Force-Measurement Using Gyroscopic Force Measuring System

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Abstract: This paper concerns the development of an entirely new force sensor called Gyroscopic Force Measuring System (simply called GFMS) for measuring a force vectorially. In a previous paper, the dynamical characteristics and the error analysis of the GFMS for measuring a force vector in 3-dimensional space were examined using numerical simulations. The results of this work are directly applicable to design and construction of the GFMS. In this paper, the GFMS is constructed by a gyro-rotor used a miniature rate-gyro for aircraft instrument and mechanical parts together. In order to verify the principle of the GFMS, our prototype GFMS made on first trial is able to measure the only one component of a force vector, excluding servomechanisms to estimate angles of incidence. The feedback gains are selected somewhat arbitrarily, but the fundamental experiments show that the force less than 0.3[N] can be measured by the GFMS. This suggests the possibility to measure a small force range useful for air-flow distribution in an air-conditioned room as an example of expected applications. No doubt the experimental results are to be released in a future publications.

Keywords: mass and force measurement, gyroscope

Introduction

A class of weight measuring device known as Gyroscopic Force Measuring System (simply called GFMS) has emerged in Germany and has earned much interest as a novel weighing scale due to its advantages of high resolution and perfect linearity. Its dependability has been proved over the last three decades at numerous installations. The gyroscopic instruments, however, have seemed to be more difficult to construct a sufficiently accurate rotor and gimbals for practical applications. This precise manufacturing difficulties have coupled with the big disadvantages of expensive production cost and have prevented these instruments from wide use [1]. Thus, the gyroscopic instruments have been manufactured by specialist firms and now used for special purpose where limited accuracy is required such as flight and navigation control and other aeronautical instruments. These instruments hold promise for the future if we assume that these disadvantages can be surmounted.

Typical resolution for present-day weighing scales on the market is shown in Fig.1 in the ranges of force to be measured. The area surrounded with the solid line denotes electro - magnetic force mass comparator (so-called “electronic balance”) and the one with the broken line is strain-gauge. The area with hatching in the middle of Fig.1 denotes vibrating string type (e. g., a tuning fork vibrator). Under practical circumstances, the loadcells by strain-gauges are widely used devices for large capacities (10~10^5[N]). On the other hand, for small capacities (10^{-3}~10[N]), the electronic balances play unchallenged roles for higher accuracy demands. The GFMS discussed here is applicable in principle to force-measurements for large and small capacities. In this paper, of particular interest to us is to explore the possibility of the GFMS as a small force sensor that is more stable, portable and easy to operate than tradition- al electronic balances.

In previous papers [2] ~ [6], the possibility of the GFMS to measurement of a force vector in 3-dimensional space has been explored. The dynamical characteristics and the error analysis of the GFMS were examined by numerical simulations. The results obtained can be directly applicable to design and construction of the GFMS. In this paper, the GFMS is constructed by a gyro-rotor used for a miniature rate-gyro for aircraft instrument and mechanical parts together. In the following, we explain the construction of the prototype GFMS, and demonstrate the fundamental characteristics of the GFMS as a force sensor through the results of the experiments.

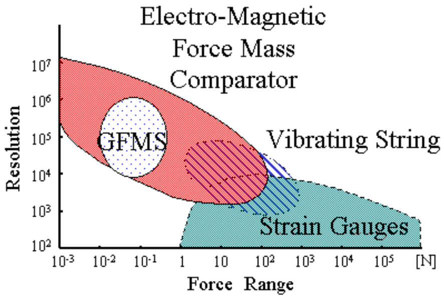


Fig.1 Comparison of measurable ranges for various types of sensor

mass of gyro-rotor M	2.24×10^{-2} kg
moment of inertia I_z	1.45×10^{-6} kgm ^{2}
revolution n	24000 rpm
spin-angular momentum H_0	0.37×10^{-2} kgm ^{2}/s
length of lever system $2a$	5.5×10^{-2} m

Table.1 Characteristics of gyro-rotor

Basic Principle and Equations of Motion

Construction and Principle Fig. 2 shows a schematic diagram of the original GFMS for measuring a force vectorially. The GFMS consists of a gyro-sensor to detect a force and two turntables to follow up the direction of a force vector. The function of the gyro-sensor is to detect one component of a force vector. Thus, two turntables must be installed around the gyro-sensor, in which turntables enable it to follow up the direction of a force vector.

In this paper, the prototype GFMS, which consists of the vertical gimbal G_1, the horizontal gimbal G_2, and the frame G_3, is constructed as a preliminary stage on an experimental basis, excluding two auxiliary turntables shown in Fig.2. Fig.3 shows a trial construction model of the GFMS. The force acts on the center of the force detector and applies a horizontal force on one end of the spin-axis of the rotor through the pivoted lever. The torque generated by the force causes the rotor in its gimbals to turn (called precession) about OY and the precession-rate $\omega = \psi$ is directly proportional to the force F applied.

When the rate ω can be measured accurately, the GFMS operates as a precise linear force transducer as follows:

$$\omega = -\frac{a}{H_0} F \qquad (1)$$

where F is the magnitude of the force, H_0 is the spin-angular momentum of the gyro-rotor and $2a$ is the length of a lever arm.

Since a mechanical gyroscope has a rotor rotating at high speed, the GFMS has inherently several factors that may cause unfavorable errors in a measurement. Frictional torques in bearings and dynamical unbalance among mechanical parts about OY axis may cause instrumental error that is the biggest problem for feasibility of the GFMS. These disturbance torques make the spin

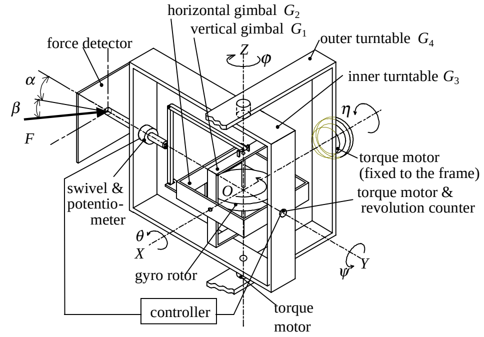


Fig.2 Construction model of original GFMS

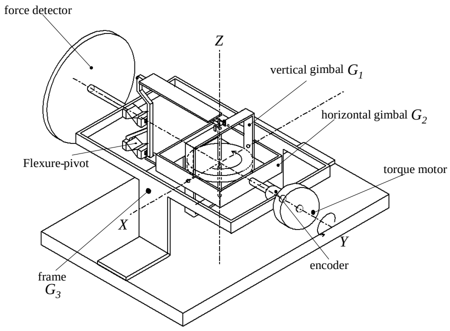


Fig.3 Trial construction model of GFMS

-axis of the rotor tilt progressively out of the vertical plane. When the deflection may be generated, Eq.(1) no longer holds and these factors affect the reading of the instrument. To avoid the unfavor- able errors, the measurement of this deflection is used in the feedback loop, which applies a con- trol torque, thereby continuously keeping the deflection closer to zero. Thus, when the precession -rate ω can be measured accurately, the GFMS operates as precision linear force transducer with high reproducibility.

Analytical Description Let us consider a set of coordinates fixed in the frame (the inertial system G_3), the horizontal gimbal (G_2), and the vertical gimbal (G_1). The spin-axis of the rotor is defined by two Eulerian angles: namely ψ about OY and θ about OX. The equations of motion for the GFMS can be described as follows:

$$\left.\begin{aligned} A\ddot{\theta} + c_1\dot{\theta} + H_0\dot{\psi} &= T_{1x1} \\ B\ddot{\psi} + c_2\dot{\psi} - H_0\dot{\theta} &= T_{2y2} \end{aligned}\right\} \qquad (2)$$

where A, B : moments of inertia of gimbals G_1 and G_2 about OX and OY,
c_1, c_2 : viscous friction coefficients about OX and OY,
T_{2y2} : torque exerted on G_2 by the torque motor.
T_{1x1} : external torque supplied by the force F to G_1.

The feedback torque T_{2y2} and the external torque T_{1x1} are given by:

$$T_{2y2} = k_p\theta \qquad (3)$$

$$T_{1x1} = -Fa \qquad (4)$$

where k_p: proportional gain of the torque motor.

Design and Implementation

Design Specifications The design specifications are determined as,
ε Measurable force range 0~0.3 [N] εMeasuring error (within 10 [s]) ϕ 10^{-6} [N]
ε Measuring time ϕ 10 [s] ε Measurable output range 20~40 [rpm]

In order to enable the instrument to be compact, the GFMS is constructed by a gyro-rotor used in a miniature rate-gyro for aircraft instrument. The constants of the gyro-sensor are summarized in Table 1.

Construction of main part The prototype GFMS has been designed and built, as shown in Fig.4. The GFMS consists essentially of the frame, the gyro-sensor, the torque motor, and the encoder etc. Transmission of the force acting on the force-detector to the gyro-rotor without loss of accuracy is most important for the force measurement by the GFMS. Friction in the transmission system may directly cause instrumental errors. Thus, the flexure pivots are employed in place of the ordinary pin-joints as fulcrums. The flexure pivot can produce frictionless bearing taking advantage of two strips spring. The steel belt at the edge of the

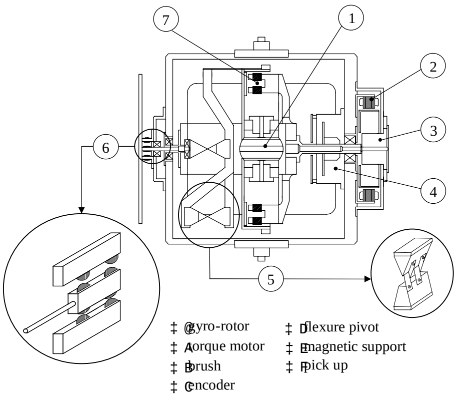


Fig.4 Schematic of GFMS

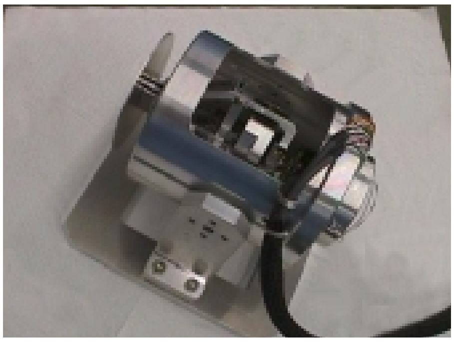


Photo 1 Overall view of GFMS

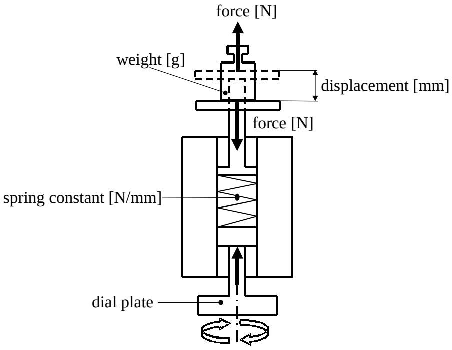


Fig.5 Calibration of loading input device

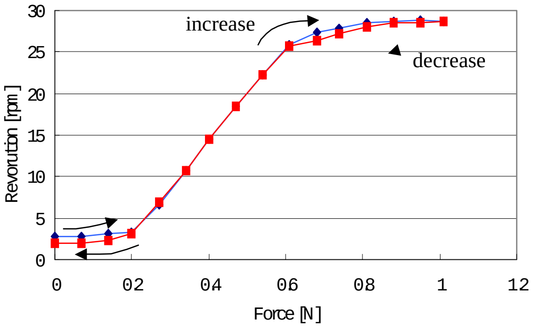


Fig.6 Static relation between force and revolution

lever is connected with the spin-axis of the gyro-rotor to add one more degree of freedom in rotation. Also, the force detector is supported by magnetic support, as shown in Fig.4, so as to prevent the rotation about *OY* from transmitting to the force detector. The magnetic support serves as a brake to avoid rotation of two axes with each other. A Hall element displacement transducer is used as a feedback device. The output (or the precession-rate) from the GFMS is generated by a rotary encoder, and can be transmitted to numerical display over any distance. Photo 1 give us the overview of the GFMS made on experimental basis.

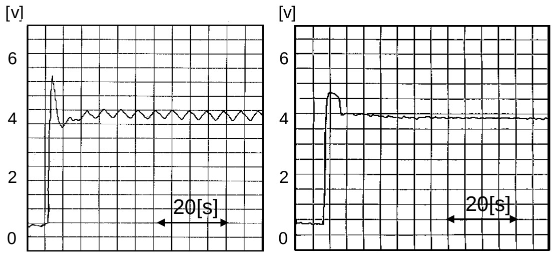
Experiments

Input-output relation First of all, the external force to the precession-rate relation is examined as one of fundamental characteristics of the GFMS. The loading input device consists of a micrometer head and a spring, as shown in Fig.5. The dial plate at the bottom can also give the initial displacement to the spring by means of producing the compressive force. Calibration involves a comparison of this device with known input source such as weighing a certain amount of weight used for a balance and recording a small displacement precisely by using a coordinate measuring machine. It should be noted that the gravitational force acting on loading input device must be cancelled out precisely, thereby calibration can be achieved. Fig.6 shows a complete precession-rate (output) measured in the range of forces (input) 0~1.5 [N]. The typical response of the output seems stable, but the effect of steady-state oscillation becomes evident.

Step-response of GFMS To investigate the dynamic characteristics of the GFMS, we examine the step-response that at any time the input load 0.4 [N] is stepwisely acted on the force-detector and then held at a constant value throughout the experiment. Fig.7 (a), (b) show two representative results in cases of (a) high feedback gain and (b) low one. The feedback gain k_p has been selected somewhat arbitrarily. Since excessive increase in k_p results in hunting (unstable behavior), the optimal adjustment of gain has been determined by these step-responses experimentally.

It can be seen from Fig.7 that the transient response shows a sustained oscillation after about 5 [s]. Moreover, the steady-state oscillations still remain regardless of variation of gain k_p. Fig.8 shows the frequencies of the oscillation versus the corresponding value of the precession-rate (output). It should be surprising that these values showed complete agreement. The reason why this agreement has been yielded will be discussed later on. The output values can be calculated by mean values of the measured signal as can be seen from Fig.6, it follows that :

1) There exists a dead zone up to 0.2 [N], but the effect of a hysteresis is not evident when input force is increasing and decreasing.
2) The linearity must be checked for the range between 0.2 and 0.6 [N], and is less than 2%.



(a) low gain (k_p) (b) high gain (k_p)

Fig.7 Step responses of GFMS

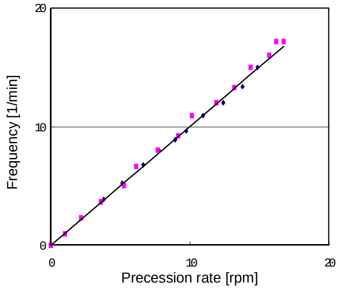


Fig.8 Static relation between revolution and frequency of steady-state oscillation

We now focus our attention on the sensitivity of the GFMS. From the slope of linear part in Fig.6, the sensitivity can be expressed by

$$S = \frac{a}{H_0} = \qquad 57.5[\text{rpm/N}] \tag{5}$$

(estimated standard deviation: 0.25[rpm]),

but this value is less than the sensitivity designed (S=71.0[rpm/N]). That is the reason why the length of a lever arm has been changed to $4 \cdot 10^{-2}$ [m] in the works.

Disturbance torque due to unbalanced mass In the configuration shown in Fig.3, the flexure-pivots, the steel-belt, and the lever-arm of the GFMS are normally installed with static balance, though a small degree of unsymmetry is always present. If the unbalanced mass exists about *OY*, the disturbance torque due to the unbalance, running on a slightly flexible mounting, should be examined. The disturbance torque S_{2y2} exerted on the gimbal G_2 about *OY* due to the unbalanced mass Δm can be written

$$S_{2y2} = \Delta mgl \cos\psi \tag{6}$$

where *l* is the distance from the axis *OY* to the center of the unbalanced mass, and *g* is the acceleration of gravity. From Eq.(2), the equation of motion can be rewritten by replacing T_{2y2} with T_{2y2}+ S_{2y2}, so that, the transfer function from S_{2y2} to the output Ψ [s] is readily derived.

$$s\Psi(s) = -\frac{a}{H_0}F + (\frac{A}{H_0^2})sS_{2y2} \tag{7}$$

In time domain, Eq.(7) can be rewritten:

$$\dot{\psi} = -\frac{a}{H_0}F + (\frac{A}{H_0^2})mgl\dot{\psi}\sin\psi \tag{8}$$

It should be noted that the first term of Eq.(8) indicates the principal component due to input loading F and the second term shows the oscillation component with the same frequency as that of the output (ψ) and with the amplitude as directly proportional to the output ($\dot{\psi}$).

For conventional gyroscopic instruments, the effect of unfavorable disturbance torque on the instrumental errors can be decreased assuming that H_0 is taken as very large value in one direction and low in the other. In designing the GFMS, increasing H_0 will decrease the sensitivity S, as expressed in Eq.(5) So, there exists some limitations on H_0 to measure a small force.

The experimental results suggest some improvement, which make it possible to construct the successful GFMS. First, mechanical parts of the GF MS, which is horizontally set up along the axis OY should be installed symmetrically. The symmetrical configuration such a circular disc cannot affect dynamically the motion of an instrument. Second, frictions in the bearings exert an additional torque and H_0 cannot be sufficiently large, a dead zone appears in the input-output relation of the GFMS (Fig.6). The operating range on characteristic curve can be removed to the specified linear part by applying the initial load to the GFMS, so that the dead zone can completely be compensated for the GFMS.

Conclusions

To enable us to appreciate the qualities of the GFMS, the prototype GFMS has been made on first trial to measure the only one component of a force vector. Through experimental results, the performance of the GFMS was examined from several points of view.

The primary results of this study are listed below.

1) It turns out that the GFMS constructed gives us a satisfactory input-output relation as a force sensor, although there exists a dead zone in the static characteristics.
2) Since there exists some limitation on the spin-angular momentum of the gyro-rotor in order to measure a small force, the unbalanced mass exerts the disturbance torque on the GFMS. The mechanical balancing about the output axis using a symmetrical configuration plays the important role for the feasibility of the GFMS.
3) There still remains a further engineering problem on the design and the structure of the G FMS for small force-measurement. The work reported here is being continued to validate conclusions obtained by experimental results.

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