DYNAMIC EVALUATION OF COLUMN TYPE MULTI-COMPONENT FORCE TRANSDUCERS

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Abstract: This paper describes the dynamic characteristics of column type 6-component force-moment sensors with force components Fx, Fy, Fz and moment components Mx, My, Mz. We have evaluated the dynamic characteristics of the force-moment sensors by using a shaker system and a multi-channel dynamic analyzer system. It reveals that the sensitivity decreases as the frequency increases except for the Fz component and that the sensor shows almost 90° symmetry due to its geometry.

Keywords: 6-component force-moment sensor, dynamic behavior, sensitivity, interference.

1. INTRODUCTION

The physical quantities force and moment are vectors which have a magnitude as well as a direction. A mechanical load can be divided into six components: 3 force components and 3 moment components. Therefore, in order to define a force and torque moment quantity completely, it is necessary to know the value of all six components. A multi-component force-moment sensor is a device that enables forces and moments to be measured simultaneously.

A multi-component force-moment sensor should be accurately evaluated before it is practically employed in the robot, machine tool and automobile fields. The static evaluation of the multi-component sensor can be done by using a multi-component force calibration machine. However, because the multi-component sensor is often used in dynamic mode, its dynamic evaluation is very important.

We have studied the dynamic evaluation of multi-component force-moment sensors. As part of the dynamic evaluation of a multi-component sensor, we have analysed the dynamic characteristics of a 3-component[1] and a binocular 6-component[2] force-moment sensors. The investigations showed that the frequency range of the multi-component force sensors were limited because of their low stiffness.

For this reason, we investigated dynamic property of column type 6-component force sensors having high stiffness. Much research has been done for the dynamic investigation of force transducers. PTB (Physikalisch-Technische Bundesanstalt) analysed the dynamic characteristics by using harmonic excitation employing an air bearing guide[3-6]. On the other hand, Y. Fujii used an impulse excitation method[7-9] and Th. Bruns also used impact method for the dynamic force evaluation[10, 11].

This paper describes the dynamic investigation of the column type 6-component force-moment sensors using the harmonic excitation facilities in the PTB in Germany.

2. PURPOSE

The purpose of this paper is to investigate dynamic properties of column type multi-component force-moment sensors. Multi-component force sensors with beam- or binocular- type sensing elements have insufficient stiffness, hence their dynamic frequency range is restricted for the application to robot, machine tools, etc. Therefore, we developed column type multi-component force transducers. We designed two force transducers each having solid cylindrical sensing part and hollow cylindrical sensing part[12]. Fig. 1 shows the column type multi-component force sensors.

Fig. 1 Column type multi-component force sensor

The capacities of the force transducers are as follow.
(1) Solid cylindrical force sensor
 - Fx : 1.5 kN
 - Fy : 1.5 kN
 - Fz : 20 kN

- Mx : 40 Nm
- My : 40 Nm
- Mz : 60 Nm
(2) Hollow cylindrical force sensor
- Fx : 2.0 kN
- Fy : 2.0 kN
- Fz : 20 kN
- Mx : 60 Nm
- My : 60 Nm
- Mz : 90 Nm

The rated output of the force sensors are 0.4 mV/V for Fz component and about 0.5 mV/V for other components.

In order to check the performance of the column type force transducers, we investigated dynamic characteristics of the transducers by using the facilities in the PTB.

3. METHODS[3-6]

When force transducers are used for dynamic measurements, errors of several percent and more can occur because of the unknown dynamic response of the force transducer. Therefore the dynamic sensitivity of a force measuring device:

$$S = \frac{U_v}{F} \quad (1)$$

must be determined from the ratio of the output signal of the force measuring device U_v and the acting dynamic force F, which must be well known. Because force standard machines are designed for static force measurement they can not be used for dynamic investigations. Special facilities and measurement procedures were therefore developed at PTB to investigate the dynamic behavior of force measuring devices. The principle of the dynamic calibration of force measuring devices is based on a defined realisation of mass forces. So the force transducer to be calibrated is mounted on an electrodynamic shaker, and a load mass is screwed onto the force transducer as shown in Fig. 2.
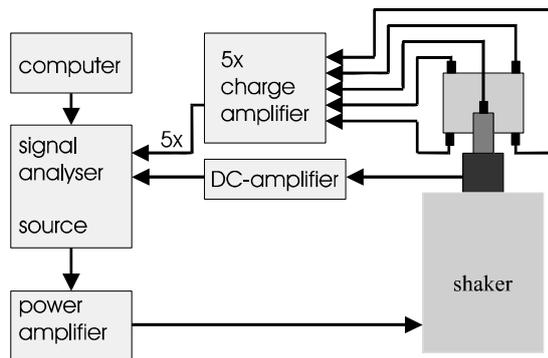

Fig. 2 Calibration principle for dynamic force measurement.

Excitation by the shaker results in a dynamic force F acting on the force transducer:

$$F = (m_1 + m_e) \cdot a_1 \quad (2)$$

where a_l is the acceleration of the load mass m_l and the end mass m_e of the force transducer. The simple equation (2)

does not take the effects of the relative motions of the load mass into account, or the influence of side force which must be considered because force is a vector quantity. Side forces can be reduced by using air bearings. To allow for the influence of relative motion, the dynamic force must be determined from the acceleration distribution $a(x,t)$ and the mass distribution of density ρ according to

$$F = \int_V \rho \cdot a(x,t) \cdot dV \quad . \quad (3)$$

For the determination of the acceleration distribution, multi-component acceleration measurements are necessary as shown in Fig. 2. According to Equation (2) or, more accurately, according to Equation (3), the dynamic force is traceable to the definition of the force according to Newton's law. The dynamic sensitivity of the whole force measuring device includes the frequency response of force transducer and measuring amplifier.
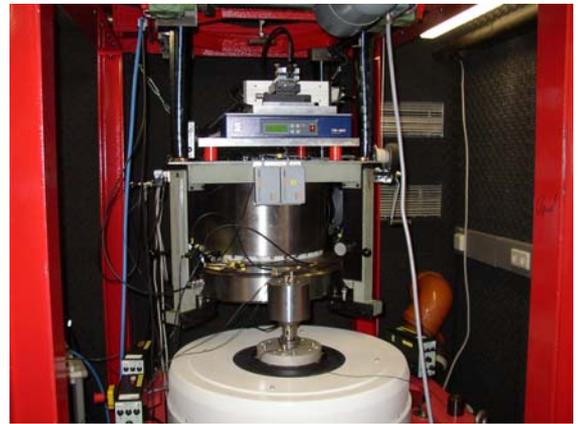

Fig. 3 Experimental scene using air bearing guide.

When using a solid cylindrical mass, internal wave characteristic of the mass can effect on the force calibration, because the mass is not a rigid one. The influence of the internal wave was investigated and a correction was proposed as follows.[3]

$$F = m_l \cdot a_{mo} \cdot K_{mo} + m_{sp} \cdot \frac{a_{mu} + a_{ma}}{2} + (m_a + m_e) \cdot a_{ma} \quad (4)$$

where, $K_{mo} = \sin\left(\sqrt{\frac{\rho}{E} \omega_o^2} \cdot l\right) \Big/ \sqrt{\frac{\rho}{E} \omega_o^2} \cdot l$

ρ = density of the mass
E = Young's modulus of the mass
l = length of the mass
ω_o = excitation frequency
a_{mo} = acceleration on the upper mass surface
a_{mu} = acceleration on the lower mass surface
a_{ma} = acceleration of the adapter
m_l = load mass
m_{sp} = mass of clamping element

m_a = mass of adapter

m_e = end mass of force transducer

The mass of the cylindrical mass was 25.4362 kg and its length was 0.35 m. Fig. 3 represents the experimental scene using air bearing guide.
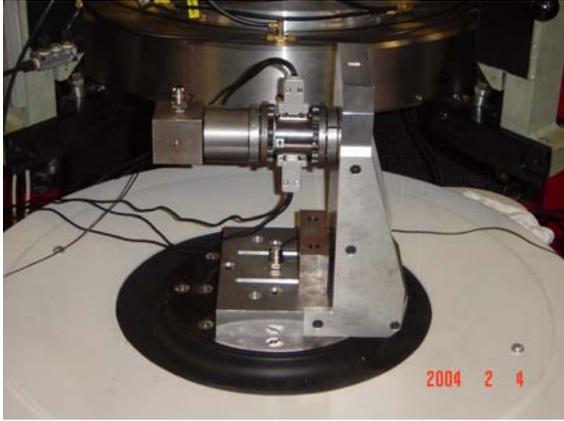

Fig. 4 Experimental scene for side force components.

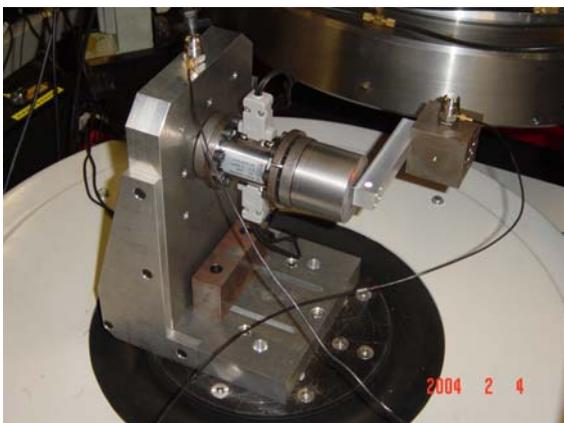**Fig. 5 Experimental scene for bending moment components.**

Fig. 6 Experimental scene for twisting moment components.

However, we could not use the air bearing guide for the measurement of side force components and moment components. Fig. 4, Fig. 5 and Fig 6 represent the experimental set-up for side force components, bending moment components and twisting moment component respectively. The external mass was 0.9 kg and the length of the beam to generate moment was 0.1 m. For the details of the experimental set-up for the side force components and moment components, please refer [2].
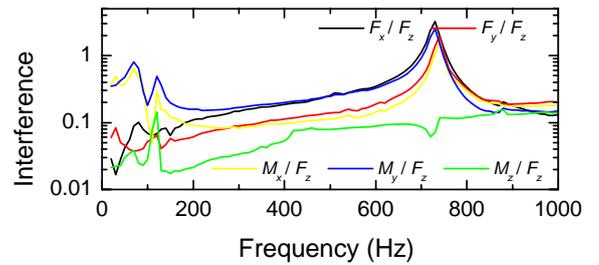
4. RESULTS

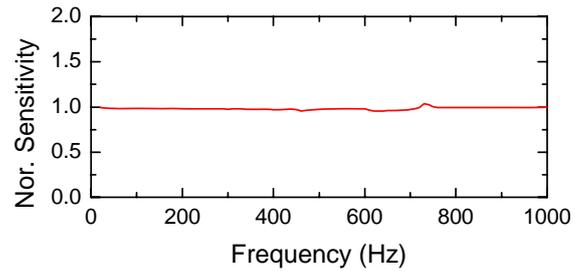### 4.1 Solid force transducer

Fig. 7 Frequency characteristic of normal force component of solid transducer using air bearing guide.
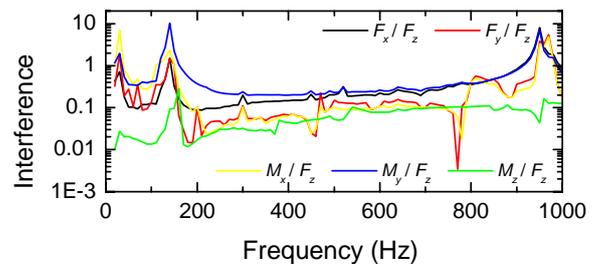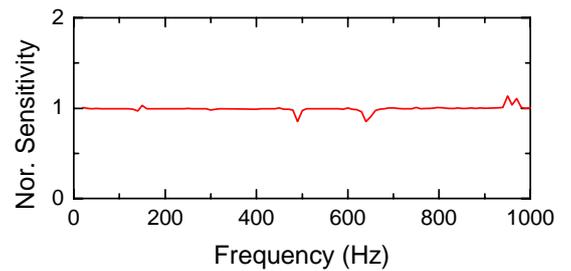

Fig. 8 Frequency characteristic of normal force component of solid transducer without using air bearing guide.

Fig. 7 represents the frequency characteristic of the normal force component Fz for the solid cylindrical force transducer. In this experiment, air bearing guide was used to minimize parasitic force components. Its frequency characteristic is flat up to 1 kHz, the maximum test frequency. The interferences with other force an d moment components are less than 1 except for the frequency of 730 Hz. At about 730 Hz, a kind of rocking motion was observed. The high interference at the frequency is caused by the rocking motion. In the figure, the interferences of the bending moment components at low frequency range are larger than that of other components. This should be investigated in the future.

Fig. 8 represents the frequency characteristic of the normal force component Fz without using air bearing guide. One can see that the interferences are much larger compared to the Fig. 7.
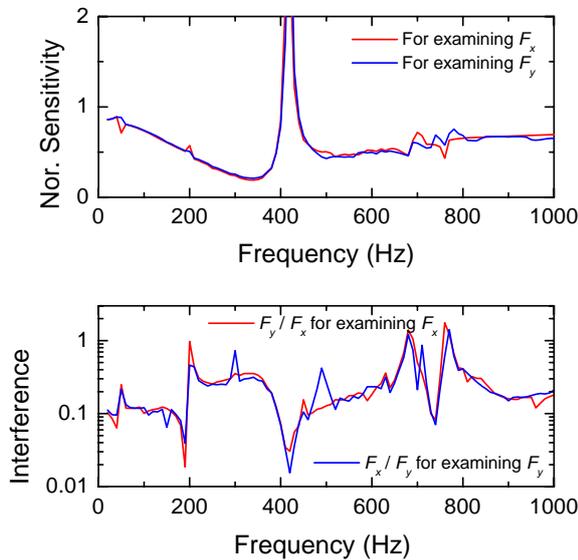
4.2 Hollow force transducer

Fig. 11 represents the frequency characteristic of the normal force component Fz for the hollow cylindrical force transducer. In this experiment, air bearing guide was used to minimize parasitic force components. Its frequency characteristic is quite similar to the result of solid cylindrical force transducer. Its sensitivity is flat within the measured frequency range. The interference is little bit less than that of solid transducer, but the difference is very small.
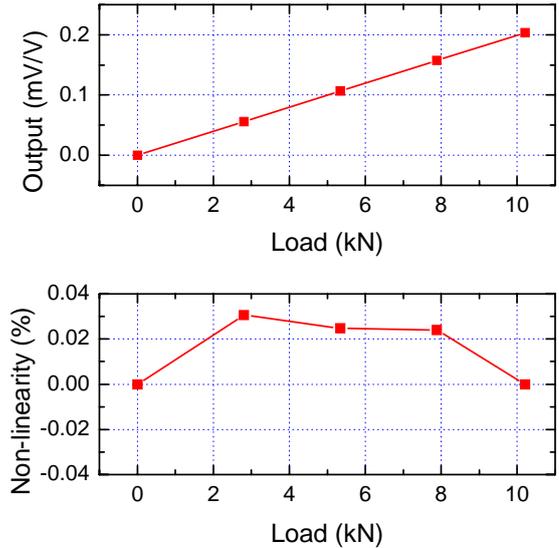

Fig. 10 Non-linearity characteristic of normal force component of solid transducer.

Fig. 9 Frequency characteristic of transverse force components of solid transducer

Fig. 9 represents the frequency characteristics of transverse force components Fx, Fy, for the solid cylindrical force transducer. The frequency range is restricted up to about 200 Hz. Within the frequency range the interference is less than 1.

Other experiments for the moment components showed that the frequency ranges of moment components are less than 100 Hz.

Fig. 10 shows the non-linearity characteristic of the normal force component Fz. To investigate the non-linearity characteristic, we repeated dynamic measurement with varying force magnitude up to 10 kN. In the measurement, air bearing guide was used. The non-linearity was estimated as about 0.03 % with respect to the maximum force, 10 kN. The output of the transducer is 0.2 mV/V at 10 kN, that is the half of the rated output of the transducer.
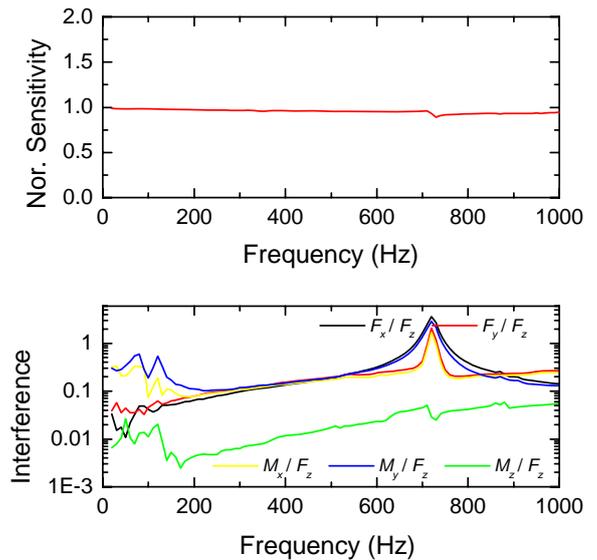

Fig. 11 Frequency characteristic of normal force component of hollow transducer using air bearing guide.

Fig. 12 represents the frequency characteristics of transverse force components Fx, Fy, for the hollow cylindrical force transducer. The frequency range is restricted up to about 200 Hz. Within the frequency range the interference is less than 1. The frequency characteristics are quite similar Fig. 9, the frequency characteristics of the solid cylindrical force transducer.

Fig. 13 represents the non-linearity characteristic of the normal force component Fz. In the measurement, air bearing guide was used. The non-linearity was estimated as about 0.04 % with respect to the maximum force, 10 kN.
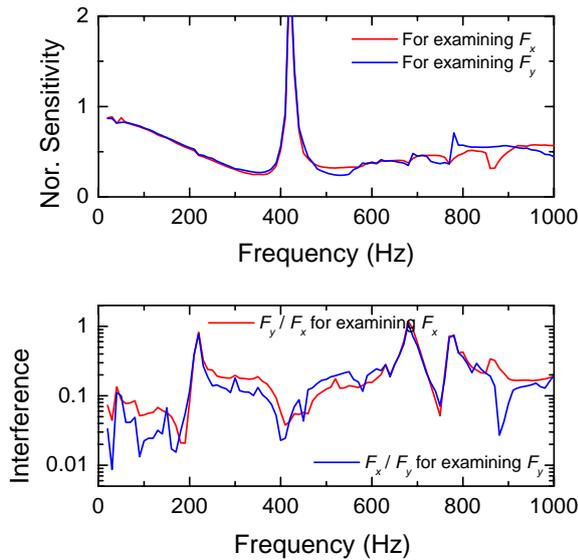

Fig. 12 Frequency characteristic of transverse force components of hollow transducer
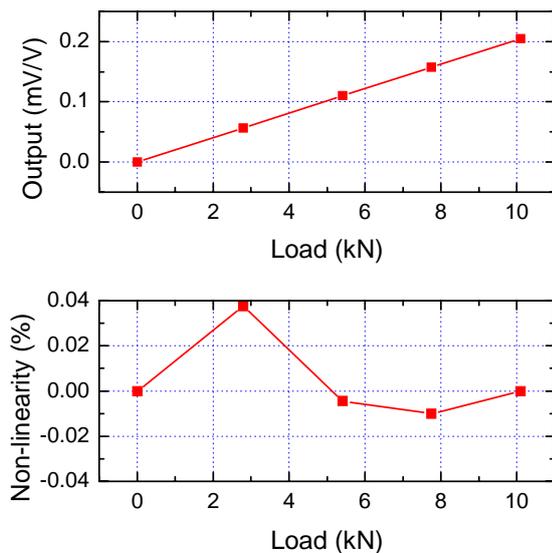

Fig. 13 Non-linearity characteristic of normal force component of hollow transducer.

5. CONCLUSIONS

We investigated dynamic properties of solid and hollow type cylindrical multi-components force transducers. Its frequency range for the normal force component exceeds 1 kHz, the maximum test frequency. The frequency range of the cylindrical force transducers are higher than the binocular type multi-component force transducer. Therefore, the cylindrical type multi-component force transducer is more suitable for dynamic application than the binocular-type multi-component force transducer.

However, its frequency ranges for the transverse force components and moment components are restricted up to 200 Hz and 100 Hz respectively.

The non-linearity of the normal force component was estimated. It was less than 0.04 % for both solid and hollow cylindrical force transducers. The dynamic measurement in this paper was the first attempt to evaluate dynamic characteristic of a force transducer up to 10 kN. Because it was possible to reach the dynamic force of 10 kN, the investigation of dynamic non-linearity was possible.

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