Characterization of Force Transducers for Dynamic Measurements

Michael Kobusch*

* Dr. Michael Kobusch, Working Group "Impact Dynamics" e-mail: michael.kobusch@ptb.de

1 Introduction

The measurement of time-dependent forces has gained particular importance over the past years. In this context, increasing demands on measurement accuracy have brought new challenges to be solved for the metrological community.

Dynamic force measurements are widely used and play an important role in many industrial areas, for example in the field of material testing, automation and handling engineering, production engineering, vibration tests of mechanical and electronical components for the aerospace industry, and crash tests for safety standards in the automotive industry.

Depending on the specific dynamic application, the nature of the dynamic force differs considerably from case to case. For example, sinusoidal (or periodic) forces are usually applied in fatigue tests, step-like and continuous forces in machining processes, and shock forces in crash tests. A requisite for reliable dynamic measurements is the establishment of an infrastructure for traceable dynamic measurements that is capable of covering such very different load conditions.

1.1 Measurement standards and practice

Whereas the static calibration of force transducers is described by international standards (DIN EN ISO 376, [1]), documentary standards or commonly accepted guidelines and procedures for dynamic measurements are still lacking. Therefore, it is common practice to perform dynamic measurements with force transducers which are only statically calibrated.

However, there is wide agreement that dynamic calibrations are actually needed. To give an example, standards on instrumentation for crash tests in the automotive industry (ISO 6487 [2], SAE J211/1 [3]) already specify error limits for the amplitude response of measurement transducers, pointing out that satisfying methods for dynamic force calibrations currently do not exist.

Only for the special application of the dynamic force calibration for uniaxial fatigue testing, an international standard (ISO 4965 [4]) has been defined which is based on comparison methods using sinusoidal excitation.

Because of the unsatisfying normative situation, some information about the dynamic performance of a force transducer is often obtained by performing additional measurements using suitable dynamic testing devices. Such measurements are especially well suited to investigate about whether the dynamic measuring behaviour of a force transducer has changed in the course of time and if a replacement is needed. Therefore, some dynamic testing for comparison purposes is already widely used in industry.

1.2 Metrological challenge

If a force transducer is subjected to dynamic loads, the mechanical structure reacts with frequency-dependent inertia forces that compromise the input force to be measured [5]. Further influences may result from the coupled mechanical environment, e.g. the force introduction, the adaptation at the base, or other components of the measurement set-up.

Moreover, the dynamic behaviour of the electrical signal chain must also be considered to fully understand the dynamic measurement data. In general, dynamic measurements are concerned with a frequency-dependent measurement behaviour that may arise to some extent.

Given the diversity of dynamic applications and their specific signals, it is important to know under which conditions dynamic effects should be taken into account and whether dynamic measurements can still be performed with statically calibrated transducers. In this context, the disturbing inertia forces must not exceed the required measurement uncertainty. To be able to give a satisfying estimation, knowledge of the dynamic behaviour of the transducer as well as of the measuring set-up is needed.

1.3 Dynamic suitability

As a first step, the selection and assessment of a force transducer to be used for dynamic measurements is frequently based on its **fundamental resonance frequency**, which denotes the lowest mechanical resonance along the measuring axis for a transducer rigidly mounted at its base. A respective frequency value is often specified in the data sheets. A normative document that includes this characteristic parameter relevant to dynamics is the German Directive VDI/VDE 2638 [6] on the characteristics of force transducers.

Knowledge of the fundamental resonance gives a first indication of the usable frequency range. However, one has to keep in mind that the resonance of a mechanical structure depends on its elastically coupled mass elements. For instance, a combination of high stiffness and small vibrating mass will give high frequencies. In a given application, force transducers are always coupled to a mechanical environment resulting in a dynamic behaviour that may differ substantially from that of the bare transducer.

It becomes clear that the fundamental resonance does not suffice to understand the dynamic measurement behaviour of a force transducer in its application. Instead, it is very important to have information about the structural distribution of the transducer's **stiffness** and **mass**, which actually is the key data for a profound understanding of its dynamic performance.

Within the scope of the European research project EMRP IND09 *Traceable Dynamic Measurement of Mechanical Quantities*, the general approach of a **model-based calibration** has been followed. The dynamic behaviour of the force transducer, as well as of its measurement set-up, is described by an appropriate physical model, which for example consists of a series arrangement of spring-coupled lumped masses. In this model, the transducer's dynamic properties are characterized by its model parameters which denote the transducer`s structural distribution of mass, stiffness and damping.

2 Force Transducers

Modern force transducers are electromechanical devices that use a force sensing element introduced into the force flow. By principle, a force transducer is always coupled to its mechanical environment on both sides of the transducer's body. An acting input force causes a small elastic deformation of the mechanical structure which is generally assumed to be proportional to the electrical output signal of the force measuring element.

Strain gauge transducers and piezoelectric transducers represent two types of force transducers that nowadays have the greatest importance for industrial applications. Figure 1 exemplarily shows three different models, two strain gauge transducers and one piezoelectric transducer, which were investigated in the aforementioned European research project. The transducers have greatly differing designs, dimensions and masses, and are all suited for compressive and tensile forces, as their mechanical couplings are realized by central threaded connectors.

For a given nominal capacity, a piezoelectric transducer is usually more compact, smaller and of higher stiffness than a strain gauge transducer. Therefore, piezoelectric force transducers have comparably high resonant frequencies, which makes them better suited for dynamic measurements at first glance.

2.1 Strain gauge force transducers

This type of force transducer uses strain gauges as the measuring principle to sense the elastic deformations resulting from an applied input force. A strain gauge picks up the surface strain of the underlying structure, and the mechanically elongated sensing element proportionally changes its electrical resistance. Typically four strain gauges

Figure 1:
Three force transducers investigated in the scope of the project EMRP IND09 (from left to right): HBM U9B / 1 kN, Interface 1610/2.2 kN, Kistler 9175B (–8 kN…30 kN).

are connected to a Wheatstone bridge circuit to compensate influences from parasitic loads and temperature effects, and to obtain a larger signal with a good signal-to-noise ratio. A connected bridge amplifier feeds the supply voltage and amplifies the small force-proportional bridge signal.

A great variety of mechanical designs of strain gauge force transducers has been developed in the past in order to optimally meet the individual measurement requirements. However, strain gauges are always bonded at defined locations of preferably strong and uniform strain. For this reason, a strain gauge transducer usually features a structural part of comparably high compliance, which can be termed *measuring spring*.

For dynamic measurements, the dynamic behaviour of the bridge amplifier has to be taken into account. For detailed information on the traceable dynamic calibration of bridge amplifiers please refer to the respective contribution given in this issue.

2.2 Piezoelectric force transducers

A piezoelectric force transducer uses a piezoelectric element to generate a force-proportional electrical charge signal. The transducer typically consists of two ring-shaped quartz disks that are contacted by an electrode foil, and a lower and upper force introduction part. A central screw connection usually pre-loads the sensor element to enable measurements of tensile forces as well.

The piezoelectric measurement principle only allows quasi-static measurements with long time constants of the amplifier's high-pass filter; however, true static measurements are not possible. As the principle is not based on mechanical deformation, the transducers have high structural stiffness which makes them well suited for dynamic measurements.

Piezoelectric force transducers are either available with electrical charge output (charge type), or with voltage output (IEPE type) featuring integrated electronics.

Again, the dynamic behaviour of the electrical signal chain has to be considered for dynamic measurements. Information on the traceable dynamic calibration of charge and voltage amplifiers is found in a respective article in this issue.

2.3 Application notes

It is difficult to make general recommendations regarding the selection of suitable force transducers for dynamic measurements, as the transducer's mechanical environment as well as superposed parasitic loads may have great influence on the dynamic measurement performance.

First of all, the user has to realize the fact that the high precision of static force measurements might be substantially compromised for dynamic measurements. Good static performance does not automatically mean good dynamic performance, and vice versa. For dynamic loads, the transducer output signal is affected by the inertia forces of the transducer's internal mechanical structure, which means that the structural design is of great importance. Some criteria for dynamic force measurements are given in the following.

Depending on the transducer's structural design and the coupling to its mechanical environment, the measurement set-up might react with low-frequency bending modes that could limit the usable frequency range. Therefore, low sensitivity against parasitic forces and moments is an important criterion for suitable force transducers if bending modes might be excited.

In order to get an estimate of the dynamic behaviour of the force transducer and/or its mechanical environment, it would be of great benefit to perform a modal analysis by means of finite element modelling. This analysis would give valuable information about the system's resonant modes that could be expected.

The stiffness of the mechanical couplings at both ends of the force transducer, i.e. the stiffness of the adaptation parts and of their respective contact surfaces, plays an important role for the dynamic performance. To shift possible coupling resonances to high frequencies and thus to obtain a broad dynamic bandwidth, the coupling stiffness should be as high as possible. The stiffness of screw connections is a complex topic with many influencing factors, e.g. material pairing, surface size, flatness, roughness, lubrication, and setting.

High stiffness requires large pretension forces, and the contacting surfaces should be large, flat and slightly lubricated, and the setting should be kept small. However, to achieve reproducible conditions for the elasticity of screw connections, it is recommended to fasten screw connections with defined torque.

One aspect sometimes not properly taken into account in dynamic applications is the asymmetric design of many force transducers, in particular of strain gauge transducers. With greatly different values of the structural mass above and below the transducer's measuring spring, the performance of the dynamic measurement application may greatly depend on the orientation of the mounted force transducer. To minimize the influences from the internal inertia forces, the larger mass component (transducer base mass) should be fixed at the more rigid part of the application where the vibrations are small, whereas the smaller mass component (transducer head mass) should be orientated towards the measuring side.

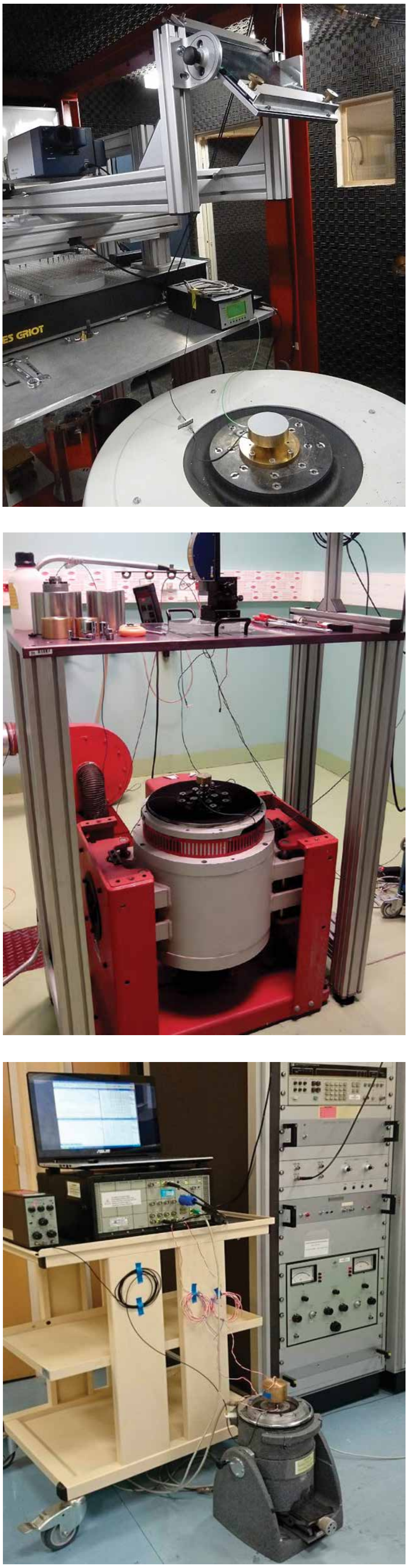

Figure 2:
Dynamic calibration devices with sinusoidal force excitation at PTB (top), CEM (centre), LNE (bottom).

Regarding the electrical measuring chain, signal conditioners and measuring amplifiers have to be suitable for the required dynamic bandwidth and their frequency responses have to be known and taken into account. In addition, special care might be taken to minimize influences from electromagnetic noise as such parasitic signal components could be in phase with the dynamic force input signal. The electromagnetic susceptibility of the force transducer with its cabling might be experimentally tested by probing the environment with an unmounted transducer.

3 Traceability Techniques

Sinusoidal forces and pulse-shaped forces have the greatest practical importance for the dynamic calibration of force transducers. With these two types of dynamic excitation, which are rather different in the time and frequency domain, the great variety of dynamic force measuring tasks can be covered with considerable good practical orientation.

Within the scope of the project EMRP IND09, the research was focused on dynamic calibration devices and measurement methods applying traceability with primary methods. Calibration devices for dynamic forces have been developed at three participating national metrology institutes providing both sinusoidal force calibrations (see figure 2, PTB in Germany, CEM in Spain, LNE in France) as well as shock force calibrations (PTB).

In each case, traceability of the dynamic force is based on the measurement of inertia forces using laser interferometers. According to Newton's law, the acting dynamic force $F(t)$ of an accelerated mass is given by the product of the mass m and the time-dependent linear acceleration $a(t)$ as $F = m \cdot a(t)$.

3.1 Sinusoidal force calibration

Whereas PTB had already started its research on dynamic force calibrations with sinusoidal excitation years ago [5, 7], the creation of a respective infrastructure at other NMIs was one of the important goals of the European joint research project.

Within the scope of the project, sine force calibration devices providing traceability with primary methods were developed and tested at PTB, LNE and CEM (cf. figure 2). The commissioned set-ups cover a frequency range from DC to 1 kHz and beyond, and provide force amplitudes up to 10 kN.

Each device uses an electrodynamic shaker system to excite the base of the force transducer under test mounted at the vibrating shaker platform and loaded at its top with a comparably large load mass. This vibrating mass body generates a sinusoidal inertia force which defines the reference signal.

A schematic drawing of such a primary sine force calibration device is shown in figure 3. The vertical

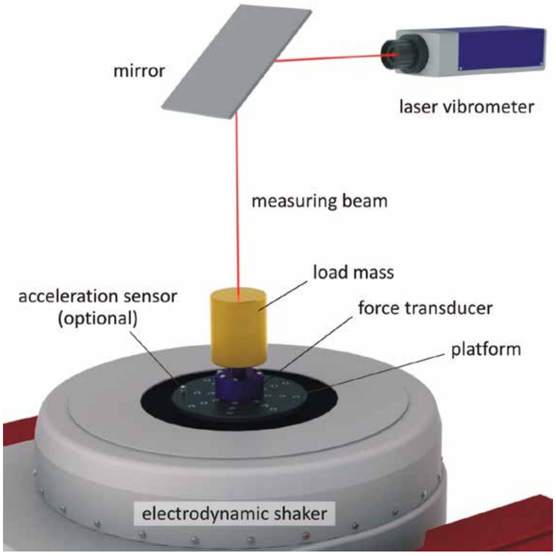

Figure 3:
Schematic drawing of the measurement set-up for sinusoidal force calibration.

dynamic motion of the load mass is measured by means of a laser vibrometer. An optional acceleration sensor is used to acquire the motion of the shaker. The excitation is controlled by the dynamic signal supplied by a function generator, fed to a power amplifier providing the current signal that drives the coil of the shaker platform. The force transducer under test is subjected to sinusoidal forces of varying frequency, and its amplitude and phase responses related to a reference force signal, i.e. the dynamic sensitivity, are evaluated as the dynamic calibration result.

The French national metrology institute LNE recently installed a shaker system providing forces up to 330 N; and the Spanish institute CEM commissioned a shaker system for sinusoidal forces up to 3 kN. Three electrodynamic shaker systems are available at PTB, a small one for force amplitudes up to 100 N and frequencies ranging from 10 Hz to 2 kHz, a medium-sized shaker (up to 800 N, frequencies 10 Hz to 3 kHz), and a large shaker providing forces up to 10 kN and sine excitations from 10 Hz to 2 kHz. At the moment, only PTB offers a calibration service for sinusoidal forces up to 2 kN force amplitude and 2 kHz excitation frequency which is anchored in its quality management system. More information about the state of the art of sinusoidal force calibrations at PTB and CEM is given in [8] and [9], respectively.

With the provision of a basic infrastructure for sine force calibrations at three European national metrology institutes, first international comparison measurements could be performed with the selected force transducers. The dynamic forces were generated with load masses of approximately 1 kg, 2 kg, 4 kg, 6 kg and 12 kg. Whereas the smallest mass bodies could be directly screwed onto the transducer under test, the larger masses required employing an adapter.

As an example, figure 4 presents the comparison of the dynamic sensitivity of the strain gauge force transducer Interface 1610 / 2.2 kN. The measurements were performed at the institutes CEM and PTB applying the small load masses of 1 kg and 2 kg. It is seen that the dynamic sensitivity generally decreases with frequency. The measurement results of both laboratories are in good agreement, as the relative deviation is in the order of about 1 %.

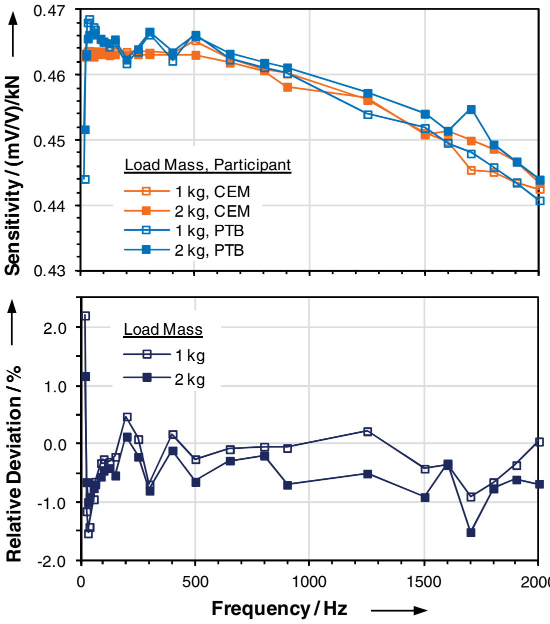

Figure 4:
Comparison of the dynamic sensitivity of the force transducer Interface 1610 / 2.2 kN measured at CEM and PTB using load masses of 1 kg and 2 kg: dynamic sensitivity (top), deviation between CEM and PTB (bottom).

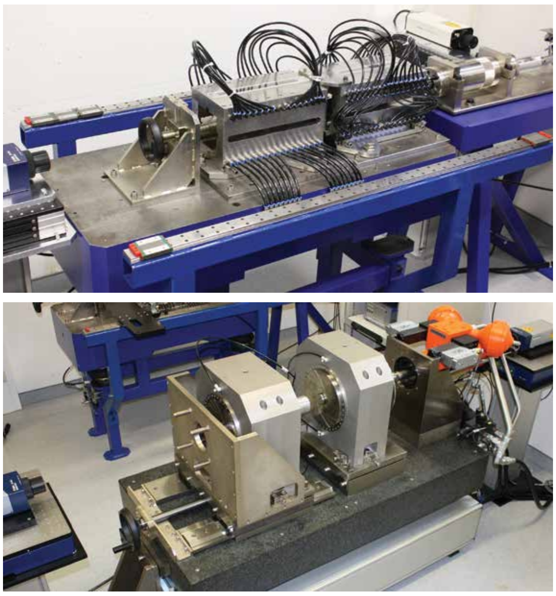

Figure 5:
Shock force calibration devices at PTB: 20 kN device (top), 250 kN device (bottom).

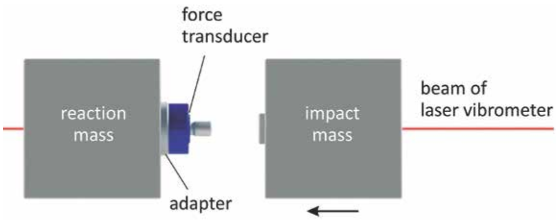

Figure 6:
Schematic drawing of the measurement set-up for shock force calibration.

3.2 Shock force calibration

Within the scope of the EMRP project, the method of shock force calibration was investigated at PTB using the two primary shock force calibration devices shown in figure 5.

Shock calibrations are performed with force pulses of defined amplitude, shape and duration. Here, the ratio between the pulse height of the transducer's output signal and the reference input force – the shock sensitivity – is often considered as the typical measurement result. However, former investigations with acceleration sensors showed that the pulse height ratio can be insufficient for calibration purposes as the associated signal shape and spectral content are of great influence. In this case, consistency between the different results from sinusoidal and shock calibration requires knowledge of the transducer's characteristic mechanical parameters that define its dynamic behaviour [10, 11].

The working principle of the primary shock force calibration devices is sketched in figure 6. Two airborne mass bodies are brought to collision with the force transducer under test mounted in between. The dynamic inertia forces of both the impacting mass body and the reacting mass body are measured using two laser vibrometers. The smaller 20 kN shock calibration device employs mass bodies of 10 kg each, and the larger 250 kN device of 100 kg. More information about the calibration devices is given in [12, 13].

Experiments at the larger 250 kN shock force calibration device proved that the shock response of a force transducer may not only depend on its internal elastic properties, but also on its mounting conditions [14]. The example in figure 7 presents a shock force pulse with strong signal ringing which exhibits two oscillation frequencies, where its lowest resonance considerably depends on the achieved stiffness of the adapter mounting, which was proved by testing different mounting surfaces and mounting torque (figure 8). In case of strong ringing, the pulse shape of the inertia forces may substantially differ from that of the transducer output. The calculation of the transducer's true dynamic input forces will consequently require the above-mentioned model-based calibration approach.

First trials on the parameter identification (see section 3.3) indicated that such signal ringing presumably carries the information to unambiguously identify the transducer's dynamic properties from

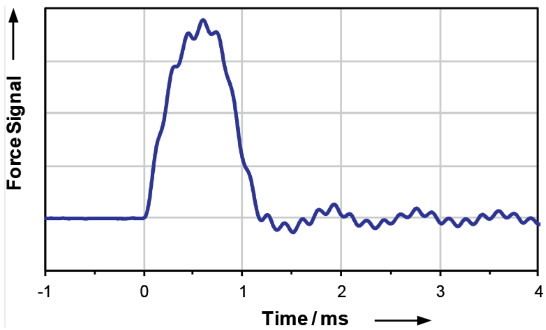

Figure 7:
Shock force signal with excited modal oscillations measured with a 225 kN strain gauge force transducer.

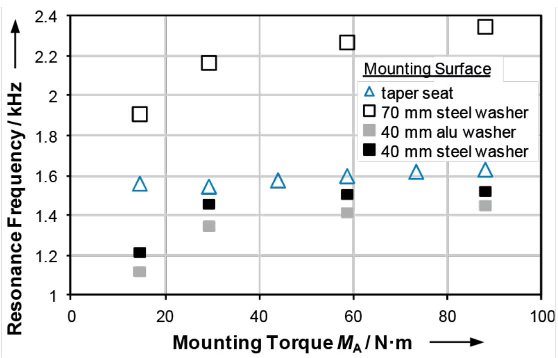

Figure 8:
Influence of the adapter's mounting conditions on the lowest resonance: variation of the mounting torque, different mounting surfaces.

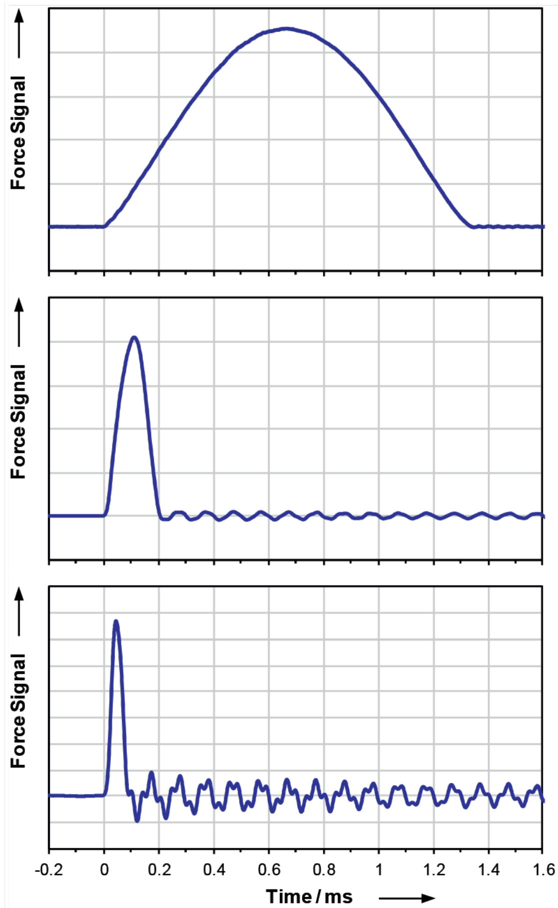

Figure 9:
Shock force pulses obtained with different impact masses: force transducer HBM U9B / 1kN, impact mass body of 10 kg (top), pendulum mass of 89 g (centre) and 7 g (bottom).

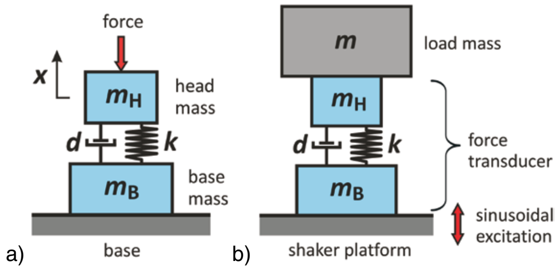

Figure 10:
Basic mass-spring-damper model of a force transducer (a), model of the sine force calibration device (b).

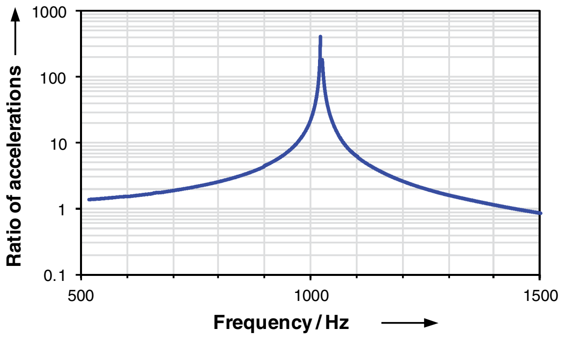

Figure 11:
Mechanical resonance of the transducer HBM U9B / 1 kN applied with a load mass of 1 kg measured at CEM.

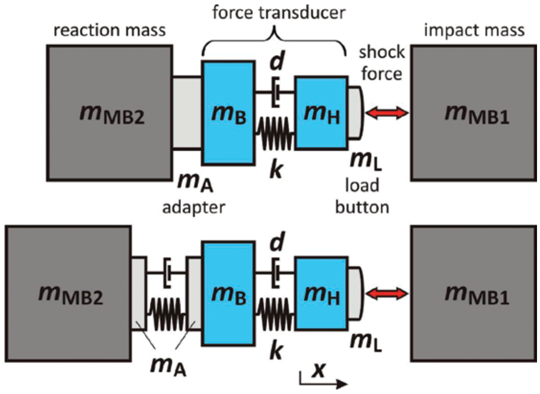

Figure 12:
Models of the shock calibration device with three and four model masses.

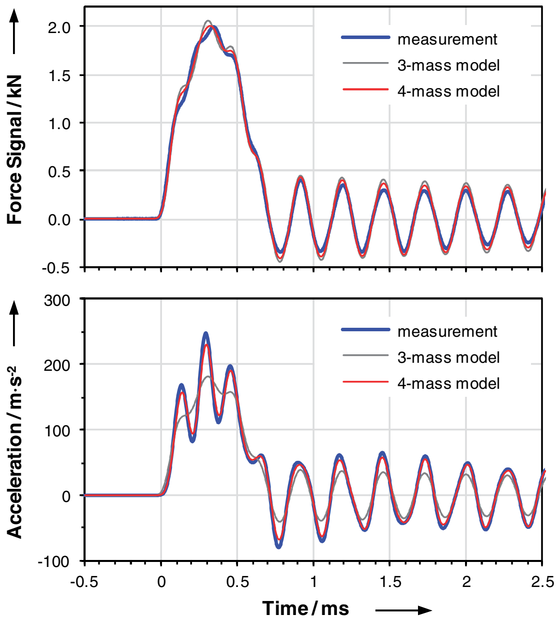

Figure 13:
Comparison of measured and modelled shock responses of the Interface 1610 / 2.2 kN, force signal and acceleration of the reaction mass.

shock force measurements. The measurements at the 20 kN device have shown that the shock pulses achieved with an impact mass of 10 kg are way too broad to considerably excite the resonances of the small UBM U9B / 1 kN. To excite the resonances to a greater extent, new shock experiments were performed in which the airborne impact mass body of 10 kg was replaced by a much smaller pendulum mass [15]. The force pulses obtained with the three different impact masses are shown in figure 9. Whereas the impact mass of 10 kg generates a smooth pulse of 1.3 ms without ringing, the pendulum mass of 7 g yields a pulse of 0.1 ms followed by a pronounced ringing that reveals the mechanical resonances of the transducer under test.

3.3 Model-based calibration

To understand the dynamic behaviour of a force transducer in a given measurement set-up and with force signals of different types in the time and frequency domain, the characteristic parameters of the force transducer under test are determined using a model-based description of the force transducer and the used calibration device. This approach principally allows a linking between the different calibration results from different calibration methods and calibration devices [16].

To be more specific, the sine force calibration method measures the frequency response of the transducer's dynamic sensitivity determined by applying different load masses, adapters and couplings. And in the case of shock force calibrations, different mechanical set-ups can give shock sensitivity results that depend on the particular pulse shape.

Figure 10a presents the basic model of a force transducer, in which the dynamic behaviour is modelled by a mass-spring-damper system of one degree of freedom (linear displacement x). The transducer is characterized by four model parameters: head mass m_H, base mass m_B, stiffness k, damping d. The transducer output signal is assumed to be proportional to the elongation of the spring element. To describe the transducer's dynamic response in a considered mechanical measurement set-up, an appropriately extended model has to be applied that accounts for the two elastic couplings that connect force transducer and mechanical environment.

The corresponding model of the sine force calibration device is shown in figure 10b. The upper end of the force transducer (model mass m_H) is rigidly connected to the load mass m that generates the desired sine force when a sinusoidal acceleration is applied at the transducer's base. This mechanical system exhibits a characteristic resonance of the spring-coupled mass. For neglected damping, the resonance frequency is given by

$$f_{Res} = \sqrt{k/(m + m_H)}/(2\pi) \,.$$

The example in figure 11 visualizes the measured resonance of the HBM U9B / 1 kN which was loaded with a load mass of 1 kg. The diagram shows the ratio of the two accelerations which were picked up at the top of the load mass and the shaker platform, respectively. At the resonance frequency near 1 kHz, the acceleration ratio exceeds the value of 400, which demonstrates that the damping is very small. With an estimate of m_H, the unknown model parameter k can be identified from the shown frequency response.

Whereas the previous consideration assumes a rigid coupling of the load mass, the more generalized case of an elastic coupling requires a model that introduces a second spring element between load mass m and head mass m_H.

In the area of shock force calibration, the parameter identification process was investigated with the models sketched in figure 12 [19]. In the upper model, the shock force calibration device is described by three model masses (impact mass, head mass with load button, reaction mass with adapter and base mass), whereas the lower model uses four model masses, in which the force transducer is elastically coupled to the reaction mass.

As an example, figure 13 compares the measured and modelled signals of a shock calibration of the force transducer Interface 1610 / 2.2 kN. The transducer output signal is shown in the upper diagram, the acceleration of the reaction mass in the lower one. The best agreement between experimental and theoretical signals is achieved with the 4-mass model that considers the elastic coupling at the base of the transducer.

The identification of the transducer's characteristic model parameters from measured sine and shock force calibration data is a topic of current research. The investigated methods and procedures for the parameter identification are based on a fitting of modelled and measured data in the time or frequency domain. The experiences with the different force transducers under test have shown that the consistency of the parameter results obtained from sine and shock force calibration data still need to be improved in order to fully understand the dynamic measurement behaviour under different conditions. For this purpose, it is helpful to analyse the modal vibrations of the mounted force transducer and its measurement set-up by means of finite element calculations [17]. Consequently, the model descriptions and fitting procedures may then be modified to better agree with the dynamic measurement signals.

4 Conclusions and Outlook

This article gives an overview of the recent research activities conducted in the work package *Dynamic Force* of the joint research project EMRP IND09 *Traceable Dynamic Measurement of Mechanical Quantities*.

The approach of a model-based calibration is proposed in which the dynamic behaviour of the force transducer is described by characteristic model parameters. Dynamic calibration measurements with sinusoidal or shock excitation are used to identify these parameters. Having identified the model parameters of the force transducer, its dynamic measurement behaviour in a given mechanical set-up can be calculated by applying an appropriately expanded model which describes the transducer connected to its mechanical environment. In this context, the corresponding model parameters of the coupled environment have to be known sufficiently well, e.g. determined by dedicated measurements. In the end, the interesting dynamic measurand, i.e. the force input signal or the signal at a specific location within the force train, can be derived by means of a signal deconvolution process.

As an important achievement for the metrological community, first international dynamic comparison measurements could be performed thanks to new dynamic force calibration devices which were put into service. In addition, the joint work on mathematical modelling and parameter identification gave great impulses and the chosen path of the model-based dynamic calibration will be continued.

Future work will focus on the application of the proposed dynamic calibration methods to the various types of force transducers. The results from sine and shock force calibration measurements will be compared, and the corresponding models will be refined until consistent results are obtained at the end. This research will further include the investigation of the numerous influences on the parameter identification process and the evaluation of the measurement uncertainties for the parameter identification.

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