

Description

This invention relates to the detection and quantification of force-torque components. This invention includes both the process and apparatus of detecting and quantifying force-torque components. This invention is a multicomponent force-torque sensor capable of detecting and quantifying force-torque components.

The applicants have an earlier application EP-A-0 182 466. The invention described and claimed in that application differs from the present invention in many significant respects. The previous invention concerns itself with the detection, quantification and distribution of a single force component, i.e. an applied force normal to the sensor surface. As more fully described below, this invention concerns itself with multicomponent forces and torques.

This invention has application and use wherever the detection and quantification of force-torque components are desired. Of particular interest to the inventors is the utilization of this invention in the area of robotics. The multicomponent force-torque sensor can be utilized on the gripping surface of a robotic end effector to allow for "touch sensitive" operation. The sensor can provide a flow of force-torque component information to facilitate the grasping, transportation and manipulation of objects. Such information can assist in the determination and control of gripping force and object position, orientation and slippage. The sensor can enable precision insertion or fitting of an object without jamming or misalignment and can lessen the impact of collisions. The sensor can enable less accurate robots to perform precision tasks. Many other applications, uses and advantages of the invention, both within and without the area of robotics, exist and it is expected that many more applications, uses and advantages will arise in the future as technology continues its ever accelerating evolution. For example, the inventors envision application and use of this invention in the areas of industrial automation and prosthetics.

II. FORCE-TORQUE COMPONENTS

As used in this disclosure and the appended claims, the term "force-torque components" means the orthogonal force components F_x , F_y and F_z and the torque (or moment) components M_x , M_y and M_z as depicted in Figure 1. The term "force-torque component" is the singular of force-torque components and means any one of F_x , F_y , F_z , M_x , M_y and M_z . As shown in Figure 1, F_z represents the force component which is perpendicular to the plane defined by the paper on which Figure 1 is drawn. F_x represents the horizontal force component and F_y represents the vertical force component. Any

force F can be expressed in terms of F_x , F_y and F_z . Each of M_x , M_y and M_z represents the torque (or moment) about the axis (x , y or z) to which it corresponds. Any torque M can be expressed in terms of M_x , M_y and M_z .

III. DESCRIPTION OF THE INVENTION

The multicomponent force-torque sensor of this invention has a loadable means to which force-torque components can be applied. Preferably, the loadable means is a metal cover plate but the loadable means can be any object or surface which can be subjected to force-torque components. For example, the loadable means can be the surface of the deformable means described below. If a material (e.g. plastic, ceramic, etc.) other than metal is employed, it is preferably a rigid material.

The sensor includes a deformable means which is deformable in response to the application of a force-torque component to the loadable means. Preferably the deformable means is affixed to the loadable means. This affixation can be accomplished, for example, by attaching the deformable means directly to the loadable means or by attaching the deformable means to some intermediate device or material attached to the loadable means. The deformable means is preferably an elastomeric material such as natural rubber, synthetic rubber or silicone rubber. The deformable means desirably behaves as a set of multidimensional linear springs. Compression, tension, shear and torsion characteristics can be experimentally measured under static and dynamic conditions for displacements and rotations to determine the suitability of any given material for use as the deformable means. Preferably the deformable means is a ring-shaped (cylindrical-shaped) elastomeric pad made of silicone rubber and is attached directly to the loadable means. A ring shape (cylindrical shape) is preferred for symmetry because this simplifies the calculation of force-torque components. The deformable means can, however, be in any other shape. Although not preferred, springs and spring-like devices can be used as the deformable means.

US-A-3 921 445 discloses a multi-component force-torque sensor in accordance with the prior art portions of claims 1 and 15. This prior construction uses complicated optical means to sense individual movements, depending upon the degree of occlusion of individual beams of light. The present invention as defined in claim 1 or 15, has a simpler construction which can be readily fabricated to give a very accurate result, depending upon the times of transmit of the individual reflected signals.

While US-A-3 140 612 discloses the idea of sensing movements using a reflected ultrasonic

signal, it in no way appreciates the very much more compact and cheaper construction which can be achieved using transducers to act both as transmitting means and as receiving means as in the present invention.

The sensor as later described in detail, includes a plurality of signal-transmission means, a plurality of signal-reflection means, a plurality of signal-detection means and at least one medium through which the signals travel. The signal-transmission means transmit signals which travel to the signal-reflection means and which are then reflected to the signal-detection means. The velocity of the signals through the medium travelled by the signals can be experimentally determined by persons of ordinary skill in the art. Ultrasonic transducers as described more fully in Sections V and VI are used as combined signal transmission means and signal detection means. The signal-reflection means can be any surface (including an interface) which reflects the signals. With the signals being ultrasonic signals, the signal-reflection means can be a material of different acoustic impedance from the medium through which the signals travel. The signal-reflection means forms an interface with the medium through which the signals travel. If the reflection-means has a lower acoustic impedance than the medium, the signal is inverted (i.e. undergoes a 180° phase shift) upon reflection at the interface. If the reflection-means has a higher acoustic impedance than the medium, the signal is reflected without a 180° phase shift. The deformable means can serve as the medium through which some or all of the signals travel. A coupling agent, such as silicone oil or silicone gel, can also serve as the medium through which some or all of the signals travel. Any fluid or deformable material capable of providing a medium for signal transmission can be used as a coupling agent in the practice of this invention.

The transit time of each signal is the time required for the signal to travel from its signal-transmission means to its signal-detection means. The distance L traveled by the signal is a function of the velocity s of the signal in the medium and the signal transit time t ($L = st$). The signal-transmission means, signal-reflection means and signal-detection means are adapted and arranged so that the distance L is altered (i.e. increased or decreased) in response to the application of a force-torque component to the loadable means. Alteration of distance L for a given signal results in the alteration of the transit time t corresponding to that signal. Alteration of distance L in response to force-torque components can be achieved, for example, by affixing the signal-reflection means to the loadable means. This affixation can be accomplished by attaching the signal-reflection means

directly to the loadable means or to an intermediate device or material attached to the loadable means. A portion of the surface of the loadable means (including an interface formed by it) can be used as the signal-reflection means and under such circumstances the signal-reflection means is deemed to be affixed to the loadable means.

Preferably, the sensor includes a substrate which can be any means for supporting the signal-transmission means and signal-detection means and thereby providing a reference position from which differences in signal transit time t (or differences in signal distance L) can be determined. The substrate provides direct support when the signal-transmission means or signal-detection means are mounted on or affixed to the substrate. The substrate provides indirect support when the signal-transmission means or signal-detection means are mounted on or affixed to an extension from the substrate.

The sensor further includes a means for determining a plurality of force-torque components. This determination can be accomplished by measuring the transit time t for a plurality of signals. These transit times can be used to calculate or measure force-torque components as demonstrated in Section V below. Force-torque components and changes in force-torque components can be monitored on a continuous basis to provide valuable information. For example, if the sensor is placed on a robotic end effector this information can be utilized for "touch sensitive" operation.

The sensor of this invention can also, of course, be used to detect and determine a single force-torque component as well as a plurality of such components. Not only can the sensor detect and determine F_z , where F_z is normal to the contact surface of the loadable means, but the sensor can detect and determine any one of F_x , F_y , M_x , M_y and M_z . The contact surface of the loadable means is the surface which comes into contact with the object or bodies to be gripped, encountered or "felt."

IV. DESCRIPTION OF THE DRAWINGS

Figure 1 depicts the force-torque components.

Figure 2 depicts the multicomponent force-torque sensor described in Section V.

Figure 3 depicts an overview of the sensor of Figure 2 with the cover plate removed.

Figure 4 depicts a side view of the sensor of Figure 2.

Figure 5 depicts an "exploded" view of the sensor of Figure 2.

Figure 6 depicts a cross-sectional view of two leads and a transducer of the sensor of Figure 2.

Figure 7 depicts an overview of the multicom-

Component force-torque sensor described in Section VI with the cover plate removed.

Figure 8 depicts a side view of the sensor of Figure 7 with the cover plate.

Figure 9 depicts two perspectives of the reflecting post of the sensor of Figure 7.

Figure 10 depicts an overview of the substrate of the sensor of Figure 7.

Figure 11 depicts a cross-sectional view of the transducers and substrate of the sensor of Figure 7.

V. FIRST EMBODIMENT OF THE INVENTION

The multicomponent force-torque sensor depicted in Figures 2, 3, 4, 5 and 6 is one embodiment of this invention. The sensor includes a brass cover plate A bonded with a silicone rubber adhesive to a ring-shaped (cylindrical-shaped) elastomeric pad B. The elastomeric pad B is bonded with the same type of adhesive to a substrate C. The cover plate A is fabricated from a 1.6 mm thick brass plate and is in the form of a square (27 mm x 27 mm). The elastomeric pad B is cast using degassed RTV-615 (Registered Trade Mark) silicone rubber (supplied by General Electric) cured overnight at 60°C. The substrate is a 6.4 mm thick aluminum plate in the form of a square (27 mm x 27 mm). The ring-shaped elastomeric pad B has an outside diameter of 25.4 mm, an inside diameter of 15.9 mm and a height of 6.4 mm. Brass reflectors R₁, R₂, R₃ and R₄ extend from the cover plate A. The dimensions of the rectangular reflectors are 5.8 mm (high) x 6.2 mm (wide) x 0.5 mm (thick).

The sensor further includes eight rectangular (2.0 mm x 3.5 mm) transducers X₁, X₂, X₃, X₄, X₅, X₆, X₇ and X₈. Transducers X₁, X₂, X₃ and X₄ are mounted on vertical post D (4.8 mm x 2.5 mm x 0 mm). The vertical post D is made of brass. Transducers X₅, X₆, X₇ and X₈ are mounted on substrate C. Each of the transducers is made of .028 mm thick polyvinylidene fluoride (PVDF) (or other piezoelectric material) and metal electrodes on both sides of the PVDF. Leads Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Y₇ and Y₈ run from transducers X₁, X₂, X₃, X₄, X₅, X₆, X₇ and X₈ to a voltage source V. The voltage source V can be a conventional pulse generator. Each transducer has a thin film of tin-aluminum H vacuum deposited on the PVDF G (see Figure 6) to serve as a first electrode. The vertical post D serves as the second electrode for transducers X₁, X₂, X₃ and X₄. The substrate C serves as the second electrode for transducers X₅, X₆, X₇ and X₈. Figure 6 depicts a cross-section of transducer X₆ and leads Y₁, Y₆ and Y₈. When subjected to excitation voltage pulses (typically ranging from about 5v to about 50v) from voltage source V and through leads Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Y₇ and Y₈, the

PVDF between electrodes is mechanically distorted. This distortion results in the transmission of ultrasonic signals of approximately sinusoidal shape from the transducers. The cover plate A, elastomeric ring B and substrate C form a cavity F which holds a coupling agent. The coupling agent can be any fluid or deformable material through which the signals can travel. Silicone gel is the preferred coupling agent, however, other gels or liquids (e.g. silicone oil, water, etc.) can be used. The coupling agent is introduced into and removed from the cavity F through a filling port E. In an alternative embodiment the cavity F is filled with an elastomeric material which serves as the coupling agent.

The substrate C serves to support the transducers X₁, X₂, X₃, X₄, X₅, X₆, X₇ and X₈ and to provide a reference position from which differences in signal transmit time (or differences in signal distance) can be determined. Substrate C directly supports transducers X₅, X₆, X₇ and X₈ which, as noted previously, are mounted on it. Substrate C indirectly supports transducers X₁, X₂, X₃ and X₄ which, as noted previously, are mounted on vertical post D which is an extension of (or fixed to) substrate C.

When an ultrasonic signal is transmitted from transducer X₁, X₂, X₃ or X₄ the signal travels through the coupling agent in cavity F, strikes the corresponding reflector R₁, R₂, R₃ or R₄ and returns to the transducer X₁, X₂, X₃ or X₄ from which the signal was transmitted. When an ultrasonic signal is emitted from transducer X₅, X₆, X₇ or X₈ the signal travels through the elastomeric pad B, strikes the cover plate A (which serves as a reflector) and returns to the transducer X₅, X₆, X₇ or X₈ from which it was transmitted. The application of force-torque components to the cover plate alters the distance L' between transducers and corresponding reflectors (note that L' = 1/2 L) and, therefore, alters signal transit times. The substrate C, as noted previously, provides the reference position from which these changes in signal distance and signal transit time can be determined.

The reflection of an ultrasonic signal occurs at the interface of the signal-reflection means (i.e. reflector or cover plate) and the medium (i.e. coupling agent or elastomeric pad B) through which the signal travels. The signal-reflection means reflects the ultrasonic signal by forming this interface. When the ultrasonic signal returns to the transducer the signal distorts the PVDF. This distortion results in an electric signal. The electric signals from transducers X₁, X₂, X₃, X₄, X₅, X₆, X₇ and X₈ run through leads Y₁, Y₂, Y₃, Y₄, Y₅, Y₆, Y₇ and Y₈ to pulse-echo electronic circuitry. The time required for an ultrasonic signal to travel from the transducer to the reflector and from the reflector

back to the transducer is the pulse-echo transit time. The pulse-echo electronic circuitry measures the pulse-echo transit time corresponding to each transducer. Conventional pulse-echo electronic circuitry is suitable for the practice of this invention. The means and technology needed for ultrasonic signal pulse generation, detection and transit time measurement are known to persons of skill in the art. Further information concerning ultrasonic transducers and related circuitry can be found, for example, in:

1. Myers, G.H., A. Thumin, S. Feldman, G. De Santis, and F. J. Lupo, A Miniature Pulser-Preamplifier for Ultrasonic Transducers, Ultrasonics, March 1972.
2. Mattila, P., and M. Luukkala, FET Pulse Generator for Ultrasonic Pulse Echo Applications, Ultrasonics, September 1981.
3. Duncan, M.G., An Automatic Noise-Blanking, Pulse-Timing Discriminator For Ultrasonic Non-destructive Testing, 1979 IEEE Ultrasonics Symposium.
4. Wells, P.N.T., Physical Principles of Ultrasonic Diagnosis, Academic Press, New York, 1969.
5. Swartz, R.G., and J. D. Plummer, On The Generation of High-Frequency Acoustic Energy with Polyvinylidene Fluoride, IEEE Transactions on Sonics and Ultrasonics, Vol. SU-27, No. 6, November 1980.
6. Shaw, H.J., D. Weinstein, L.T. Zitelli, C.W. Frank, R.C. DeMattei, and K. Fesler, PVF₂ Transducers, To Be Published.
7. DeReggi, A.S., S.C. Roth, J.M. Kenney, S. Edelman, and G.R. Harris, Piezoelectric Polymer Probe for Ultrasonic Applications, J. Acoust. Soc. Am. 69(3), March 1981.

The change in pulse-echo transit times (Δt_1 , Δt_2 , Δt_3 , Δt_4 , Δt_5 , Δt_6 , Δt_7 and Δt_8) produced by an applied force and/or torque are used to calculate the force-torque components as follows:

$$\begin{aligned} F_x &= (1/2a) (\Delta t_1 - \Delta t_2) \\ F_y &= (1/2b) (\Delta t_3 - \Delta t_4) \\ F_z &= (-1/2c) (\Delta t_5 + \Delta t_6) \\ F_z &= (-1/2c) (\Delta t_7 + \Delta t_8) \\ M_x &= (1/2d) (\Delta t_5 - \Delta t_6) \\ M_y &= (1/2e) (\Delta t_7 - \Delta t_8) \\ M_z &= (1/2f) (\Delta t_3 + \Delta t_4) \end{aligned}$$

Coefficients a, b, c, d, e and f are $2(k_i s_i)$ where k_i is the elastomeric spring constant for the appropriate force or torque component (to be measured experimentally) and s_i is the speed of the ultrasonic signal in the elastomeric pad B or the coupling agent, whichever is applicable. It is also noted that the distance L'_1 between a transducer and its reflector is equal to $(1/2) (s_i t_i)$. For example, $L'_2 =$

$(1/2) (s_2 t_2)$ where L'_2 is the distance between X_2 and R_2 , where s_2 is the speed of the signal in the coupling agent and t_2 is the pulse-echo transit time.

When the cover plate A is loaded, i.e. subjected to one or more forces (F_x , F_y , F_z) and/or torques (M_x , M_y , M_z) the transducer-reflector distance (L'_1) is altered and, therefore, the pulse-echo transit time (t_i) is altered. Using the above-described equations, the forces (F_x , F_y , F_z) and torques (M_x , M_y , M_z) can be monitored using periodically measured pulse-echo transit times.

Transducers X_1 and X_2 measure translation of the cover plate A along the x-axis (see Figure 2) due to F_x and rotation of the cover plate A due to M_z . Transducers X_3 and X_4 measure translation of the cover plate A along the y-axis (see Figure 2) due to F_y and rotation of the cover plate A due to M_z . The sign (positive or negative) of M_z in the formula given above depends upon whether t_3 and t_4 increase or decrease. If reflectors R_3 and R_4 are rotated clockwise, reflector R_3 rotates closer to transducers X_3 (thus decreasing t_3) and reflector R_4 rotates closer to transducer X_4 (thus decreasing t_4). Therefore, when t_3 and t_4 decrease, it is known that M_z is in a clockwise direction and when t_3 and t_4 increase, it is known that M_z is in a counterclockwise direction.

In a variation of the embodiment depicted in Figures 2, 3, 4, 5 and 6 the post D can be three-sided (i.e. a cross-section viewed from above is triangular). The three-sided post has one transducer on each side. Three reflectors extending from the cover plate are positioned to reflect the signals from those transducers. Three other transducers are mounted in a triangular pattern on the substrate below the elastomeric pad. This arrangement can be utilized to determine all of the force-torque components. Although this arrangement requires only six transducers it is less favorable because the calculations necessary for determination of force-torque components are more complex.

VI. PREFERRED EMBODIMENT OF THE INVENTION

The multicomponent force-torque depicted in Figures 7, 8, 9, 10 and 11 is the preferred embodiment of the invention and is a modification of the embodiment depicted in Figures 2, 3, 4, 5 and 6. The dimensions of the various components of the preferred embodiments are the same as the dimensions of their counterparts in the first embodiment except as stated otherwise. The preferred sensor includes a brass cover plate A bonded with an adhesive to a ring-shaped (circular shaped) elastomeric pad B. The elastomeric pad B is bonded with adhesive to a ceramic substrate C. The

Cover plate A is fabricated from 1.6 mm thick brass. The elastomeric pad is made of RTV-615 silicone rubber as before.

The ceramic substrate C and ultrasonic transducers $X_1, X_2, X_3, X_4, X_5, X_6, X_7$ and X_8 are shown in better detail in Figures 10 and 11. All of the transducers are on one continuous sheet of PVDF and are mounted on the planar surface of the substrate C which greatly simplifies construction of the sensor and improves sensor accuracy because all transducers are mounted at the same time in a fixed geometric relationship. Figure 10 shows the ceramic substrate C with a pattern of leads Y and electrodes H formed thereon. The pattern can be formed by vacuum depositing a thin film of gold (or other material capable of performing an electrode function) on the substrate and by subtracting undesired gold from the substrate through conventional photo-etching techniques. The subtraction leaves the desired pattern of leads Y and electrodes H. Other conventional methods of deposition, subtraction, addition, etc. can be utilized in the practice of this invention. Figure 11 shows, in addition to ceramic substrate C and the lead and electrode pattern thereon, a thin sheet of PVDF G having a thin film of tin-aluminum H' vacuum deposited on it. Each transducer $X_1, X_2, X_3, X_4, X_5, X_6, X_7$ and X_8 is formed by the electrodes H and H' and the PVDF G material between the electrodes. The voltage pulse generator and pulse-echo circuitry described in Section V can be utilized in connection with this embodiment. Voltage excitation of the electrodes results in the transmission of ultrasonic signals.

The reflecting post D has four 45° metal reflecting surfaces D'. The reflecting post D, including its reflecting surfaces D', is made of brass (but can be made of any other metal or material capable of creating a good reflecting interface). Each reflecting surface D' is positioned above a transducer (i.e. X_1, X_2, X_3 or X_4) and forms a 45° angle with the plane defined by substrate C. When transducers X_1, X_2, X_3 and X_4 transmit ultrasonic signals, the signals are reflected 90° off of reflecting surfaces D' towards reflectors R_1, R_2, R_3 and R_4 . Reflectors R_1, R_2, R_3 and R_4 reflect the signals back to the reflecting surfaces D' which in turn reflect the signals 90° back towards transducers X_1, X_2, X_3 and X_4 . The ultrasonic signals from transducers X_1, X_2, X_3 and X_4 travel through a silicone gel coupling agent (or other coupling agent) which occupies cavity F. The coupling agent is introduced into and removed from the cavity F through a filling port E.

Transducers X_5, X_6, X_7 and X_8 operate as described in the description of the first embodiment in Section V. The force-torque equations and related mathematics given in the description of the

first embodiment are also applicable here, except that $M_z = (-1/2f) (\Delta t_3 + \Delta t_4) = (-1/2f) (\Delta t_1 + \Delta t_2)$. The sensor can detect and determine the force normal to the contact surface of cover plate A (i.e. the upper surface of cover plate A in Figure 8). With reference to Figure 8, F_z is normal to the plane defined by cover plate A and therefore normal to the contact surface of the cover plate A (or loadable means). The sensor can also detect and determine any one or more of the other force-torque components (i.e. F_x, F_y, M_x, M_y and M_z in Figure 8).

Claims

1. A multi-component force-torque sensor comprising:

(a) a loadable means (A) having a contact surface to which at least one force-torque component selected from F_x, F_y, M_x, M_y and M_z can be applied, F_x and F_y being in mutually orthogonal directions parallel to said contact surface;

(b) a plurality of signal-transmission means (X_1 - X_8) for transmitting signals;

(c) a plurality of signal detection means (X_1 - X_8) for detecting signals;

(d) at least one medium through which the signals can travel;

(e) a deformable means (B) which is deformable in response to the application of said force-torque component to the loadable means; and

(f) means for using said detected signals to determine said at least one force-torque component,

characterised in that there are provided (g) a plurality of signal reflection means (R_1 - R_4, A) for reflecting said transmitted signals, and in that each said signal transmission means comprises a transducer (X_1 - X_8) which also serves as the signal detection means for a signal from that transducer reflected by an associated one of said signal reflector means (R_1 - R_4, A), the means (a), (b), (c), (d), (e) and (g) being adapted and arranged such that the application of a force-torque component to the loadable means results in the alteration of the distance travelled by signals between at least certain of the transmission and associated detection means whereby the determining means (f) can determine said at least one force-torque component.

2. A sensor in accordance with claim 1, wherein the means for using said detected signals is comprised of an electronic circuitry means for determining the transit time of each of said signals and for using said signal transit times

Cover plate A is fabricated from 1.6 mm thick brass. The elastomeric pad is made of RTV-615 silicone rubber as before.

The ceramic substrate C and ultrasonic transducers $X_1, X_2, X_3, X_4, X_5, X_6, X_7$ and X_8 are shown in better detail in Figures 10 and 11. All of the transducers are on one continuous sheet of PVDF and are mounted on the planar surface of the substrate C which greatly simplifies construction of the sensor and improves sensor accuracy because all transducers are mounted at the same time in a fixed geometric relationship. Figure 10 shows the ceramic substrate C with a pattern of leads Y and electrodes H formed thereon. The pattern can be formed by vacuum depositing a thin film of gold (or other material capable of performing an electrode function) on the substrate and by subtracting undesired gold from the substrate through conventional photo-etching techniques. The subtraction gives the desired pattern of leads Y and electrodes H. Other conventional methods of deposition, subtraction, addition, etc. can be utilized in the practice of this invention. Figure 11 shows, in addition to ceramic substrate C and the lead and electrode pattern thereon, a thin sheet of PVDF G having a thin film of tin-aluminum H' vacuum deposited on it. Each transducer $X_1, X_2, X_3, X_4, X_5, X_6, X_7$ and X_8 is formed by the electrodes H and H' and the PVDF G material between the electrodes. The voltage pulse generator and pulse-echo circuitry described in Section V can be utilized in connection with this embodiment. Voltage excitation of the electrodes results in the transmission of ultrasonic signals.

The reflecting post D has four 45° metal reflecting surfaces D'. The reflecting post D, including its reflecting surfaces D', is made of brass (but can be made of any other metal or material capable of creating a good reflecting interface). Each reflecting surface D' is positioned above a transducer (i.e. X_1, X_2, X_3 or X_4) and forms a 45° angle with the plane defined by substrate C. When transducers X_1, X_2, X_3 and X_4 transmit ultrasonic signals, the signals are reflected 90° off of reflecting surfaces D' towards reflectors R_1, R_2, R_3 and R_4 . Reflectors R_1, R_2, R_3 and R_4 reflect the signals back to the reflecting surfaces D' which in turn reflect the signals 90° back towards transducers X_1, X_2, X_3 and X_4 . The ultrasonic signals from transducers X_1, X_2, X_3 and X_4 travel through a silicone gel coupling agent (or other coupling agent) which occupies cavity F. The coupling agent is introduced into and removed from the cavity F through a filling port E.

Transducers X_5, X_6, X_7 and X_8 operate as described in the description of the first embodiment in Section V. The force-torque equations and related mathematics given in the description of the

first embodiment are also applicable here, except that $M_z = (-1/2f) (\Delta t_3 + \Delta t_4) = (-1/2f) (\Delta t_1 + \Delta t_2)$. The sensor can detect and determine the force normal to the contact surface of cover plate A (i.e. the upper surface of cover plate A in Figure 8). With reference to Figure 8, F_z is normal to the plane defined by cover plate A and therefore normal to the contact surface of the cover plate A (or loadable means). The sensor can also detect and determine any one or more of the other force-torque components (i.e. F_x, F_y, M_x, M_y and M_z in Figure 8).

Claims

1. A multi-component force-torque sensor comprising:

(a) a loadable means (A) having a contact surface to which at least one force-torque component selected from F_x, F_y, M_x, M_y and M_z can be applied; F_x and F_y being in mutually orthogonal directions parallel to said contact surface;

(b) a plurality of signal-transmission means (X_1-X_8) for transmitting signals;

(c) a plurality of signal detection means (X_1-X_8) for detecting signals;

(d) at least one medium through which the signals can travel;

(e) a deformable means (B) which is deformable in response to the application of said force-torque component to the loadable means; and

(f) means for using said detected signals to determine said at least one force-torque component,

characterised in that there are provided (g) a plurality of signal reflection means (R_1-R_4, A) for reflecting said transmitted signals, and in that each said signal transmission means comprises a transducer (X_1-X_8) which also serves as the signal detection means for a signal from that transducer reflected by an associated one of said signal reflector means (R_1-R_4, A), the means (a), (b), (c), (d), (e) and (g) being adapted and arranged such that the application of a force-torque component to the loadable means results in the alteration of the distance travelled by signals between at least certain of the transmission and associated detection means whereby the determining means (f) can determine said at least one force-torque component.

2. A sensor in accordance with claim 1, wherein the means for using said detected signals is comprised of an electronic circuitry means for determining the transit time of each of said signals and for using said signal transit times



- to determine said plurality of force-torque components.
3. A sensor in accordance with claim 1 or 2, wherein said signal-reflection means (R_1 - R_4 , A) are affixed to said loadable means (A).
 4. A sensor in accordance with any preceding claim, wherein said deformable means (B) is an elastomeric material.
 5. A sensor in accordance with any preceding claim, wherein said deformable means (B) has a cylindrical shape.
 6. A sensor in accordance with any one of claims 1 to 4, wherein the deformable means has an elliptical shape.
 7. A sensor in accordance with any preceding claim further comprising a substrate (C) which supports said signal-transmission means (X_1 - X_8) and signal detection means (X_1 - X_8) and which provides a reference position from which differences in signal transit time can be determined.
 8. A sensor in accordance with any preceding claim, wherein said loadable means contact surface is a surface of said deformable means.
 9. A sensor in accordance with any one of claims 1 to 7, wherein said loadable means comprises a cover plate (A).
 10. A sensor in accordance with claim 9, when appendant to claim 7, wherein said coverplate (A), said deformable means (B) and said substrate (C) form a cavity; and wherein said cavity contains a coupling agent which serves as a medium through which ultrasonic signals can travel.
 11. A sensor in accordance with claim 10, wherein said deformable means also serves as a medium through which ultrasonic signals can travel.
 12. A sensor in accordance with any preceding claim, comprising a post (D) to which at least one of said transducers is affixed.
 13. A sensor in accordance with any one of claims 1 to 10, comprising a reflector post (D) having at least one reflecting surface (D_1) for reflecting at least one of said signals to its reflector (R) and back to the transducer (X) from which it was transmitted.

14. A sensor according to claim 13, when appendant to claim 7, wherein all the transducers (X_1 - X_8) are mounted on the substrate (c) in generally coplanar arrangement.
15. A process for determining a plurality of force-torque components comprising: subjecting a loadable means to a plurality of force-torque components; transmitting signals from a signal-transmission means; reflecting said transmitted signals with a signal-reflection means; detecting said signals with a signal-detection means; and using the detected signals to determine a plurality of force-torque components; characterised in that the signals from the transmission means are reflected back to the transmission means which comprises transducers also serving as said signal-detection means, such that the signal transit times are altered in response to the force-torque components to which said loadable means is subjected with the transit times of the signals being used to determine the force-torque components.
16. A process in accordance with claim 14, wherein said transit times and said force-torque components are determined utilising an electronic circuitry means.

Revendications

1. Capteur de force-couple à composantes multiples, comprenant:
 - (a) un moyen chargeable (A) comportant une surface de contact à laquelle peut être appliquée au moins une composante de force-couple choisie parmi F_x , F_y , M_x , M_y et M_z , F_x et F_y étant dans des directions mutuellement orthogonales et parallèles à ladite surface de contact;
 - (b) une pluralité de moyens d'émission de signaux (X_1 - X_8) pour émettre des signaux;
 - (c) une pluralité de moyens de détection de signaux (X_1 - X_8) pour détecter des signaux;
 - (d) au moins un milieu par lequel les signaux peuvent circuler;
 - (e) un moyen déformable (B) qui est déformable en réponse à l'application de ladite composante de force-couple sur le moyen chargeable; et
 - (f) des moyens pour utiliser lesdits signaux détectés pour déterminer ladite au moins une composante de force-couple, caractérisé en ce que sont prévus:
 - (g) une pluralité de moyens de réflexion de signaux (R_1 - R_4 , A) pour réfléchir lesdits signaux émis,
 et en ce que chacun desdits moyens



d'émission de signaux comprend un transducteur (X_1 - X_8) servant également de moyen de détection de signal pour un signal provenant de ce transducteur et réfléchi par l'un desdits moyens réflecteurs de signaux associé (R_1 - R_4 , A), les moyens (a), (b), (c), (d), (e) et (g) étant adaptés et agencés de manière que l'application d'une composante de force-couple sur le moyen chargeable se traduit par une modification de la distance parcourue par les signaux entre au moins certains des moyens d'émission et de détection associés, moyennant quoi les moyens de détermination (f) peuvent déterminer ladite au moins une composante de force-couple.

2. Capteur selon la revendication 1, dans lequel les moyens pour utiliser lesdits signaux détectés sont constitués par des moyens à circuits électroniques pour déterminer la durée de transit de chacun desdits signaux et utiliser lesdites durées de transit des signaux pour déterminer ladite pluralité de composantes de force-couple.

3. Capteur selon la revendication 1 ou 2, dans lequel lesdits moyens de réflexion de signaux (R_1 - R_4 , A) sont fixés audit moyen chargeable (A).

4. Capteur selon l'une quelconque des revendications précédentes, dans lequel ledit moyen déformable (B) est constitué en un matériau élastomère.

5. Capteur selon l'une quelconque des revendications précédentes, dans lequel ledit moyen déformable (B) a une forme cylindrique.

6. Capteur selon l'une quelconque des revendications 1 à 4, dans lequel le moyen déformable a une forme elliptique.

7. Capteur selon l'une quelconque des revendications précédentes, comprenant en outre un substrat (C) qui supporte lesdits moyens d'émission de signaux (X_1 - X_8) et lesdits moyens de détection de signaux (X_1 - X_8) et qui fournit une position de référence à partir de laquelle peut être déterminée la différence de durée de transit des signaux.

8. Capteur selon l'une quelconque des revendications précédentes, dans lequel ladite surface de contact du moyen chargeable est une surface dudit moyen déformable.

9. Capteur selon l'une quelconque des revendica-

tions 1 à 7, dans lequel ledit moyen chargeable comprend une plaque de recouvrement (A).

10. Capteur selon la revendication 9 quand elle dépend de la revendication 7, dans lequel ladite plaque de recouvrement (A), ledit moyen déformable (B) et ledit substrat (C) forment une cavité; et dans lequel ladite cavité contient un agent de couplage qui sert de milieu par lequel peuvent circuler des signaux ultrasonores.

11. Capteur selon la revendication 10, dans lequel ledit moyen déformable sert également de milieu par lequel peuvent circuler les signaux ultrasonores.

12. Capteur selon l'une quelconque des revendications précédentes, comprenant une colonne (D) à laquelle est fixé l'un au moins desdits transducteurs.

13. Capteur selon l'une quelconque des revendications 1 à 10, comprenant une colonne réfléchissante (D) comportant au moins une surface réfléchissante (D_1) pour réfléchir au moins l'un desdits signaux vers son réflecteur (R) et en retour vers le transducteur (X) à partir duquel il a été émis.

14. Capteur selon la revendication 13 lorsqu'elle dépend de la revendication 7, dans lequel tous les transducteurs (X_1 - X_8) sont montés sur le substrat (C) selon un agencement généralement coplanaire.

15. Procédé pour déterminer une pluralité de composantes de force-couple consistant à : soumettre un moyen chargeable à une pluralité de signaux ; émettre des signaux de composantes de force-moment de torsion à partir de moyens d'émission de signaux; réfléchir lesdits signaux émis par des moyens de réflexion de signaux; détecter lesdits signaux par des moyens de détection de signaux; et utiliser les signaux détectés pour déterminer une pluralité de composantes de force-couple caractérisé en ce que les signaux provenant des moyens d'émission sont réfléchis vers les moyens d'émission qui comprennent des transducteurs servant également à constituer lesdits moyens de détection de signaux, de manière que les durées de transit des signaux soient modifiées en réponse aux composantes de force-couple auxquelles ledit moyen chargeable est soumis, la durée de transit des signaux étant utilisée pour déterminer les composantes de force-



couple.

16. Procédé selon la revendication 15, dans lequel lesdites durées de transit et lesdits composantes de force-couple sont déterminées en utilisant des moyens à circuits électroniques.

Patentansprüche

1. Mehrkomponenten-Kraft-Drehmoment-Sensor mit
 - (a) einer belastbaren Einrichtung (4), die eine Berührungsfläche hat, die mit mindestens einer aus F_x , M_x , M_y und M_z ausgewählten Kraft-Drehmoment-Komponente beaufschlagbar ist, wobei F_x und F_y in zueinander rechtwinkligen und zu der Berührungsfläche parallelen Richtungen wirksam sind;
 - (b) einer Mehrzahl von Signalsendeeinrichtungen (X_1 bis X_8) zum Senden von Signalen;
 - (c) einer Mehrzahl von Signalerfassungseinrichtungen (X_1 bis X_8) zum Erfassen von Signalen;
 - (d) mindestens einem Medium, das die Signale durchwandern können;
 - (e) einer verformbaren Einrichtung (B), die auf Grund der Beaufschlagung der belastbaren Einrichtung mit der genannten Kraft-Drehmoment-Komponente verformbar ist; und
 - (f) einer Einrichtung zum Auswerten der erfaßten Signale zur Bestimmung der genannten mindestens einen Kraft-Drehmoment-Komponente,
 dadurch gekennzeichnet, daß (g) eine Mehrzahl von Signalreflexionseinrichtungen (R_1 bis R_4 , A) zum Reflektieren der gesendeten Signale vorgesehen ist und daß jede der Signalsendeeinrichtungen einen Wandler (X_1 bis X_8) besitzt, der auch als die Signalerfassungseinrichtung für ein von dem Wandler kommendes und von einer zugeordneten der Signalreflexionseinrichtungen (R_1 bis R_4 , A) reflektiertes Signal dient, wobei die Einrichtungen (a), (b), (c), (d), (e) und (g) so beschaffen und angeordnet sind, daß die Beaufschlagung der belastbaren Einrichtung mit einem Kraft-Drehmoment-Komponente eine Änderung der Strecke bewirkt, über die Signale zwischen mindestens bestimmten der Sende- und zugeordneten Erfassungseinrichtungen wandern, so daß die Bestimmungseinrichtung (f) die genannte mindestens eine Kraft-Drehmoment-Komponente bestimmen kann.
2. Sensor nach Anspruch 1, dadurch gekenn-

zeichnet, daß die Einrichtung zum Auswerten der erfaßten Signale eine elektrische Schaltungsanordnung aufweist, die dazu dient, die Laufzeit jedes der genannten Signale zu bestimmen und die Signallaufzeiten zum Bestimmen der Mehrzahl von Kraft-Drehmoment-Komponenten auszuwerten.

3. Sensor nach Anspruch 1 oder 2, dadurch gekennzeichnet, daß die Signalreflexionseinrichtungen (R_1 bis R_4 , A) an der belastbaren Einrichtung (A) befestigt sind.
4. Sensor nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die verformbare Einrichtung (B) aus einem elastomeren Werkstoff besteht.
5. Sensor nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die verformbare Einrichtung (B) zylinderförmig ist.
6. Sensor nach einem der Ansprüche 1 bis 4, dadurch gekennzeichnet, daß die verformbare Einrichtung ellipsenförmig ist.
7. Sensor nach einem der vorhergehenden Ansprüche, der ferner ein Substrat (C) besitzt, das die Signalsendeeinrichtungen und die Signalerfassungseinrichtungen (X_1 bis X_8) trägt und eine Bezugsstellung bestimmt, auf die Unterschiede zwischen Signallaufzeiten bezogen werden können.
8. Sensor nach einem der vorhergehenden Ansprüche, dadurch gekennzeichnet, daß die Berührungsfläche der belastbaren Einrichtung eine Oberfläche der verformbaren Einrichtung ist.
9. Sensor nach einem der Ansprüche 1 bis 7, dadurch gekennzeichnet, daß die belastbare Einrichtung wenigstens teilweise von einer Deckplatte (A) gebildet wird.
10. Sensor nach Anspruch 9, soweit er auf Anspruch 7 rückbezogen ist, dadurch gekennzeichnet, daß die Deckplatte (A), die verformbare Einrichtung (B) und das Substrat (C) einen Hohlraum begrenzen, der ein Koppelungsmittel enthält, das als ein Medium dient, das Ultraschallsignale durchwandern können.
11. Sensor nach Anspruch 10, dadurch gekennzeichnet, daß auch die verformbare Einrichtung als ein Medium dient, das Ultraschallsignale durchwandern können.



2. Sensor nach einem der vorhergehenden Ansprüche mit einer Stütze (D), an der mindestens einer der Wandler befestigt ist.
13. Sensor nach einem der Ansprüche 1 bis 10 mit einer Reflexionsstütze (D), die mindestens eine Reflexionsfläche (D₁) zum Reflektieren mindestens eines der genannten Signale zu dem zugeordneten Reflektor (R) und zurück zu dem Signal sendenden Wandler (X) besitzt.
14. Sensor nach Anspruch 13, soweit er auf Anspruch 7 rückbezogen ist, dadurch gekennzeichnet, daß alle Wandler (X₁ bis X₈) in einer allgemein koplanaren Anordnung auf dem Substrat (c) montiert sind.
15. Verfahren zum Bestimmen einer Mehrzahl von Kraft-Drehmoment-Komponenten, in dem eine belastbare Einrichtung mit einer Mehrzahl von Kraft-Drehmoment-Komponenten beaufschlagt wird; von einer Signalsendeeinrichtung Signale gesendet werden; die gesendeten Signale von einer Signalreflexionseinrichtung reflektiert werden; die genannten Signale von einer Signalerfassungseinrichtung erfaßt werden; und durch Auswerten der erfaßten Signale eine Mehrzahl von Kraft-Drehmoment-Komponenten bestimmt wird, dadurch gekennzeichnet, daß die von der Sendeeinrichtung kommenden Signale zu der Sendeeinrichtung zurückreflektiert werden, die Wandler besitzt, die auch als die genannte Signalerfassungseinrichtung dienen, so daß auf Grund der Kraft-Drehmoment-Komponenten, mit denen die belastbare Einrichtung beaufschlagt wird, die Signallaufzeiten verändert werden, und die Laufzeiten der Signale zum Bestimmen der Kraft-Drehmoment-Komponenten ausgewertet werden.
16. Verfahren nach Anspruch 14, dadurch gekennzeichnet, daß die Laufzeiten und die Kraft-Drehmoment-Komponenten mit einer elektronischen Schaltungsanordnung bestimmt werden.

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