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A NEW CALIBRATION FACILITY FOR DYNAMIC FORCES UP TO 10 kN

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Abstract – Dynamic forces realised by accelerated load masses are traceable to acceleration and mass according to the force definition. For the extension of the dynamic force range a new facility based on an electrodynamic shaker system is developed.

Keywords: Dynamic force; Electrodynamic shaker; Air bearings, Calibration.

1. INTRODUCTION

In many applications force transducers are used for the measurement of dynamic forces. Force measuring devices intended for dynamic applications should be calibrated by static procedures and the dynamic properties should be determined by dynamic measurement procedures. Therefore different methods and facilities are developed at PTB to determine the dynamic properties of force measuring devices. The investigation and calibration of dynamic force measuring devices covers static and dynamic measurements. Effects such as linearity, hysteresis, rotation, repeatability, creep, etc. are investigated by static procedures. Dynamic measurements are carried out to determine the differences between static and dynamic characteristics. But in the past the dynamic force was limited to a maximum force of about 1 kN according to the properties of the used electrodynamic shaker. In most applications of dynamic force measurement like for example in automobile industry, robotics or material testing force transducers are used in the kN range. Because of the small shaker systems which was used in the past it wasn´t possible to calibrate force transducers with forces above 1 kN. Therefore it was necessary to extend the force range of the dynamic facilities at PTB by combining the past developments with an elctrodynamic shaker of larger capacity. Furthermore the measurement uncertainty has to be reduced. Therefore a new facility for larger forces is under development which combines the past developments of PTB with a larger shaker system lake described in this paper.

2. THE CONCEPT OF A NEW FACILITY FOR DYNAMIC FORCES UP TO 10 kN

The new facility for dynamic forces up to 10 kN combines the past developments of PTB with a large electrodynamic shaker system. The shaker generates a maximum force vector of 17,8 kN sine amplitude.

If a force transducer with an additional load mass is mounted on the shaker the force acting on the sensing element depends on the detailed mass combination which is mounted on top of the force transducer and the acceleration distribution of the mechanical structure.

The shaker is combined with the air bearing system, which was developed in the past years at PTB [1,2]. For large mechanical structures it is absolute necessary to consider the relative motions of the load mass by the theory developed in [1,3]. The dynamic force must be determined from the acceleration distribution $\ddot{u}(x,t)$ and the mass distribution with density ρ according to

$$F = \int_V \rho \cdot \ddot{u}(x,t) \cdot dV \,. \qquad (1)$$

For the determination of the acceleration distribution, multicomponent acceleration measurements are necessary as shown in Fig. 1, and the theory presented in [1,3] must be used to calculate the dynamic force. The drawing in Fig. 1 shows the different parts of the new facility. In the acceleration measuring system acceleration transducers or laser interferometer can be used to determine the acceleration distribution of the load mass. The different parts of the new facility are described in this paper.

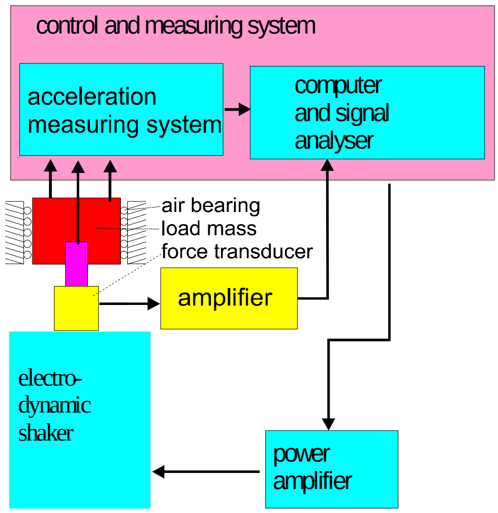

Fig.1: Facility for dynamic force calibration

3. ELECTRODYNAMIC SHAKER

The shaker generates a maximum force vector of 17,8 kN sine force peak and 40 kN half sine bump force. The

performance of the shaker depends of the shaker specifications, which can be summarised as follows:
Maximum sine force: 17,8 kN sine amplitude
Maximum force vector 40 kN half sine bump force
Maximum acceleration: 1225 m/s^2 sine amplitude
Maximum velocity: 2 m/s sine amplitude
Maximum displacement: 25,4 mm sine amplitude
Effective mass of moving element: 14,1 kg
Armature resonance: 2400 Hz

These are the maximum values which are possible but in detail it depends on the combination of the shaker and the used power amlifier. For dynamic force calibration the shaker will be operated in the frequency range from 20 Hz up to 1000 Hz. But according to the specifications it will be also possible to extend the frequency range up to 2000 Hz but it is dependent on the mechanical structure which is mounted on the shaker table.

Because of the conditions in the laboratory care has to be taken to the vibration generated from the shaker to the basement and to the heat dissipation in the laboratory. To reduce the vibration to the ground a shaker with an air suspension system is used. To reduce the influence of side motions the shaker body is guided on shafts. For the use of the shaker in the air conditioning system of the laboratory it was necessary to take the cooling air from outside directly to the shaker and a blower blows the air direct to outside. For short time measurements the blower can be switched off and the temperature of the shaker coils are monitored during the measurement. The advantage is that switching off the blower can reduce the noise in the system.

4. THE AIRBEARING SYSTEM

Measurements have shown that side forces considerably limit the accuracy of the calibration. In the past a calibration facility with an air bearing system was developed for the guidance of the load masses. The main part of the facility for the dynamic calibration of force transducers is the air-bearing unit, which is now combined with the larger shaker system like shown in Figure 2. The main part of the testing facility is a cylindrical air bearing with an inner diameter of 120 mm for the guidance of the load mass. To reduce the side movements of the mass during the dynamic test, the mass which is between 10 kg and 50 kg is guided without friction in the cylinder bearing and remains in the measuring position due to the inertia of a large mass of about 500 kg surrounding the cylinder bearing.

The axis of the cylindrical air bearing must be aligned to the axis of the load mass to avoid side forces acting on the transducer during the calibration. For this purpose a lower air-bearing unit consisting of a spherical and a horizontal bearing carries the cylindrical bearing. The spherical bearing is to adjust the angle and the horizontal bearing to adjust an axial offset. The radius of the spherical bearing is aligned to the centre of the cylinder mass to enable a test to be made without moments. For a precision adjustment of the radius to the centre of mass, a tare mass is used which is arranged on top of the cylinder. The cylindrical bearing is self-adjusted to the load mass by the air-bearings.

The air bearing is supported by an elevating mechanism fixed to a frame mounted around the shaker. With this mechanism the alignment of the whole testing facility can be precisely adjusted. Each measurement position can be reached by means of the elevating mechanism driven by an electrometer, making it possible to test force transducers of different heights.

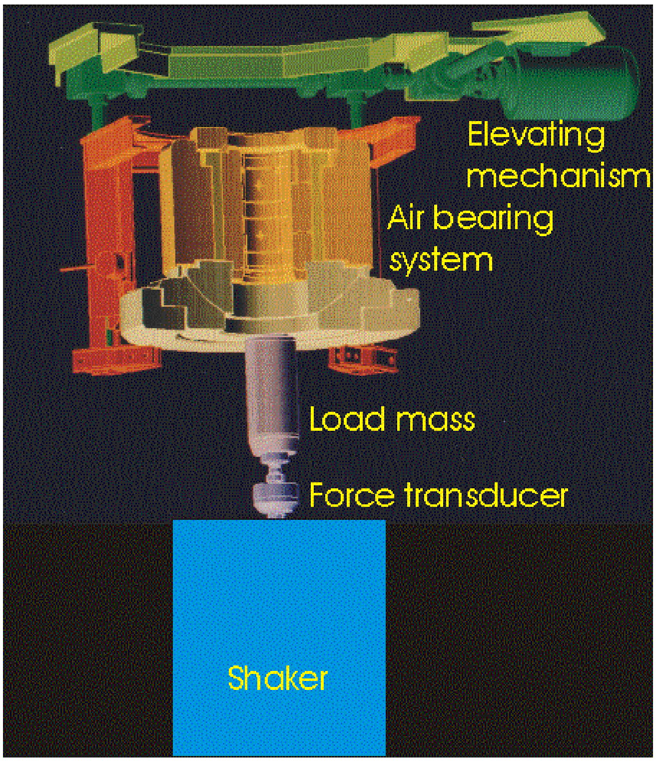

Fig.2: Shaker with air-bearing system and elevating mechanism

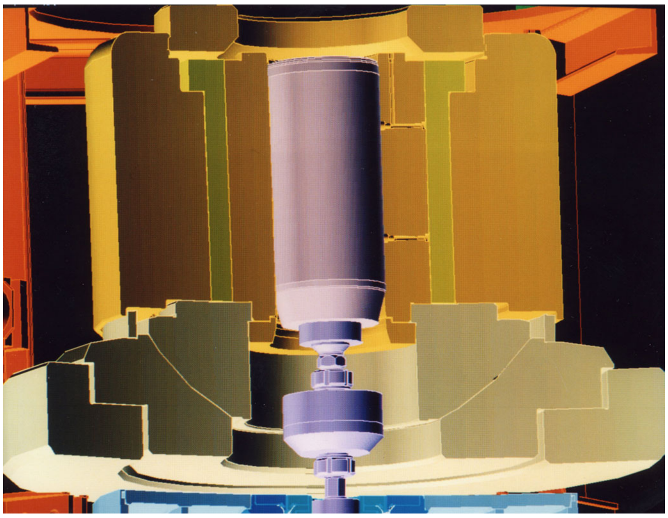

Fig.3: Air-bearing unit with cylindrical air bearing, spherical air bearing and horizontal air bearing.

Air-bearings arranged in the cylinder (120-mm inner diameter) are used to ensure frictionless guidance of the load mass during the dynamic test. The bearings consist of 8 air-bearing pockets, 4 arranged in the upper and 4 in the lower part of the cylinder and offset by 90 degrees. The dimensions of the air bearing system determine the size of the load masses. This means that only cylindrical load masses with a diameter of 120 mm can be used in the bearing. In the past load masses of 275-mm length are used. But the length can be changed a little for future experiments. Nevertheless it is not possible to use smaller load masses in combination with this air bearing system. But for the determination of the end mass of force transducers and for the investigation of the resonance behaviour of the force transducers it is necessary to change the load mass to smaller dimensions. Therefore the shaker can be operated without the air bearing. The air-bearing unit can be moved in the horizontal direction so that the shaker can also be used for other experiments with out air bearing unit.

5. THE MEASURING SYSTEM

The dynamic force, which is acting on the force transducer, has to be determined from the acceleration distribution of load mass, which is mounted on top of the force transducer. In the past the acceleration was measured with acceleration transducers which are calibrated by interferometric procedures. But with this system the acceleration could not be measured on the whole surface of the load mass and the uncertainty is limited by the uncertainty of the calibrated acceleration transducers. For a reduction of the measurement uncertainty laser interferometric methods can be used directly. The acceleration distribution can be measured for example with a scanning laser interferometer. But it has to be taken into account that the measurement uncertainty is limited by the interferometric data evaluation system. Therefore instead of a commercial scanning interferometer the method, which was developed in the field of acceleration transducer calibration, was used and combined with the scanning mode like described in [4].

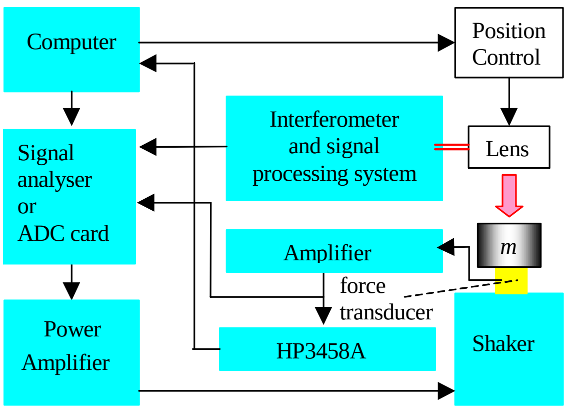

Fig.4. The measuring system

For the determination of the dynamic force it is very important to measure the acceleration distribution not only on the upper surface. The dynamic force has to be calculated from the acceleration distribution over the whole volume of the load mass like can be seen in results which are obtained with acceleration transducers. For the discussion of the acceleration distribution results obtained with acceleration transducers are discussed in this paper. But in future the measurements will be also carried out with laser interferometric methods [4].

To determine the relative motions, the acceleration was measured on the adapter (using one acceleration transducer) and on the upper and lower surface of the load mass (using two transducers on each surface) as shown in Figure 1. The mean value of the results of the measurements carried out on the upper surface and the mean value of the results of the measurements performed on the lower surface of the mass have been taken into account in the evaluations [2,3].

Figure 5 shows the results of the measurements of the amplitude response obtained with a steel mass of 17,5 kg (about 19 kg including the adapter). At a frequency of 1000 Hz, the differences between the measurements on adapter and load mass amount to 9%, and they are 3,4% between the measurements carried out on the upper and the lower surface of the mass. The phase shifts between the output signal of the force measuring device and the accelerations at the different points of the load mass have been measured [2,3]. The quality of the phase distribution between force signal and acceleration is the same in all measurements, i.e. all "mass particles" of the additional mass oscillate in phase in the frequency range under consideration. As there are no phase differences either between the measurements carried out on the upper and lower surface of the load mass, it can be assumed that the influences of material damping are very small.

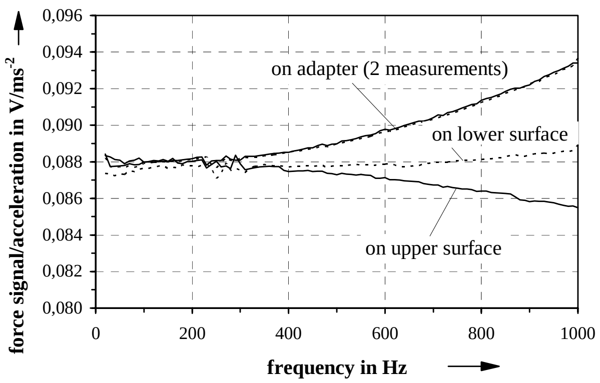

Fig. 5: Measurement with light steel mass (about 17,5 kg). Force transducer signal/acceleration ratio for acceleration measurements on adapter, upper mass surface, and lower mass surface.

The measurements clearly show that at higher frequencies and with greater masses the load masses can no longer be considered to be rigid bodies but must rather be described as a continuum. The dynamic force acting on the force transducer is determined by the distribution of mass and acceleration. The greatest deviations are found between the accelerations on the adapter and on the mass. This effect is taken into account by splitting the total mass *m* in different parts.

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the accelerations on the adapter and on the mass. This effect is taken into account by splitting the total mass *m* in different parts. This experimental result which was obtained in earlier measurements by using acceleration transducers demonstrate that the load mass has to be designed in a way that the whole acceleration distribution can easy be measured. Instead of the conical bore used in this experiment the mass can be constructed for example with different steps inside on which the laser can measure the acceleration. Furthermore the adapter can be scanned on the upper surface and can contain a whole inside to measure the acceleration in the adapter. For the dimensions of the used load mass the acceleration distribution has to be calculated by a model for example with Finite Elements.

6. DYNAMIC FORCE CALCULATION

The dynamic sensitivity of a force-measuring device is defined by the ratio of the output signal of the measuring amplifier U_V to the acting dynamic force F according to equation (2):

$$S = \frac{U_V}{F} \quad . \qquad (2)$$

The dynamic force must be determined from the acceleration distribution $\ddot{u}(x,t)$ and the mass distribution with density ρ according to

$$F = \int_V \rho \cdot \ddot{u}(x,t) \cdot dV \quad . \qquad (3)$$

The dynamic force, which is generated by the adapter, is calculated from the adapter mass and the adapter acceleration [2,3]. The dynamic force generated by the load mass is calculated taking the correction factor K into consideration.

Multicomponent acceleration measurements are necessary for the determination of the acceleration distribution, and the theory presented in [1,3] must be applied to calculate the dynamic force. As the load masses were of cylindrical shape, the acceleration distribution was calculated by solving the wave equation, and the dynamic force was calculated according to equation (3). It was found that the dynamic force could be calculated by equation

$$F = m \cdot a \cdot \mathrm{K} \qquad (4)$$

where a is the acceleration on the upper surface of the load mass and K a correction term which takes the continuum vibration of the cylinder into account. For a solid cylinder, K was calculated to be [1]:

$$\mathrm{K} = \sin\left(\sqrt{\frac{\rho}{E} \cdot \omega_0^2} \cdot l\right) \cdot \frac{1}{\sqrt{\frac{\rho}{E} \cdot \omega_0^2} \cdot l} \qquad (5)$$

where ρ is the density, E the elasticity modulus and l the length of the load mass and ω_0 the angular frequency of the excitation. The correction terms depend on the shape of the load mass and can be determined by interferometric measurements. But if the shape is not a cylinder an analytical solution of the wave equation is difficult or not possible. Therefore for example Finite Element Calculations can be used for the determination of the correction factor.

7. CONCLUSION

It is pointed out that the force range of dynamic force calibration can be extended in the kN range by using larger electrodynamic shaker systems. In the case of larger mechanical structures it is very import to take the acceleration distribution into account. Theoretical models developed in the past have to be used for an accurate determination of the acting dynamic force and interferometric methods can be used in future for a reduction of the measurement uncertainty. The air bearing system is combined with a larger shaker system to increase the force range.

Acknowledgments

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REFERENCES

[1] R. Kumme, Untersuchung eines direkten Verfahrens zur dynamischen Kalibrierung von Kraftmeßgeräten – ein Beitrag zur Verringerung der Meßunsicherheit, PTB-Bericht MA-48. 1996

[2] Kumme, R.; Peters, M.; Sawla, A.: Improvements of dynamic force calibration, Part 2. Brussels, Luxembourg: Commission of the European Communities, 1995 (BCR information, Report EUR No. 16497EN), ISBN 92-827-5344-1, 122 p.

[3] Kumme, R.: The determination of the effective dynamic force for the calibration of force transducers, with due regard to the distribution of mass and acceleration. In: Proceedings of the 15th IMEKO TC3 Conference, Madrid (Spain), 7-11 October, 1996, pp.129-138.

[4] Zhang, Li; Kumme, R.: Investigation of interferometric methods for dynamic force measurement. To be published in: Proceedings of the XVII. IMEKO World Congress, Dubrovnik (Croatia), 2003.

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