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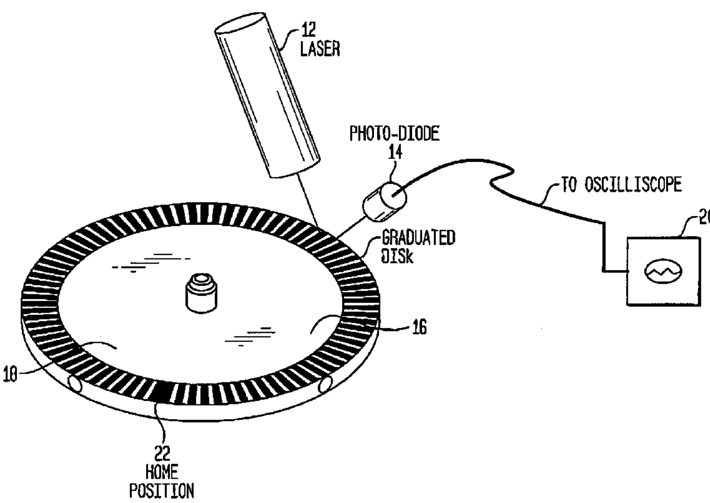
(54) Title: TORQUE MEASUREMENT SYSTEM

FIG. 1



(57) Abstract: A system and method is provided for determining the torque and kinetic energy of a rotating body without contacting the rotating body. Graduation markings are applied to mark regular angular displacements on the object. Reflected laser light from the graduations is sensed and converted into a pulsed signal. The pulses of the signal are time stamped and used to determine the velocity of the rotating object at angular displacements which can be less than 360 degrees. Changes in angular velocity during each rotation can be measured and used to determine changes in torque and kinetic energy during each rotation.

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Torque Measurement System

Field of the invention

The present invention is in the field of the measurement systems and, more particularly, systems for measuring kinetic energy and torque of a rotating body.

Background

Numerous commercial systems are available to measure the angular displacement, angular velocity, kinetic energy, and torque acting on a disk during rotation. However, most commercial systems that are available to perform such measurements require test sensors to be in physical contact with the rotating body being measured. Therefore, such systems detrimentally affect the dynamics of the system being measured.

Previously known optical encoders use reflected laser beams to accurately measure the angular displacement of a body, but are not generally used to measure angular velocity for a given displacement. Such devices have been used to measure the average angular velocity of a body over a large angular displacement, typically over several revolutions, but are not generally used to measure the instantaneous angular velocity for rotating bodies during acceleration over small angular displacements or to associate instantaneous velocity with a particular displacement.

Because optical angular velocity measurements have typically been performed using average angular velocity over a relatively large angular displacement, the use of such measurements to determine other dynamic conditions of a rotating body, such as torque or kinetic energy, provides average values over the large displacement and do not provide accurate nearly instantaneous information such as nearly the instantaneous torque or nearly instantaneous kinetic energy of a rotating body for a given displacement.

Previously known systems and methods for measuring nearly instantaneous torque or kinetic energy of a rotating body during less than one revolution of the body typically employ torque sensors which make contact with the body, thus detrimentally affecting the dynamics being measured.

Summary of the Invention

Embodiments of the present invention measure nearly instantaneous angular velocity for each of a plurality of small angular displacements of a rotating body using a laser measurement sensor. A flat graduated disk, such as a paper disk, is applied to the body being tested. The graduated disk is selected such that it will not substantially change the moment of inertia of the body being tested or its air resistance. A laser diode is aimed at the disk and laser light reflected from the disk is received by a photo-diode. As the disk rotates, the laser light alternatively reflects from graduated portions and the spaces between graduated portions. The different reflective properties between the graduated portions and the space between graduations causes the intensity of the reflected light to pulsate. The output from the photo-diode provides a series of signal pulses which are each associated with corresponding graduations of the disk. Each pulse is time-stamped so that the angular velocity of the rotating disk can be measured for each graduation. The kinetic energy and torque acting on the rotating disk is then calculated for each graduation of the disk. Because torque is calculated without using conventional torque sensors, no part of the inventive measurement system makes contact with the rotating object to detrimentally affect the dynamics being measured.

The inventive measurement device has the capability to measure the kinetic energy and torque of a rotating disc without making any contact with the disc or anything connected to the disc during measurement. It does this by accurately measuring speed changes during angular displacement of a 360 degree rotation of a disc and the speed at specific positions of the disc.

Existing non-contact Optical encoders use a reflective lasers that measure position use a similar type of reflective laser concept, from which the general speed of the disc can be calculated. However, the output of such existing encoders is primarily focused on position precision. Speed changes during a 360 degree rotation are not a main consideration. In such existing systems speed changes can only be crudely calculated on a number of revolutions per minute basis. If speed changes during a 360 degree rotation are required a torque sensor has generally been employed. Such torque sensors must typically come in contact with the disk being measured.

The present invention overcomes the limitations of the prior art by using a non-contact encoder concept, recording data for graduation on for a disk within each 360 degree rotation.

This data is used to determine speed changes during a rotation to calculate torque and kinetic energy variations which take place during each rotation.

Brief Description of the Drawings

The foregoing and other features and advantages of the present invention will be better understood from the following detailed description of illustrative embodiments, taken in conjunction with the accompanying drawings in which:

Fig. 1 is a schematic diagram of a measurement system according to an illustrative embodiment of the invention;

Fig. 2 is an oscilloscope measurement of the light monitoring device output signal according to an illustrative embodiment of the invention;

Fig. 3 is a plot of kinetic energy and torque versus angular displacement as measured according to an illustrative embodiment of the invention; and

Fig. 4 is a flow diagram illustrating a method of measuring kinetic energy and torque according to an illustrative embodiment of the invention.

Detailed Description

An illustrative embodiment of the invention as shown in Fig. 1 provides a test system 10 having a light emitting device 12 such as a laser diode, a light monitoring device 14 such as a photodiode, and a graduated encoder disk 16 which is affixed to a rotating body 18 being measured. A time-stamping device 20 such as an oscilloscope is provided in communication with the light monitoring device 14 and receives output signals therefrom. The graduated disk has a radial array of graduations printed on a contrasting background. In the illustrative embodiment, the graduated disk is constructed of paper and has a white background with black graduations printed in a radial fashion at assigned intervals (typically one degree). A home position graduation 22 that has a greater width than the other printed graduations acts as a reference or home position marker. The graduated disk is securely attached to the disk that is being measured.

The light emitting device 12 emits a light beam that is directed at the rotating graduated disk 16. The light emitting device 12 and light monitoring device 14 are aligned so that the light is reflected from the graduated disk into the light monitoring device 14. The light emitting device 12 and light monitoring device 14 are securely fixed with respect to the rotation of the rotating body 18.

In an illustrative embodiment, direct current is provided to power the light emitting device and light monitoring device. An analog output signal from the light monitoring device input to a time stamping device such as a digital oscilloscope so that the signal may be digitally sampled and analyzed. Illustratively, the oscilloscope records a voltage produced by the light monitoring device and the time at which the voltage was recorded, so that all voltage measurements are time-stamped.

Operation of the inventive measurement system is described with reference to Fig. 1 and Fig. 2. Light from the light emitting device 12 is reflected off the surface of the graduated disk 16. The intensity of the reflected light varies depending on the reflective properties, (i.e. color) of the section of the graduated disk 16 at which the light emitting device is pointing.

Illustratively, the light monitoring device 14 produces an output voltage that is proportional to the intensity of the light reflected by the graduated disk 16. Accordingly, if the light emitting device is pointing at a section of the graduated disk 16 that is black, the light monitoring device 14 will produce a lower voltage than if the light emitting device 12 is pointing at a section of the graduated disk that is white. Hence, as the graduated disk rotates, the light monitoring device 14 produces a voltage that varies as the intensity of reflected light changes due to the passing of the graduations under the light emitting device 12. When recorded on an oscilloscope, the analog signals 24 from the light monitoring device 14 vary as the graduations pass the light emitting device as shown in Fig. 2.

The angular velocity of the disk is determined by measuring the time between leading edges of the analog signal 24. Illustratively one graduation is printed on the disk per degree of angular displacement. Since the angular displacement between the graduations is known and the time taken to travel between these graduations can be measured, the angular velocity can be determined. A system can provide a measurement of any change in the angular velocity during a single revolution.

The angular displacement of the disk at any point in time is determined by counting the number of pulses from a known reference position (the "home" position). In the illustrative embodiment, the home position of the system is a graduation that is of greater physical width than the other graduations on the disk. Hence, the home pulse 26 recorded by the oscilloscope can be identified because it is of greater width than the other pulses of the analog signal 24.

According to illustrative embodiments of the invention, the moment of inertia of the disk is accurately calculated. The moment of inertia and angular velocity data are then used to calculate the kinetic energy of the disk during rotation, using the standard formula:

$$\text{Kinetic energy} = \tfrac{1}{2} I\omega^2$$

where I=moment of inertia of the disk (Kg/m^2) and ω is angular velocity (radians/second).

Since the kinetic energy is calculated at known positions (the graduation markings) and the distance between these graduations is also known, the torque acting on the disk is calculated by differentiating the kinetic energy with respect to angular displacement. Hence, from the angular displacement, and angular velocity measurements, the kinetic energy and torque of the system can be calculated during the system's revolution. An exemplary plot of kinetic energy 28 and torque 30 versus angular displacement measured according to the present invention is shown in Fig. 3.

Measurement uncertainty in the test system may be caused by several factors including the response time of the light monitoring device, the accuracy of the placement of disk graduations, the sampling frequency of the light monitoring device output signal, the accuracy of the time stamping oscilloscope and the accuracy of moment of inertia calculations.

For example, a time lag in the photo-diode between the change of light intensity that enters the sensor and associated change in the output voltage level; this will lead to measurement uncertainty. Also, the lower the oscilloscope sampling frequency the greater the measurement uncertainty. Further, for a fixed sampling frequency, the measurement uncertainty will increase with an increase in angular velocity because the number of samples taken between the leading edges will determine the timing and positioning accuracy of the system.

Since both the kinetic energy and torque values are calculated based upon the moment of inertia of the disk being tested, inaccuracies in calculating the moment of inertia of a rotating body will increase the measurement uncertainty of the kinetic energy and torque values.

The moment of inertia can be calculated through the use of parametric mechanical design and modeling software. In an illustrative embodiment, Solid Edge ™ 3D CAD software by Siemens PLM Software of Plano, Texas is used to calculate the disk's moment of inertia based on information such as the disk's material, dimensions, weight, density and point of rotation.

Fig. 4 illustrates a method of measuring kinetic energy and torque according to the invention. In an application step 40, a graduations are applied to the disk. While the disk is rotating, a first sensing step 42 is performed in which a light source such as a laser diode is directed to shine upon graduations. In a second measurement step 44, light reflected from the graduations is received by a sensor such as a photo-diode. The sensor converts reflected light into a signal having pulses which correspond to the passage of graduations beneath the light source. In time stamping step 46, signal pulses output from the sensor are time stamped, for example by recording the pulses on a digital oscilloscope. In a correspondence step 48, each of the time stamped signal pulse is associated with a corresponding angular displacement according to the angular displacement between graduations. In a velocity calculation step 50, the angular displacement between graduations is divided by the time between the time stamped signal pulses which correspond to the graduations. In a kinetic energy calculation step, the measured angular velocity and the disks moment of inertia are used to calculate the disk's kinetic energy during a specified angular displacement. In a torque calculation step 52, the measured angular velocity and the disk's moment of inertia are used to calculate the disk's torque during a specified angular displacement.

Although illustrative embodiments of the invention have been described herein as using a digital oscilloscope as a time stamping device, persons skilled in the art should recognize that the use of an oscilloscope may be impractical for various desired implementations of a torque measurement system. Furthermore, the maximum sampling rate of a typical digital oscilloscope may not be high enough to accurately measure the projected maximum rotational speed of about 10,000 rotations per minute (RPM) for certain embodiments of the invention. It should therefore be appreciated that alternative embodiments of the present invention may be implemented without using an oscilloscope. For example, in an illustrative embodiment of the invention, time stamping circuitry includes high speed electronics which overcome the disadvantages of using an oscilloscope for time stamping. The high speed electronics can generate and capture signals from a rotating body capable of detecting kinetic energy and toque changes during disk rotation at speeds up to 10,000 RPM.

In an illustrative embodiment, the high speed electronics for times stamping include a quartz crystal which outputs an oscillating signal having a frequency of about 2 gigahertz, for example. This provides a time period between time stamps in the output signal of about 5×10^{-10} seconds which can be used to time the pulses from the photodiode.

The high speed electronics detect the pulses from the photo diode when changes from black graduation to white graduation produces a rising edge and changes from white graduation to black graduation produces a falling edge. For each graduation, a counter in the high speed electronics counts the number of time stamps from the quartz crystal during each graduation detected by the photo-diode. After each graduation, the high speed electronics reads the number of pulses from the counter, then resets the counter to start a new count for the next graduation.

The time stamps counted per graduation are summed and multiplied by the period of the oscillator signal to calculate the time for the measured graduation on the rotating body to pass the photodiode. Since, in the illustrative embodiment, one graduation is equal to one degree of angular displacement of the rotating body, the measured time period per pulse is readily converted to an angular velocity to provide a nearly instantaneous measurement of the body's angular velocity at any time.

In an illustrative embodiment the high speed pulse counting may be performed by channelling the quartz crystal output signals and the photodiode output signals through counting circuitry on a printed circuit board (PCB) having a series of high speed gates and providing a low speed output. The low speed output can then be channelled to a low speed counter. One or more microcontrollers or other custom hardware can perform counting of the time stamps per pulse on the PCB board for output to a computer.

A Serial Peripheral Interface (SPI) to Universal Serial Bus (USB) converter can be used to receive data from the PCB board and convert it into USB format for the computer. Alternatively, the SPI to USB convertor may be replaced by other custom interface circuitry. The computer may be used to execute software for converting the number of time stamps per pulse and the number of pulses to a nearly instantaneous angular velocity, kinetic energy and/or torque for the rotating body.

Although the invention is described with reference to a light source such as laser diode, and a light monitoring device such as a photo-diode, persons having ordinary skill in the art should appreciate that various other types of light sources and light monitoring devices can be used within the scope of the invention.

Although the invention is described with reference to an encoding disk being affixed to the rotating body, it should be understood that encoding graduations can be printed directly onto a rotating body within the scope of the invention.

While the invention has been described with reference to an exemplary embodiment, it should be understood by those skilled in the art that various changes, omissions and/or additions may be made and equivalents may be substituted for elements thereof without departing from the spirit and scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims. Moreover, unless specifically stated any use of the terms first, second, etc. do not denote any order or importance, but rather the terms first, second, etc. are used to distinguish one element from another.

Claims

What is claimed is:

1. A method for quantifying dynamics of a rotating body comprising:

applying a graduated disk to the rotating body, the graduated disk having a radial array of graduations;

directing light from a light emitting device to the graduated disk;

receiving, by a light monitoring device, light originating from the light emitting device and reflected by the graduated disk;

monitoring an output from the light monitoring device, the output including signal pulses generated by receiving pulses of the reflected light from the graduated disk;

time-stamping a plurality of the signal pulses;

associating the plurality of signal pulses with corresponding angular displacements of the rotating body by matching the signal pulses with graduations on the disk; and

calculating an angular velocity of the rotating body between at least two time stamped signal pulses as a function of the time stamp for at least two signal pulses and the angular displacement corresponding to the at least two signal pulses.

2. The method of claim 1, further comprising:

determining the moment of inertia of the rotating body; and

calculating torque of the rotating body between at least two signal pulses as a function of the moment of inertia and the angular velocity.

3. The method of claim 1, further comprising:

determining the moment of inertia of the rotating body; and

calculating kinetic energy of the rotating body between the at least two signal pulses as a function of the moment of inertia and the angular velocity.

4. An apparatus for quantifying dynamics of a rotating body, comprising:

a graduated disk applied to the rotating body, the graduated disk having a radial array of graduations;

a light emitting device arranged to direct light onto the graduations;

a light intensity monitoring device arranged to receive light reflected from the graduations, the light intensity monitoring device generating an output signal having attributes corresponding to the intensity of the reflected light; and

a time stamping device receiving the output signal and providing time stamps for a plurality of pulses in the output signal; and

a database associating the timestamps with angular displacements of the rotating body corresponding to the graduations.

5. The apparatus of claim 4, further comprising:

calculating means in communication with the database, the calculating means adapted to calculate an angular velocity of the rotating body between at least two time stamped signal pulses as a function of the time stamp for the at least two signal pulses and the angular displacement corresponding to the at least two signal pulses

6. The apparatus of claim 5, wherein the calculating means are further adapted to calculate kinetic energy of the rotating body between the at least two signal pulses as a function of a moment of inertia of the rotating body and the angular velocity

7. The apparatus of claim 5, wherein the calculating means are further adapted to calculate torque of the rotating body between the at least two signal pulses as a function of a moment of inertia of the rotating body and the angular velocity

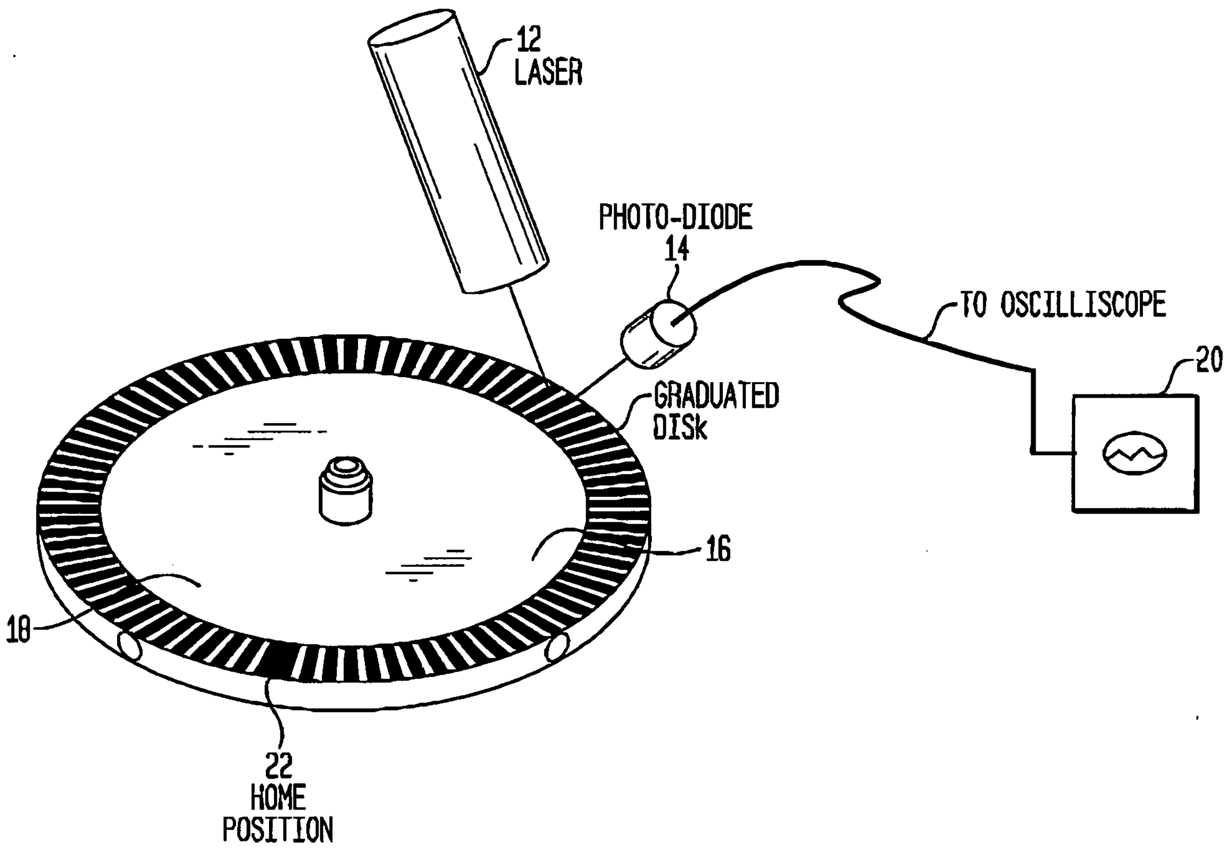
8. The apparatus of claim 4 wherein the graduated disk further comprises a home position marker.

9. The apparatus of claim 4 wherein the light emitting device is a laser diode.

10. The apparatus of claim 4 wherein the light intensity monitoring device is a photo-diode.

11. The apparatus of claim 4 wherein the time stamping device is an oscilloscope.

FIG. 1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POSITION

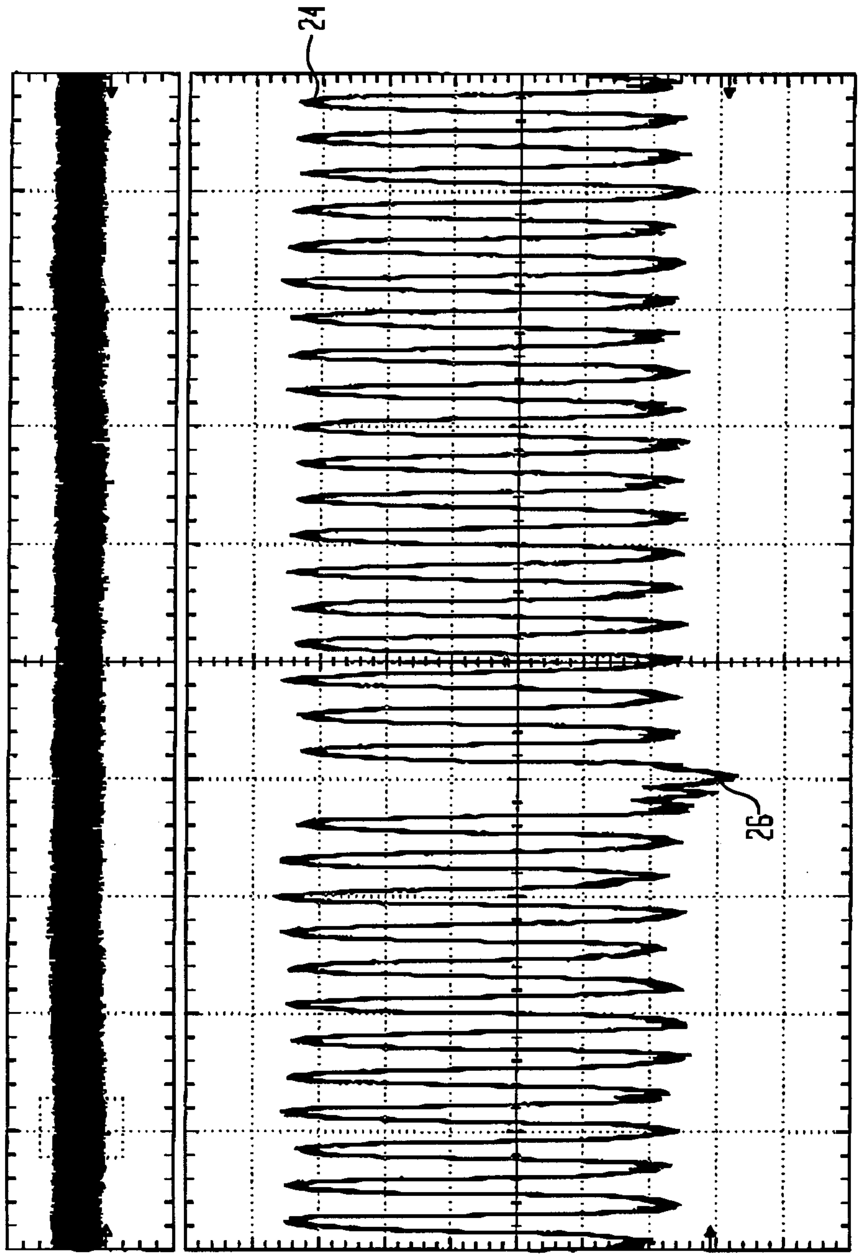
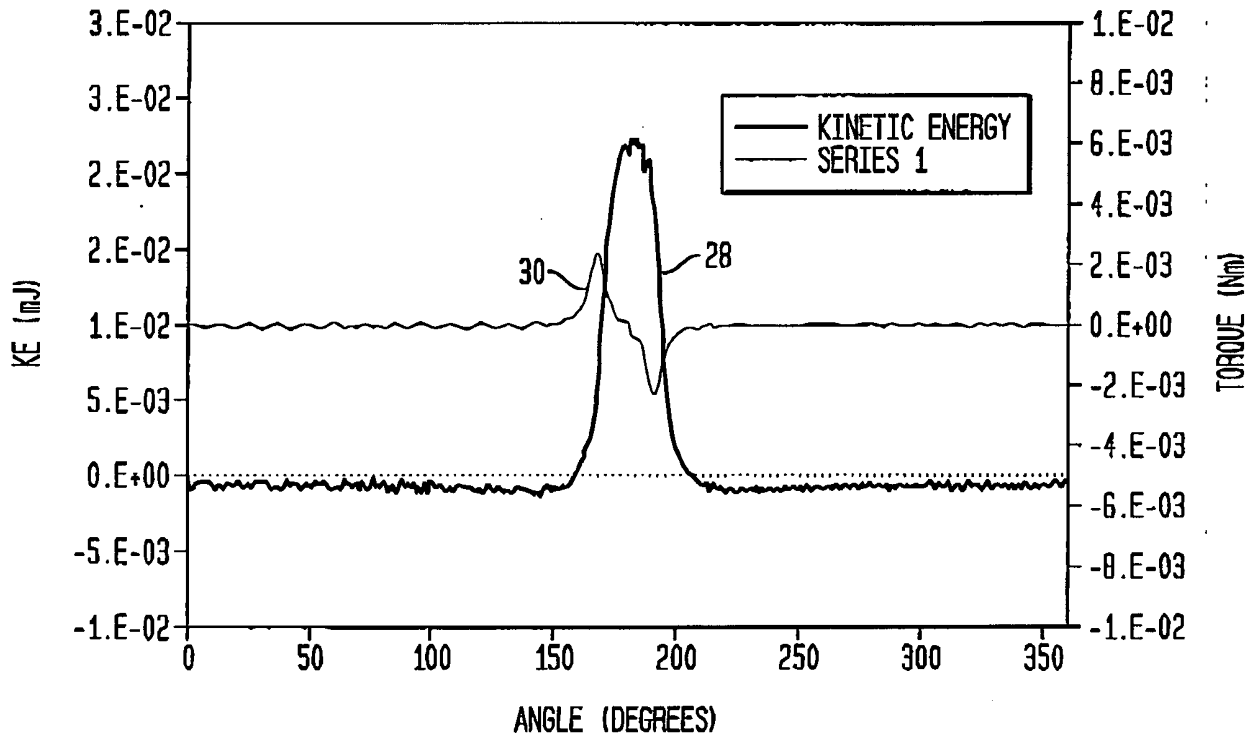


FIG. 2

FIG. 3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2.E-03
0.E+00
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-6.E-03
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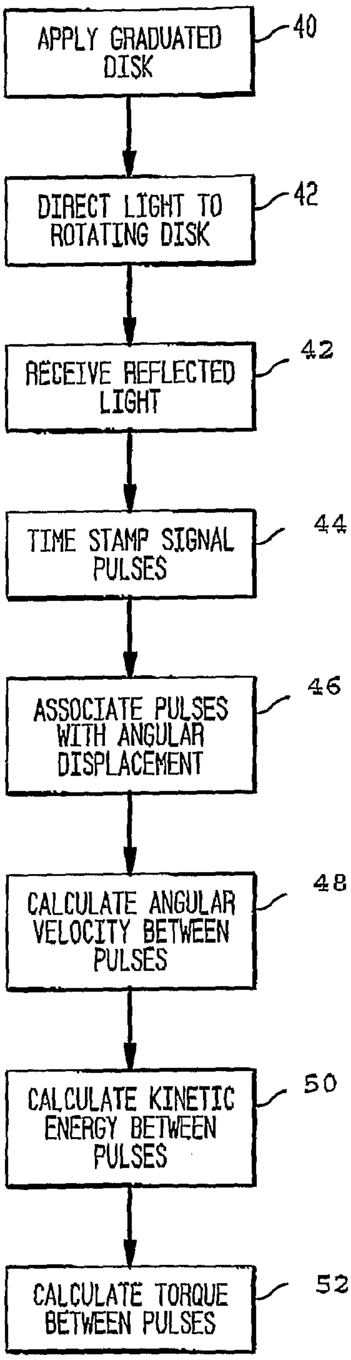
250
300
350
ANGLE (DEGREES)

FIG. 4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DIRECT LIGHT TO ROTATING DISK
42
RECEIVE REFLECTED LIGHT
42
TIME STAMP SIGNAL PULSES
44
ASSOCIATE PULSES WITH ANGULAR DISPLACEMENT
46
CALCULATE ANGULAR VELOCITY BETWEEN PULSES
48
CALCULATE KINETIC ENERGY BETWEEN PULSES
50
CALCULATE TORQUE BETWEEN PULSES
52