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EVALUATION OF MULTI-COMPONENT FORCE TRANSDUCERS HAVING COLUMN TYPE SENSING ELEMENT

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Abstract – We describe the dynamic evaluation of two multi-component force–moment transducers having column-type sensing element. Among them, one has a solid cylindrical sensing element and the other has a hollow cylindrical shape. They were calibrated statically with a force–moment calibration machine in the Physikalisch-Technische Bundesanstalt (PTB), Germany. We evaluated the dynamic characteristics of the force–moment transducers by using a shaker system and a multi-channel dynamic analyser system. We have examined and presented basic dynamic characteristics of the force transducers. In this paper, we will describe the dynamic characteristics of the force transducers in detail.

Keywords : multi-component force transducer, dynamic characteristics, evaluation

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 also very important.

We developed column-type six-component force–moment transducers[1]. Its static characteristics were estimated by using a multi-component force calibration machine developed by Roeske[2]. This paper describes the static calibration of the force transducers. The basic dynamic characteristics of the force transducers were described in our previous paper[3]. The detail analysis of the dynamic characteristics of the transducers will be described in this paper.

2. MULTI-COMPONENT FORCE TRANSDUCERS

Figure 1 shows the sensing element of a column-type force transducer to measure three forces, F_x, F_y and F_z, and three moments, M_x, M_y and M_z, using strain gauges. Table 1 shows the capacities of the force transducers. The capacity for the F_z component is 20 kN for both transducers. The rated outputs of the force transducers are 0.4 mV/V for the F_z component and about 0.5 mV/V for the other components.

Fig. 1. Column-type multi-component force transducers.

Table 1. Capacity of the column-type force transducers.

Component	Solid transducer	Hollow transducer
F_x	1.5 kN	2 kN
F_y	1.5 kN	2 kN
F_z	20 kN	20 kN
M_x	40 N·m	60 N·m
M_y	40 N·m	60 N·m
M_z	60 N·m	90 N·m

Figure 2 shows the schematic diagram of the column-type force transducers. The solid force transducer is 19.4 mm in diameter and 38.8 mm high. The outer diameter, inner diameter and height of the hollow force transducer are 22.4, 11.2 and 44.8 mm respectively. The force transducers

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were manufactured as mono bodies including additional parts at the bottom and top to mount them in the force evaluating system.

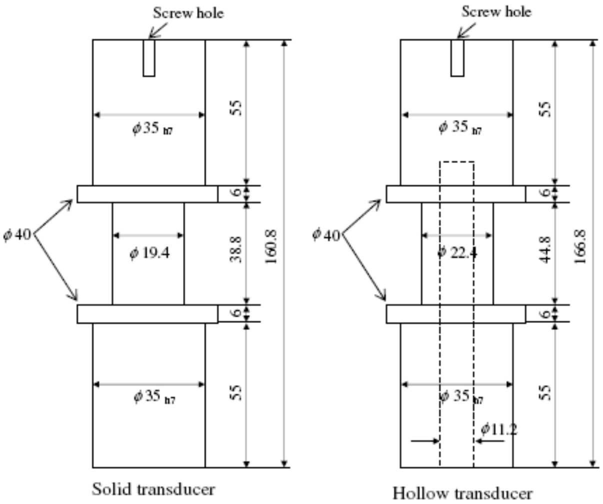

Fig. 2. Schematic drawings of column-type force transducers.

3. STATIC CALIBRATION

Fig. 3. Multi-component force–moment calibration machine.

The force transducers were statically evaluated using a multi-component force–moment calibrating system developed by the PTB of Germany[2]. Figure 3 shows a photograph of the system. It consists of six electrical driving units for load generation in the upper part of the machine and six force transducers for the accurate measurement of the acting components in the lower part. Both sets are realized as hexapod structures with the same geometry but mirrored arrangements. The force and moment ranges of the system are 10 kN and 1 kN·m respectively. Except for the axial force, these values are much higher than the corresponding capacity of our multi-component force–moment transducers. The calibrations were carried out with care to avoid overloading or damage.

For the investigations, the transducers were loaded with the single components F_z (axial force), M_z (torque), M_x and M_y (two bending moment components). These components can be generated so that their values do not depend on the reference point on the middle axis of the transducers. The cross force components, F_x and F_y, can cause a problem because they are always associated with a bending moment that is not constant along the axis. This moment is zero at one point only and, therefore, the result depends on this reference point. For our two transducers, the geometrical centres of the transducers' bodies were taken as the reference points.

The multi-component calibration machine has no control that would allow a given load state to be reached automatically. The control is able to generate a target load situation only with an uncertainty of a few percent. Therefore, it was necessary to calculate the sensitivities for the single components from the results obtained for a mixed load, where one component was the main one, but all other five components were present with a known, non-negligible amount.

The resulting sensitivities are given in Table 2 for the solid cylinder and in Table 3 for the hollow cylinder. The tables also show the cross-talk. For example, a torque of 1 N·m (M_z) generates a signal of 0.000074 mV/V in the F_z bridge of the solid transducer, whereas the same torque acting on the hollow transducer causes a signal of 0.000050 mV/V in F_z.

Table 2. Sensitivities and cross-talk of the solid transducer.

Bridge circuit #	S_{Fx} mV/V/N	S_{Fy} mV/V/N	S_{Fz} mV/V/N	S_{Mx} mV/V /(N·m)	S_{My} mV/V /(N·m)	S_{Mz} mV/V /(N·m)
Cir1 (F_z)	0.000000	0.000000	**–0.000021**	0.000006	0.000036	0.000074
Cir2 (M_z)	–0.000004	0.000002	0.000009	–0.000067	–0.000089	**–0.008346**
Cir3	0.000004	–0.000119	0.000019	**–0.012818**	0.000626	–0.000024
Cir4	0.000013	0.000048	0.000018	**–0.012832**	0.000887	–0.000109
Cir5	–0.000121	0.000017	–0.000014	0.000618	**0.012992**	0.000153
Cir6	0.000047	0.000009	–0.000013	0.000869	**0.012954**	–0.000019

Table 3. Sensitivities and cross-talk of the hollow transducer.

Bridge circuit #	S_{Fx} mV/V/N	S_{Fy} mV/V/N	S_{Fz} mV/V/N	S_{Mx} mV/V /(N·m)	S_{My} mV/V /(N·m)	S_{Mz} mV/V /(N·m)
Cir1 (F_z)	–0.000001	0.000000	**–0.000021**	0.000010	–0.000017	0.000050
Cir2 (M_z)	–0.000003	0.000002	0.000006	0.000020	–0.000029	**–0.005849**
Cir3	0.000000	–0.000091	0.000014	**–0.008963**	0.000507	–0.000078
Cir4	0.000010	0.000042	0.000013	**–0.008973**	0.000607	–0.000061
Cir5	–0.000092	0.000012	–0.000009	0.000432	**0.008999**	0.000069
Cir6	0.000041	0.000006	–0.000009	0.000548	**0.008983**	–0.000087

4. DYNAMIC SENSITIVITY

Figures 4~7 represent experimental set-up for dynamic evaluation of the column-type force transducers. Figure 4 shows the experimental scene to evaluate the normal force component F_z. We used an air bearing guide to minimize parasitic motion and estimated the actual dynamic force. The cylindrical mass was 25.4362 kg and its length was 0.35 m.

However, we could not use the air bearing guide for the measurement of transverse force components and moment components. Figure 5 shows the experimental arrangement for the transverse force components F_x and F_y. The force transducer was mounted on the side surface of a vertical wall to make the transverse force direction of the sensor coincide with the vertical direction of the shaker. An external mass of 0.9 kg was mounted on the force transducer to generate a transverse dynamic force. An accelerometer was mounted on the external mass to measure its acceleration.

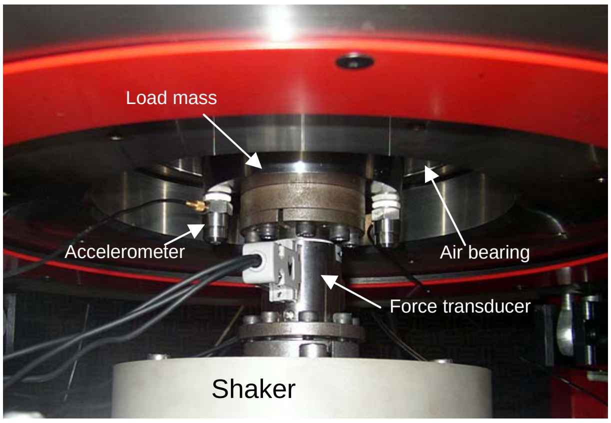

Fig. 4. Experimental set-up for normal force component.

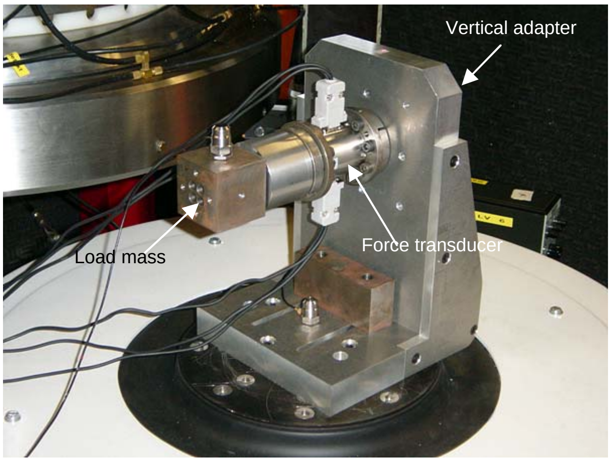

Fig. 5. Experimental set-up for transverse force component.

Figure 6 shows the experimental set-up to evaluate the bending moment components M_x and M_y, and Figure 7 shows the arrangement for the twisting moment component M_z. For the bending moment evaluation, the force transducer was mounted vertically. For the twisting moment component, the force transducer was mounted on a side surface of a vertical wall. A beam of length 0.1 m was used to activate the dynamic moment. The beam was made of aluminium and its cross-sectional dimensions were 18 × 18 mm. One end of the beam was attached to the centre of the transducer. An external mass was mounted at the other end of the beam and accelerometers were mounted on the mass.

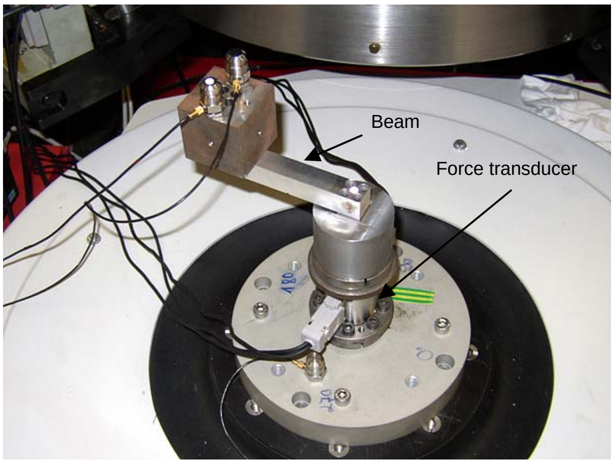

Fig. 6. Experimental set-up for bending moment component.

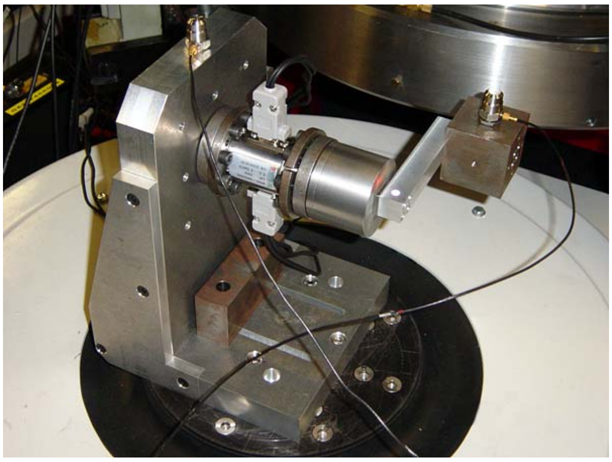
Fig. 7. Experimental set-up for twisting moment component.

Figure 8 shows the dynamic sensitivity of the force component F_z, normalized to its static sensitivity. All sensitivities in this paper are normalized to their static ones. Figures 8(a) and (b) are for the solid and hollow force transducers respectively. Both force transducers show acceptable frequency characteristic up to 1 kHz, the maximum test frequency. This operational frequency range is much wider than that of a binocular-type multi-component force transducer, which is about 420 Hz [4]. The wide frequency range enables us to use the column-type multi-component force transducer for dynamic force measurements. The solid force transducer shows disturbances at about 450 Hz and from 600 to 750 Hz. The disturbance at about 730 Hz is caused by the rocking motion; however, the others are caused by the transducer itself, because there is no singular behaviour at those frequencies in the FRF between acceleration signals. In contrast, the hollow transducer has fewer disturbances than the solid transducer. For the hollow transducer, the disturbances occurred at about 350 and 730 Hz. The disturbance at 730 Hz is caused by the rocking motion;

therefore, the frequency coincides with the solid transducer. The dynamic sensitivity of the solid transducer is almost flat under 1 kHz; in contrast, it reduces slightly with frequency for the hollow transducer.

Figure 9 shows the dynamic sensitivity of the twisting moment component, M_z. The sensitivity seems to tend towards 1 at low frequency and decreases as the frequency increases. The operational frequency range is restricted to about 130 Hz. The dynamic sensitivity of the hollow force transducer is similar to that of the solid force transducer. Although the frequency range of the moment component is narrow, it is much wider than that of the binocular-type multi-component force transducer of which frequency range is about 30 Hz. The six-component force transducers not only show 90° symmetrical dynamic characteristics but also asymmetrical properties in the *x*- and *y*-axes because of their geometry.

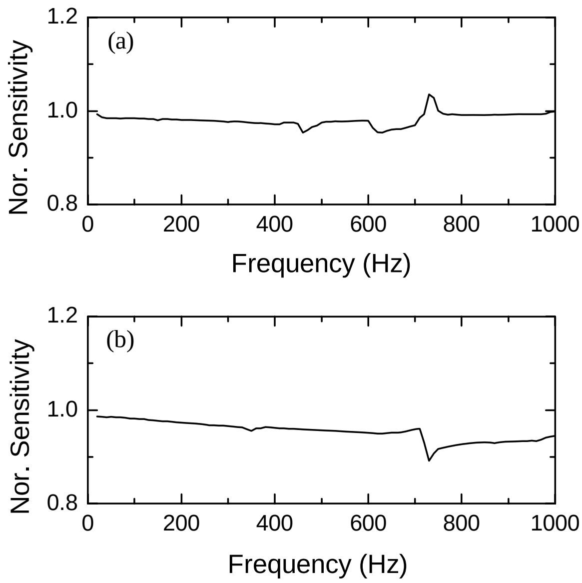

Fig. 8. Dynamic sensitivity of normal force component: (a) solid force transducer; (b) hollow force transducer.

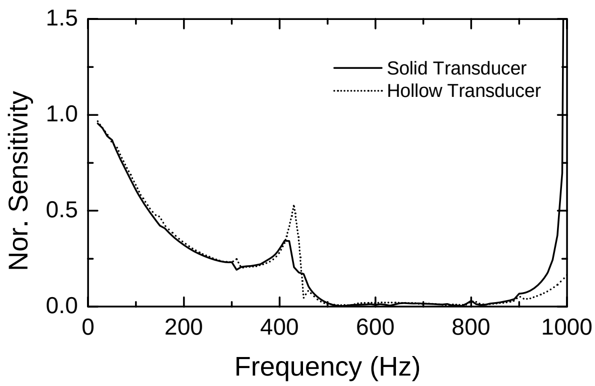

Fig. 9. Dynamic sensitivity of the twisting moment component.

5. NONLINEARITY AND REPEATABILITY

Figure 10 shows the non-linearity characteristic of the normal force component F_z at 200 Hz. The relative deviation is estimated as the difference between measured force and linear fit from zero to maximum force value. Figure 10(a) shows the non-linear behaviour of the solid transducer, and Figure 10(b) shows that of the hollow transducer. To investigate the non-linearity characteristic, we repeated dynamic measurement with varying force magnitude up to 10 kN using the air bearing guide. The non-linearity was estimated to be about 0.02% for the solid transducer and 0.03% for the hollow transducer. The non-linearity is estimated as the ratio of the maximum deviation from the linear estimation with respect to the transducer output at the maximum force, 10 kN.

Figure 11 shows the non-linearity of column-type force transducers at various frequencies. Overall, the non-linearity is lower than 0.25%, especially in the low frequency range. However, it has some peaks at which the level approaches 2%. When comparing Figure 11 with Figure 8, we can see that the peaks occur at the frequencies at which the dynamic sensitivity is disturbed. The uncontrollable disturbances cause bad non-linear behaviour. The hollow transducer shows lower non-linearity and fewer peaks.

Figure 12 shows the repeatability characteristic of the transducer. To evaluate this, we performed the same measurements three times. To estimate the repeatability error, the difference between the maximum and minimum values among the three signals was estimated and divided by two. The repeatability error shows some peaks like the non-linearity, and the peaks occur at similar frequencies, where uncontrollable disturbances occur in the dynamic sensitivity.

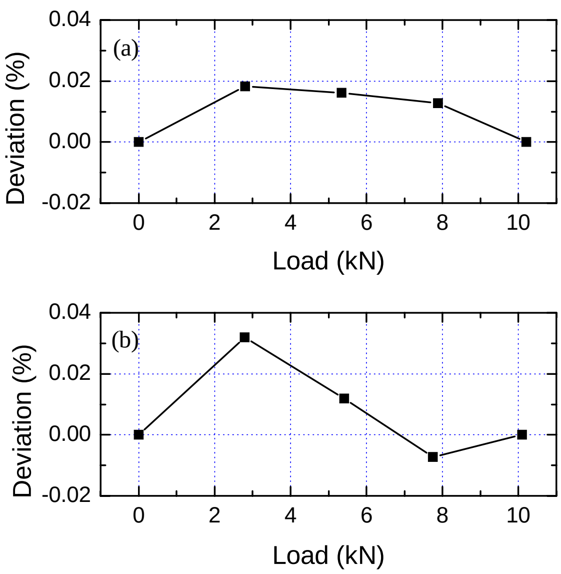

Fig. 10. Non-linearity characteristic of normal force component: (a) solid force transducer; (b) hollow force transducer.

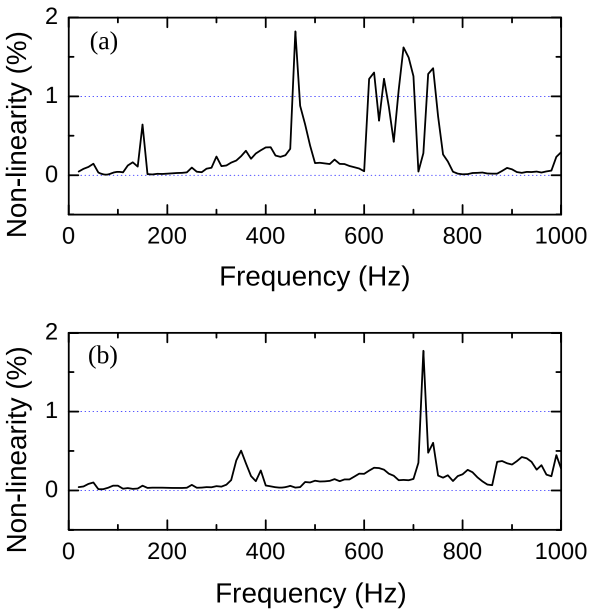

Fig. 11. Non-linearity of normal force component: (a) solid force transducer; (b) hollow force transducer.

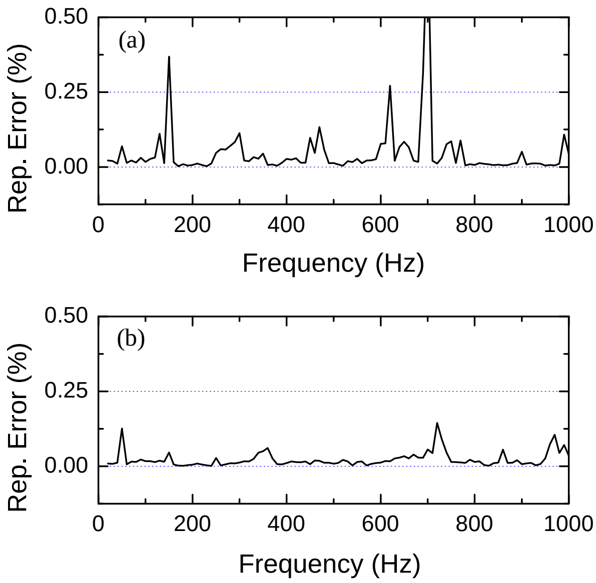

Fig. 12. Repeatability error of normal force component: (a) solid force transducer; (b) hollow force transducer.

6. CONCLUSIONS

We have examined two column-type force transducers using the force calibration machine in PTB. And the dynamic sensitivities of the transducers wee also examined. The transducers' frequency range for the normal force component exceeds 1 kHz, the maximum test frequency. The frequency range of these column-type force transducers is higher than that of a binocular-type multi-component force transducer. Therefore, the cylindrical multi-component force transducer is much better suited for dynamic applications than the binocular-type multi-component force transducer. However, its frequency ranges for the transverse force components and moment components are restricted to 200 and 130 Hz respectively.

Because we could generate high dynamic forces, the non-linearity of the normal force component could be estimated. It was less than 0.03% for both solid and hollow cylindrical force transducers at 200 Hz. However, it approaches 2% at several frequencies. The repeatability error was less than 0.5 % for both transducers. The repeatability was estimated from three sets of measurement.

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