored to a specific type of physical object in order to take advantage of, e.g., homogeneity or heterogeneity of the material of the physical object, symmetry or asymmetry of the spatial configuration of the physical object, etc., in order to render the determining of the first shape and of the second shape more efficient. Note that the determining of the first shape and the second shape is carried out by the signal processing system, and the determining of the mechanical load can be carried out by another computing entity on the basis of the first shape and the second shape as determined by the signal processing system.

A further embodiment of a signal processing system of the invention is configured for determining a difference between the first shape and the second shape; and determining the mechanical load based on the difference.

The determining of the first shape and the second shape on the one hand, and the determining of the mechanical load on the other hand, are both carried out by the above further embodiment of the signal processing system.

In a further embodiment of the signal processing system, the first shape is represented as a first truncated series of natural-mode shapes of the physical object; and the second shape is represented as a second truncated series of the natural-mode shapes.

Different types of physical objects may have different sets of natural-mode shapes. Accordingly, a signal processing system can be marketed as configured to determine and process the first truncated series of natural-mode shapes and the second truncated series of natural-mode shapes, wherein the natural-mode shapes are specific to a specific type of physical object.

A further embodiment of the signal processing system of the invention is configured for determining a rate of change of the temperature at at least the first location; determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and determining the second shape using the temperature and the further temperature.

A further embodiment of the signal processing system of the invention is configured for: receiving an accelerometer sensor signal representative of an acceleration of the physical object; determining from the accelerometer sensor signal an inertial load on the physical object; and subtracting the inertial load from the mechanical load as determined.

The invention also relates to control software on a computer-readable medium for configuring a signal processing system for use in a load sensing system that is designed for determining a mechanical load on a physical object. The control software comprises: first instructions for receiving a deformation sensor signal representative of a deformation of the physical object at at least a particular location on the physical object; second instructions for receiving a temperature sensor signal representative of one or more temperature gradients within the physical object, measured by sensing a temperature of the physical object at at least a first location and a second location on the physical object; third instructions for determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed; and fourth instructions for determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients as measured.

As mentioned earlier, an aspect of the invention resides in the processing of the deformation sensor signal and the temperature sensor signal for determining the first shape and the second shape. The control software according to the invention can

therefore be used for installing on a general-purpose computer for configuring the general-purpose computer as the signal processing system according to the invention. Alternatively, the control software can be implemented in a dedicated microcontroller making up a functional part of a load sensing system of the invention.

An embodiment of the control software of the invention comprises fifth instructions for determining a difference between the first shape and the second shape; and sixth instructions for determining the mechanical load based on the difference.

In a further embodiment of the control software, the third instructions are configured for representing the first shape as a first truncated series of natural-mode shapes of the physical object; and the fourth instructions are configured for representing the second shape as a second truncated series of the natural-mode shapes.

A further embodiment of the control software comprises seventh instructions for determining a rate of change of the temperature at at least the first location; eighth instructions for determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and ninth instructions for determining the second shape using the temperature and the further temperature.

A further embodiment of the control software comprises tenth instruction for receiving an accelerometer sensor signal representative of an acceleration of the physical object; eleventh instruction for determining from the accelerometer sensor signal an inertial load on the physical object; and twelfth instructions for subtracting the inertial load from the mechanical load as determined.

What has been mentioned above with respect to the signal processing system according to the invention applies also to the control software according to the invention. The software according to the invention can be marketed as a dedicated component for use in a load sensing system. For example, the processing of the deformation sensor signal and the temperature sensor signal can be tailored to the specific type of physical object on which the mechanical load is to be determined. That is, each specific type of control software according to the invention is tailored to a specific one of a plurality of types of physical objects. Different types of physical

objects may be composed of different materials having different thermal properties (e.g., thermal conductivity) and different mechanical properties (e.g., stiffness, compressibility). Different types of different physical objects may have different sizes and natural-mode shapes. The control software as marketed can therefore be tailored to a specific type of physical object.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is explained in further detail, by way of example and with reference to the accompanying drawings, wherein:

Fig.1 is a block diagram of a load sensing system according to the invention; and

Fig.2 is a diagram explaining an embodiment of the method of the invention.

DETAILED EMBODIMENTS

In short, an embodiment of the invention relates to determining a mechanical load on a rolling element bearing from the deformation of a bearing ring. Computational efficiency is obtained by expressing the deformation as a first linear combination of natural-mode shapes of the bearing ring. A thermal load on the bearing ring is also expressed as a second linear combination of the same natural- mode shapes. Subtracting the second linear combination from the first linear combination enables to remove a thermally induced deformation from the sensed deformation.

Consider a rolling element bearing that has its axis of rotation oriented in a horizontal plane and that is carrying a load under gravity. The heat that causes the thermally induced deformation is at least partly due to the frictional forces that are exerted on the rolling elements when they are travelling along their circular path relative to the coaxially mounted inner ring and outer ring. The weight of the load is transferred from, e.g., the inner ring to the outer ring via specific ones of the rolling elements that happen to be in the lower half of the path. The rolling elements in the upper half of the path do not carry the weight of the load. As a result the frictional forces operating on, on the one hand, a particular one of the rolling elements and, on the other hand, the inner ring and the outer ring are largest when the particular rolling element is travelling in the lower half of the path. The frictional forces give rise to local heating and, hence, to thermally induced deformation of the inner ring and the outer ring. In "On the dynamics of ball bearings", J.A. Wensing, ISBN 90-36512298, page 38, it is stated

that the temperature increase as a result of friction is independent of the (mechanical) load in case of pure rolling contact between the rolling elements, on the one hand, and the inner ring and the outer ring on the other hand.

Another cause of the thermally induced deformation is a result from the local compression of the material of the inner ring and the material of the outer ring under the load. To explain this, consider the following. A piston is allowed to slide without friction in a cylinder filled with gas. If the piston is being moved so as to decrease the volume occupied by the gas, the gas molecules collide with the surface of the moving piston. Assuming that this is an elastic collision, the molecules leave the piston with a higher kinetic energy than they had prior to the collision. Random collisions with other gas molecules cause at least part of the kinetic energy to be transferred to the other gas molecules. In other words, the kinetic energy of the gas, and therefore the temperature, increases. That is, the piston performs work (in the physics sense) on the gas. Similarly, if the piston is moved so as to increase the volume of the gas, the molecules colliding with the retreating piston will leave the piston with less kinetic energy than they had just before colliding. The gas now performs work on the piston. As a result, the temperature of the gas decreases.

Now consider the rolling element bearing again, and consider the material at the surface of the inner ring or of the outer ring that makes contact with the rolling elements when they pass. The surface has molecules in a lattice, and the molecules vibrate around their equilibrium positions. The vibration of a molecule is representative of the kinetic energy of the molecule. This kinetic energy is associated with the temperature of the material and is taken to be an integer number times the quantity ½ kT, wherein "k" is Boltzmann's constant and "T" stands for the temperature in degrees Kelvin. The local compression results from a particular rolling element being forced against the material of the inner ring and against the material of the outer ring. As in the cylinder filled with a gas, the collision of the rolling element with the surface locally increases the kinetic energy of the molecules, and the temperature rises at the location of the collision. Owing to the temperature difference between the location and its environment, i.e., owing to the temperature gradient, the local temperature will decrease as heat is transported away from the location through thermal conduction. When the rolling element leaves the location of compression, the material expands again. The kinetic energy of the molecules decreases and the local temperature

drops. Again, a temperature gradient is created and this time heat is transported towards the location from the location's environment. The amount of compression is dependent on the load.

The mechanically induced deformation of the bearing ring is representative of the load on the rolling element bearing. However, the deformation sensed on the bearing ring is a superposition of the mechanically induced deformation and the thermally induced deformation. In order to be able to identify the mechanically induced deformation, the thermally induced deformation is to be identified and subtracted from the deformation as sensed.

The deformation as sensed is the total deformation being the sum of the mechanically induced deformation and the thermally induced deformation. The sensor signal is representative of the total deformation.

Fig.1 is a diagram of a load sensing system 100 in the invention. The load sensing system 100 is configured for determining a mechanical load on a physical object 102, here a rolling element bearing, that is installed as a functional part of piece of machinery, e.g., a vehicle, a wind turbine, a piece of industrial equipment, etc. In order to not obscure the drawing, the other parts of the piece of machinery have not been drawn.

The rolling element bearing 102 comprises an inner ring 104 and an outer ring 106 that are positioned coaxially. The rolling element bearing 102 further comprises a plurality of rolling elements located between the inner ring 104 and the outer ring 106. In order to not obscure the drawing, only a single one of the plurality of the rolling elements has been indicated with a reference numeral 108. In operational use of the rolling element bearing 102, the inner ring 104 is mounted so as to be stationary with respect to a first physical part (not shown) of the piece of machinery, e.g., a shaft, and the outer ring 106 is mounted so as to be stationary with respect to a second physical part (not shown) of the piece of machinery, e.g., a device for driving the shaft, such as an engine or an electric motor. The plurality of rolling elements enables the inner ring 104 and, therefore, the first physical part, to freely rotate relative to the outer ring 106 around their common axis and, therefore relative to the second physical part.

In operational use of the piece of machinery, the rolling element bearing 102 is subjected to a mechanical load and a thermal load.

The mechanical load causes a mechanically induced deformation of the rolling element bearing 102. The thermal load causes a thermally induced deformation of the rolling element bearing 102.

A mechanically induced deformation (or: mechanically induced strain) of the rolling element bearing 102 is caused by applying a force and/or a torque on the rolling element bearing 102. The applied force or torque locally affects the equilibrium distance between the atoms or molecules making up the rolling element bearing 102. The rolling element bearing 102 deforms until the inter-molecular or inter-atomic forces are large enough to resist the applied force or torque. If the applied forces and torques are such, that the rolling element bearing 102 assumes its original shape after the applied forces and torques are removed, the deformation is referred to as an elastic deformation.

A thermally induced deformation of the rolling element bearing 102 is caused by heat supplied to, or drawn from, the rolling element bearing 102. The supply of heat to the rolling element bearing 102 or the extraction of heat from the rolling element bearing 102 causes the temperature distribution within the rolling element bearing 102 to change. On the atomic or molecular level, the temperature is representative of the amount of kinetic energy per atom or molecule. The kinetic energy is associated with the vibrations of the atom or molecule in the lattice that makes up at least part of the material from which the rolling element bearing 102 is made, e.g., steel. If the temperature increases relative to a reference temperature, the magnitude of the kinetic energy increases with respect to the magnitude of the kinetic energy at the reference temperature. The interactions between atoms or molecules in the lattice are described according to the Lennard-Jones potential. The atom or molecule vibrates around an equilibrium distance from a neighbour atom or neighbour molecule under the influence of a repulsive force between atoms or molecules and an attractive force between the atoms or molecules. The repulsive force increases if the atoms or molecules get closer to each other. The attractive force increases if the atoms or molecules get farther away from each other. When the atoms or molecules come closer to each other, the increase in the repulsive force per unit distance is much

larger than the increase in the attractive force per unit distance when the atoms or molecules get farther away from each other. As a result, an increase in temperature implies that the atoms or molecules spend more time at a larger distance than the original equilibrium distance. This is the microscopic justification of the macroscopic thermal expansion of a material when the temperature of the material increases.

If the temperature is not uniform throughout the rolling element bearing 102, there is a temperature gradient within the rolling element bearing 102. The temperature gradient drives the transport of heat within the rolling element bearing 102 as a result of a finite thermal conductivity of the material of the rolling element bearing 102. If the rolling element bearing 102 is put into an environment of a constant temperature after heat has been added to, or extracted from, the rolling element bearing 102, the temperature gradient causes the temperature distribution to change until the rolling element bearing 102 is in thermal equilibrium with the environment. As a result, the thermally induced deformation evolves as long as heat is transported throughout the rolling element bearing 102, driven by a non-zero temperature gradient, until thermal equilibrium with the environment is reached. The character of the thermally induced deformation of the rolling element bearing 102 depends on the temperature distribution across the rolling element bearing 102, the shape of the rolling element bearing 102, the distribution of materials across the rolling element bearing 102, and on the thermal properties of the materials such as the thermal expansion coefficients of the materials and the thermal conductivity of the materials.

Consider now that, in operational use of the piece of machinery, a force or a torque is applied to the rolling element bearing 102 and that, at the same time, a temperature gradient exists within the rolling element bearing 102 or between the rolling element bearing 102 and an environment of the rolling element bearing 102. Then, the rolling element bearing 102 deforms as a result of both the mechanical load and the thermal load. As a result, individual load-carrying parts of the bearing 102, i.e. the inner ring 104, the outer ring 106 and loaded rolling elements 108, are deformed due to the thermal and mechanical load. Bearing deformation can therefore be measured by measuring a deformation of the inner ring 104, the outer ring 106 or a rolling element 108.

In the example shown, deformation of the bearing outer ring 106 is measured by means of, e.g., one or more deformation sensors. The deformation is sensed by means of e.g. strain gauges, such as a first strain gauge 110, a second strain gauge 112, a third strain gauge 114, a fourth strain gauge 116, a fifth strain gauge 118, a sixth strain gauge 120, and a seventh strain gauge 122. In the example shown in Fig.1, the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122 are mounted on an outer circumference of the bearing outer ring 106. The first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122 may also be mounted on an inner circumference of the bearing inner ring 104, or on both the outer circumference of the outer ring 106 and the inner circumference of the inner ring 104. Preferably, the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122 are mounted on the stationary one of the inner ring 104 and the outer ring 106, in order to have reliable signal paths for receiving the respective sensor signals from the respective ones of the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122.

The first strain gauge 110 provides a first strain signal S110 representative of the deformation of the outer ring 106 at the location of the first strain gauge 110. The second strain gauge 112 provides a second strain signal S112 representative of the deformation of the outer ring 106 at the location of the second strain gauge 112. The third strain gauge 114 provides a third strain signal S114 representative of the deformation of the outer ring 106 at the location of the third strain gauge 114. The fourth strain gauge 116 provides a fourth strain signal S116 representative of the deformation of the outer ring 106 at the location of the fourth strain gauge 116. The fifth strain gauge 118 provides a fifth strain signal S118 representative of the deformation of the outer ring 106 at the location of the fifth strain gauge 118. The sixth strain gauge 120 provides a sixth strain signal S120 representative of the deformation of the outer ring 106 at the location of the sixth strain gauge 120. The seventh strain gauge 122 provides a seventh strain signal S122 representative of the deformation of the outer ring 106 at the location of the seventh strain gauge 122.

The load sensing system 100 also comprises a signal processing system 125. The signal processing system 125 is configured for receiving and processing the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122. The signal processing system 125 comprises, for example, a general-purpose computer with dedicated software on a computer-readable medium for processing the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122. Alternatively, the signal processing system 125 comprises one or more dedicated signal processors or dedicated electronic hardware for processing the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122.

The signal paths between the signal processing system 125 and the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122, have been omitted from the drawing in order to not obscure the drawing. The signal paths may be implemented by wired connections and/or wireless connections between the signal processing system 125 and the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122.

Assume that the signal processing system 125 were to process the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122, in order to determine the mechanical load on the rolling element bearing 102. The mechanical load on the rolling element bearing 102 could be determined using, for example, the approach disclosed in US patent 7,444,888 and US patent 7,389,701, referred to above. That is, the mechanical load could be determined from a first truncated series of natural-mode shapes for approximating a first shape of the bearing outer ring 106 corresponding to the deformation as sensed.

However, the mechanical load thus determined would not be an accurate representative of the actual mechanical load, because the deformation of the outer ring 106 as sensed contains also a contribution arising from a thermal load, in addition to another contribution from the mechanical load. In order to extract, from the deformation as sensed, information about the actual mechanical load on the rolling element bearing 102, the inventors proceed as follows.

In order to determine the thermal deformation of the bearing outer ring 106, the load sensing system 100 is provided with at least one pair of temperature sensors. Because the thermal load on the bearing 102 and bearing outer ring 106 is due to temperature gradients, the temperature sensors are suitably located at first and second locations on the bearing outer ring where different temperatures are expected, in order to sense a temperature gradient. For example, one temperature sensor of the pair may be located in a loaded zone of the bearing outer ring and the other temperature sensor of the pair may be located in a non-loaded zone of the bearing outer ring.

For greater accuracy, the load sensing system 100 is suitably provided with more than one pair of temperature sensors for sensing more than one temperature gradient. The system depicted in Fig. 1 comprises a first temperature sensor 124, a second temperature sensor 126, a third temperature sensor 128, a fourth temperature sensor 130, a fifth temperature sensor 132, a sixth temperature sensor 134, a seventh temperature sensor 136, and an eighth temperature sensor 138. In the depicted embodiment, the temperature sensors are mounted on the outer circumference of the bearing outer ring 106. Advantageously, an inner circumference of the bearing outer ring 106 may also be provided with at least one temperature sensor, so as to sense a temperature gradient across the bearing ring in a radial direction. Needless to say, in embodiments where the deformation of the bearing inner ring 104 is sensed, the at least one pair of temperature sensors is provided on the inner ring.

The first temperature sensor 124 supplies a first temperature signal T124 representative of the temperature sensed at the location of the first temperature sensor 124. The second temperature sensor 126 supplies a second temperature signal T126 representative of the temperature sensed at the location of the second temperature sensor 126. The third temperature sensor 128 supplies a third

temperature signal T128 representative of the temperature sensed at the location of the third temperature sensor 128. The fourth temperature sensor 130 supplies a fourth temperature signal T130 representative of the temperature sensed at the location of fourth temperature sensor 130. The fifth temperature sensor 132 supplies a fifth temperature signal T132 representative of the temperature sensed at the location of the fifth temperature sensor 132. The sixth temperature sensor 134 supplies a sixth temperature signal T134 representative of the temperature sensed at the location of the sixth temperature sensor 134. The seventh temperature sensor 136 supplies a seventh temperature signal T136 representative of the temperature sensed at the location of the seventh temperature sensor 136. The eighth temperature sensor 138 supplies an eighth temperature signal T138 representative of the temperature sensed at the location of eighth temperature sensor 138.

The signal processing system 125 receives and processes the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138. The processing comprises determining temperature gradients between individual pairs of the temperature signals and further comprises determining a second truncated series of the natural-mode shapes for approximating a second shape of the bearing outer ring 106 corresponding to a spatial distribution of the temperature of the bearing outer ring 106 that corresponds to the temperature gradients determined from the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138. The local temperature in a piece of material is a measure of the local thermal expansion or local thermal contraction relative to a shape of the material at a reference temperature. Accordingly, the spatial distribution of the temperature throughout the bearing outer ring 106 at a particular moment determines the shape that the bearing outer ring assumes at that very moment in the absence of a mechanical load exerted from outside on the rolling element bearing 102.

The spatial distribution of the temperature as derived from the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth

temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138 may be used as an input to an associative memory or an artificial neural network (not shown) in the signal processing system 125. The associative memory or the artificial neural network maps the spatial distribution of the temperature as derived on a particular thermally induced deformation of the bearing outer ring 106. For example, the associative memory stores a number of pre-determined spatial temperature distributions. Each respective one of the spatial temperature distributions is associated with a respective one of a number of pre-determined thermally induced deformations of the bearing outer ring 106. The associative memory selects that particular one of the number of pre-determined spatial distributions of the temperature that resembles the spatial distribution of the temperature as derived the most according to a pre-determined criterion. Then, the thermally induced deformation is selected that is associated with the particular distribution of the temperature. The thermally induced deformation selected is represented as a particular linear combination of the natural-mode shapes. This particular linear combination is then taken as the truncated second series of the natural-mode shapes to be subtracted from the first truncated series of natural mode shapes, which is determined on the basis of the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122.

The thermally induced deformation of the bearing outer ring 106 as determined from the temperature gradients as sensed is approximated by a second truncated series of natural-mode shapes corresponding to the deformation as determined on the basis of the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138.

The deformation as sensed by the first strain gauge 110, the second strain gauge 112, the third strain gauge 114, the fourth strain gauge 116, the fifth strain gauge 118, the sixth strain gauge 120 and the seventh strain gauge 122 is expressed as the first truncated series of the natural-mode shapes. If the second truncated series of natural-mode shapes is subtracted from the first truncated series of the natural-mode shapes,

a third truncated series of natural-mode shapes remains that is interpreted as the thermally compensated deformation suitable for determining the actual mechanical load using the methods as described in US patent 7,444,888 and US patent 7,389,701, referred to above.

The number of temperature sensors employed, and the number of deformation sensors employed is a design choice of the system designer. For example, the number of deformation sensors employed should be large enough to be able to distinguish individual ones of the number of natural-mode shapes considered relevant to determining the mechanical load to a desired accuracy.

The load sensing system 100 may further comprise an accelerometer 127 that supplies an accelerometer signal A127 representative of an acceleration to which the rolling element bearing 102 is subjected as a whole. The accelerometer signal A127 is supplied to the signal processing system 125. The signal processing system 125 is configured to subtract the acceleration from the mechanically induced load determined on the basis of the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122, and the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138. Removal of the influence of the acceleration from the mechanical load as determined provides information about the mechanical load exerted on the rolling element bearing 102 by the other components of the machinery of which the rolling element bearing 102 forms a functional part.

As noted earlier, the signal processing system 125 may be implemented by way of a general-purpose computer that processes the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122, and the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136,

the eighth temperature signal T138 and the accelerometer signal A127, under control of a dedicated piece of control software 129 on a computer-readable medium.

Fig.2 is a process diagram for illustrating an embodiment 200 of the method according to the invention. In a first step 202, the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122 are received.

In a second step 204, the first shape is determined of the bearing outer ring 106 that corresponds to the first strain signal S110, the second strain signal S112, the third strain signal S114, the fourth strain signal S116, the fifth strain signal S118, the sixth strain signal S120 and the seventh strain signal S122. The first shape is representative of the deformation of the bearing outer ring 106 as sensed.

In a third step 206, the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138 are received.

In a fourth step 208, the second shape is determined of the bearing outer ring 106 that corresponds to temperature gradients determined from the first temperature signal T124, the second temperature signal T126, third temperature signal T128, the fourth temperature signal T130, the fifth temperature signal T132, the sixth temperature signal T134, the seventh temperature signal T136 and the eighth temperature signal T138. The second shape is representative of the thermally induced deformation of the bearing outer ring 106 as calculated.

In a fifth step 210, the difference is determined between the first shape and the second shape. That is, the thermally induced deformation as calculated is removed from the deformation as sensed.

In a sixth step 212, the difference is considered the proper mechanically induced deformation of the bearing outer ring 106, on the basis of which the mechanical load can be calculated, using the approach as described in, e.g., US patent 7,444,888 and

US patent 7,389,701, referred to above, or as described in US patent 5,952,587 referred to above.

The method of the invention has been described with regard to determining the mechanical load on a rolling element bearing by determining the mechanically induced deformation of the bearing outer ring. The method is not restricted to rolling element bearings, however, and may be applied in any system where deformation of an object is measured in order to determine a mechanical load acting on the object and whereby the object is also subject to thermal loading. For example, the method may be also applied to a load cell in order to improve the accuracy of the load measured. In a further example, a housing of a machine component, such as a rolling element bearing, may be instrumented with one or more deformation sensors and two or more temperature sensors for executing the method of the invention. Numerous applications exist, and the invention may thus be varied within the scope of the accompanying patent claims.

CLAIMS

1. A method of determining a mechanical load on a physical object (106), wherein the method comprises:
   - sensing a deformation of the physical object at at least a particular location on the physical object;
   - determining (204) a first shape of the physical object corresponding to the deformation as sensed;
   - measuring one or more temperature gradients within the physical object by sensing a temperature of the physical object at at least a first location and a second location on the physical object;
   - determining (208) a second shape of the physical object corresponding to the one or more temperature gradients as measured;
   - determining (210) a difference between the first shape and the second shape; and
   - determining (212) the mechanical load based on the difference.

2. The method of claim 1, wherein the method comprises:
   - representing the first shape as a first truncated series of natural-mode shapes of the physical object; and
   - representing the second shape as a second truncated series of the natural-mode shapes;

   and the determining of the difference comprises subtracting the second truncated series of the natural-mode shapes from the first truncated series of the natural-mode shapes.

3. The method of claim 1 or 2, comprising:
   - determining a rate of change of the temperature at at least the first location;
   - using the rate of change to determine a further temperature at a further location on the physical object other than the first location; and
   - using the temperature and the further temperature in the determination of the second shape.

4. The method of claim 1, 2 or 3, comprising:
   - determining an acceleration of the physical object for determining an inertial load on the physical object; and
   - subtracting the inertial load from the mechanical load as determined.

5. A load sensing system (100) for determining a mechanical load on a physical object (106), wherein the load sensing system comprises:
   - one or more deformation sensors (110, 112, 114, 116, 118, 120 ,122), configured for supplying a deformation sensor signal representative of a deformation of the physical object at at least a particular location on the physical object;
   - two or more temperature sensors (124, 126, 128, 130, 132, 134, 136, 138) configured for supplying a temperature sensor signal representative of one or more temperature gradients within the physical object, measured by sensing a temperature of the physical object at at least a first location and a second location on the physical object; and
   - a signal processing system (125) configured for:
     - receiving the deformation sensor signal and the temperature sensor signal;
     - determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed;
     - determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients distribution as measured;
     - determining a difference between the first shape and the second shape; and
     - determining the mechanical load based on the difference.

6. The load sensing system of claim 5, wherein the signal processing system is configured for:
   - representing the first shape as a first truncated series of natural-mode shapes of the physical object; and
   - representing the second shape as a second truncated series of the natural-mode shapes;

and the determining of the difference comprises subtracting the second truncated series of the natural-mode shapes from the first truncated series of the natural-mode shapes.

7. The load sensing system of claim 5 or 6, wherein the signal processing system is configured for:
   - determining a rate of change of the temperature at at least the first location;
   - determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and
   - determining the second shape based on the temperature and the further temperature.

8. The load sensing system of claim 5, 6 or 7, wherein:
   the load sensing system comprises an accelerometer (127) for supplying an accelerometer sensor signal representative of an acceleration of the physical object; and
   the signal processing system is configured for:
   - receiving the accelerometer sensor signal;
   - determining from the accelerometer sensor signal an inertial load on the physical object; and
   - subtracting the inertial load from the mechanical load as determined.

9. A signal processing system (125) for use in a load sensing system (100) for determining a mechanical load on a physical object (106), wherein the signal processing system is configured for:
   - receiving a deformation sensor signal representative of a deformation of the physical object at at least a particular location on the physical object; and
   - receiving a temperature sensor signal representative of one ore more temperature gradients within the physical object, measured by sensing a temperature of the physical object at at least a first location and a second location on the physical object;
   - determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed; and

- determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients as measured.

10. The signal processing system of claim 9, configured for:
    - determining a difference between the first shape and the second shape; and
    - determining the mechanical load based on the difference.

11. The signal processing system of claim 9 or 10, configured for:
    - representing the first shape as a first truncated series of natural-mode shapes of the physical object; and
    - representing the second shape as a second truncated series of the natural-mode shapes.

12. The signal processing system of claim 9, 10 or 11, configured for:
    - determining a rate of change of the temperature at at least the first location;
    - determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and
    - determining the second shape based on the temperature and the further temperature.

13. The signal processing system of claim 9, 10, 11 or 12, configured for:
    - receiving an accelerometer signal representative of an acceleration of the physical object;
    - determining from the accelerometer signal an inertial load on the physical object; and
    - subtracting the inertial load from the mechanical load as determined.

14. Control software (129) on a computer-readable medium for configuring a signal processing system (125) for use in a load sensing system (100) that is designed for determining a mechanical load on a physical object (106), wherein the control software comprises:
    - first instructions for receiving a deformation sensor signal representative of a deformation of the physical object at at least a particular location on the physical object;
    - second instructions for receiving a temperature sensor signal representative of one or more temperature gradients within the physical object, measured by sensing a temperature of the physical object at at least a first location and a second location on the physical object;
    - third instructions for determining from the deformation sensor signal a first shape of the physical object corresponding to the deformation as sensed; and
    - fourth instructions for determining from the temperature sensor signal a second shape of the physical object corresponding to the one or more temperature gradients as measured.

15. The control software of claim 14, comprising:
    - fifth instructions for determining a difference between the first shape and the second shape; and
    - sixth instructions for determining the mechanical load based on the difference.

16. The control software of claim 14 or 15, wherein:
    - the third instructions are configured for representing the first shape as a first truncated series of natural-mode shapes of the physical object; and
    - the fourth instructions are configured for representing the second shape as a second truncated series of the natural-mode shapes.

17. The control software of claim 14, 15 or 16, comprising:
    - seventh instructions for determining a rate of change of the temperature at at least the first location;
    - eighth instructions for determining from the rate of change of the temperature a further temperature at a further location on the physical object other than the first location; and
    - ninth instructions for determining the second shape based on the temperature and the further temperature.

18. The control software of claim 14, 15, 16 or 17, comprising:
    - tenth instructions for receiving an accelerometer sensor signal representative of an acceleration of the physical object;
    - eleventh instructions for determining the accelerometer sensor signal an inertial load on the physical object; and
    - twelfth instructions for subtracting the inertial load from the mechanical load as determined.

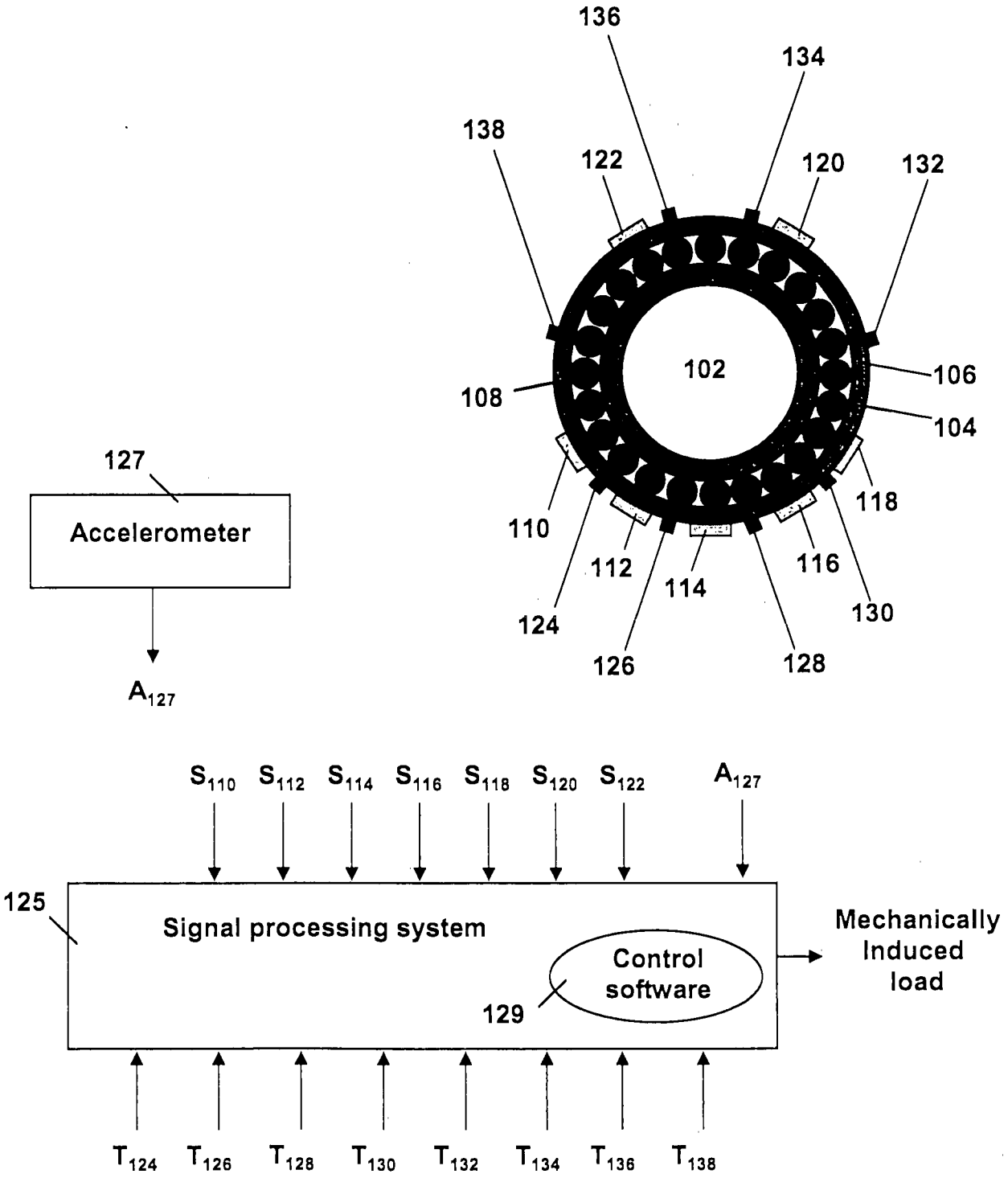
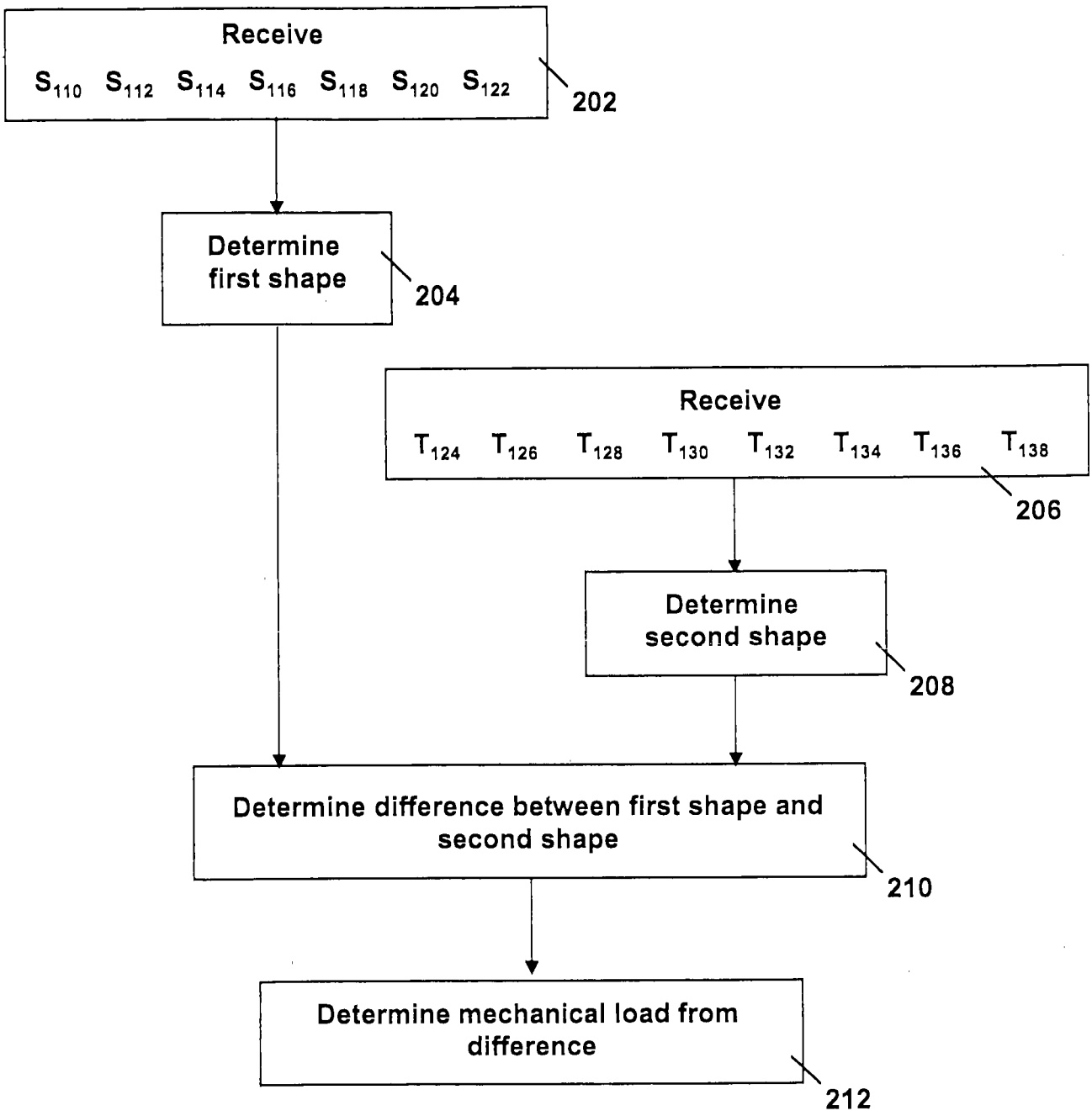

136
134
138
122
120
132
102
106
108
104
127
Accelerometer
110
118
112
116
114
130
124
126
128
A_{127}
S_{110} S_{112} S_{114} S_{116} S_{118} S_{120} S_{122} A_{127}
125
Signal processing system
Control software
129
Mechanically Induced load
T_{124} T_{126} T_{128} T_{130} T_{132} T_{134} T_{136} T_{138}

Fig.1

100


Receive
S_{110} S_{112} S_{114} S_{116} S_{118} S_{120} S_{122}
202
Determine first shape
204
Receive
T_{124} T_{126} T_{128} T_{130} T_{132} T_{134} T_{136} T_{138}
206
Determine second shape
208
Determine difference between first shape and second shape
210
Determine mechanical load from difference
212

200

Fig.2

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2011/001779

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01L1/26 G01L5/00 G01B21/04 G01D3/036
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01L G01B G01D

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

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2002/026835 A1 (JACOB JOERN [DE] ET AL) 7 March 2002 (2002-03-07) paragraph [0019] - paragraph [0040]; figures 1-6	1,5,9, 10,14,15 2-4,6-8, 11-13, 16-18

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
8 July 2011	19/07/2011

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gruss, Christian

INTERNATIONAL SEARCH REPORT

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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