# Dynamic measurements of elastomer elements

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**Summary:** The paper describes the process of preliminary tests for dynamic measurements of elastomer elements and the identification of their dynamic transfer stiffness. The aim of these preliminary tests is to clarify whether the existing test setup fulfils the requirements of the customer. In the second step of the testing it is clarified how exact the test setup and the test procedure meet the norms DIN prEN ISO 10846-1 and -2.

## 1. INTRODUCTION

The customers' decision for buying a vehicle depends largely on emotions. These emotions are basically influenced by the sensations subjectively perceived by the customer. This and the additional fact of a strong competition result for the automobile manufacturers in the need to strengthen their development efforts in the fields of visual, auditory and tactile appearance of their vehicles to the customer. Big efforts to improve the optical design are made in the field of visual perception since the beginning of automobile development. This applies for both, the outer appearance of the vehicle and the design of the interior. The fields of auditory and tactile perception on the other hand come in the focus of the automobile development in recent times. Today this development field is called NVH (Noise Vibration Harshness). Noise stands for the auditory aspect and vibration for the tactile aspect. Harshness describes combined effects of auditory and tactile perceptions. A major part of the sound and vibrations in a vehicle is made by systems e.g. the engine or chassis parts, which transfer excitations from street to car body. To reduce the unwanted sounds and vibrations the power train and its components and chassis parts are linked elastically to the car body by elastomer elements. For the design of the elastomer elements the mechanical transfer behavior must be determined by characteristic quantities. The determination of static quantities is mandatory, but not enough because the transfer behavior of elastomer elements is amongst others related to the excitation frequency. For this reason an often used characteristic quantity is the dynamic stiffness. In this paper the dynamic stiffness is determined by a test rig.

## 2. BASICS

The behavior of mechanical structures and thus also of elastomer elements can be described by dint of the system theory.

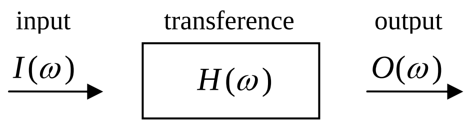



**Figure 1:** System theory

The transfer function $H(\omega)$ characterizes the relation between input and output. It is a complex quantity.

$$H(\omega) = \frac{I(\omega)}{O(\omega)} \tag{1}$$

$H(\omega)$ transfer function

$O(\omega)$ output (system response)

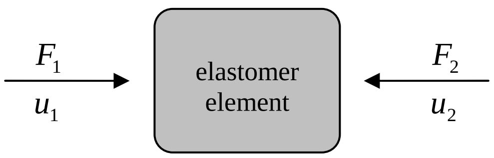
$I(\omega)$ input (excitation)

If the excitation and the response of a system are known, the transfer behaviour can be determined. The data for the excitation and the system response are measured in terms of physical quantities. In Table 1 examples of transfer functions are listed.

**Table 1:** Transfer functions

| | | |
|---|---|---|
| dynamic flexibility | $\frac{\text{displacement}}{\text{force}}$ | $\frac{X}{F}$ |
| dynamic stiffness | $\frac{\text{force}}{\text{displacement}}$ | $\frac{F}{X}$ |
| mechanical admittance | $\frac{\text{speed}}{\text{force}}$ | $\frac{\dot{X}}{F}$ |
| mechanical impedance | $\frac{\text{force}}{\text{speed}}$ | $\frac{F}{\dot{X}}$ |
| inertance | $\frac{\text{accelerartion}}{\text{force}}$ | $\frac{\ddot{X}}{F}$ |
| virtual mass | $\frac{\text{force}}{\text{acceleration}}$ | $\frac{F}{\ddot{X}}$ |

The dynamic stiffness is divided into dynamic input stiffness and dynamic transfer stiffness. The dynamic input stiffness is the ratio of input force and input displacement, whereas the dynamic transfer stiffness is the ratio of output force and input displacement.




$F_1$ input force

$u_1$ input displacement

$F_2$ output force

$u_2$ output displacement

**Figure 2:** Input / output quantities

According to Figure 2 the balance of forces can be described by the following equations.

$$F_1 = k_{1,1}\, u_2 + k_{1,2}\, u_2 \tag{2}$$

$$F_2 = k_{2,1}\, u_1 + k_{2,2}\, u_2 \tag{3}$$

$k_{1,1}$ and $k_{2,2}$ dynamic input stiffness, if the elastomer element is fixed each at the opposite side (i.e. $u_2 = 0$ and respectively $u_1 = 0$)

$k_{1,2}$ and $k_{2,1}$ dynamic transfer stiffness - For passive elastomer elements applies because of the reciprocity $k_{1,2} = k_{2,1}$

The matrices notation of the equations (2) and (3) can be seen in equation (4).

$$\mathbf{F} = [k]\mathbf{u} \tag{4}$$

*General case (six oscillation directions)*

If the forces and oscillations are represented by six orthogonal components for each side (three translatory and three rotatory), the elastomer element can be specified as 12-pol [4]. The dimensions of the stiffness matrix are 12 x 12. The stiffness matrix can be cut into four matrices containing 6x6 elements.

$$[k] = \begin{bmatrix} [k_{1,1}] & [k_{1,2}] \\ [k_{2,1}] & [k_{2,2}] \end{bmatrix} \tag{5}$$

$[k_{1,1}]$ and $[k_{2,2}]$ matrices of the dynamic input stiffness

$[k_{1,2}]$ and $[k_{2,1}]$ matrices of the dynamic transfer stifness

*Special case (one oscillation direction)*
In case of one oscillation direction the dynamic stiffness matrix is reduced to the matrix shown in equation (6).

$$[k] = \begin{bmatrix} k_{1,1} & k_{1,2} \\ k_{2,1} & k_{2,2} \end{bmatrix} \qquad (6)$$

In the following the focus is put on the dynamic transfer stiffness $k_{1,2}$. The unit of the dynamic transfer stiffness is Newton per millimeter. As mentioned above the dynamic transfer stiffness is an important quantity to characterize the mechanical vibration behavior of elastomer elements.

$$k(\omega) = \frac{F(\omega)}{X(\omega)} \qquad (7)$$

$k(\omega)$ dynamic transfer stiffness

$F(\omega)$ output force (system response)

$X(\omega)$ input displacement (excitation)

There are different standardized methods for the determination of the dynamic transfer stiffness by rig testing. In this paper the “direct method” (see [1]) is the background for the measurements.

## 3. TEST SETUP

The rig consists of

- Measuring and analysis equipment
- Excitation system
- Concrete block and gibbet
- Test object

*Measuring and analysis equipment*
The measuring and analysis equipment has as hardware a standard computer and a VXI-front-end. For measuring and analysis the software PAK is used. Forces and accelerations are measured by two sensors. On the input side of the test object forces and accelerations are measured by an impedance sensor. On the output side the force is measured by a mono axial force sensor.

*Excitation system*
The measuring and analysis software PAK offers the possibility to generate different signals by a waveform generator for the excitation of test objects. For the measurements described in this paper, the used excitation signals are white noise, band noise and sinusoidal signals. The excitation signal, which is generated by the wave form generator, is transferred to the amplifier by the VXI-front-end. The amplifier controls an electro-dynamic shaker. The electro-dynamic shaker is voltage adjusted. That means the operator can only adjust the output voltage of the amplifier but not accelerations or displacements. Accelerations and displacements are results of the systems behavior and the adjusted voltage. The operator is only able to influence the accelerations and displacements indirectly. The electro-dynamic shaker is linked to the impedance sensor by a so called stinger (Figure 3).

**Figure 3**: Stinger

For exact measuring data the stinger must transfer the excitation force axial and free of transversal forces into the test structure. Because of this, the stinger is thin, long and made of carbon fiber. The opportunity of this linkage is the high axial stiffness and the low transversal and rotational stiffness [3].

*Concrete block and gibbet*
The mass of the concrete block is nearly 2.500 kg. The great mass of the concrete block restrains it to vibrate with the test structure. The gibbet is to hang up the electro dynamic shaker. The shaker is linked to the gibbet by four spring elements. With the help of this elastic mounting it is possible to shift the eigenfrequencies of the oscillating shaker into a low frequency range, which is outside the interesting frequencies. The gibbet is not mounted direct at the concrete block but on a separate

steel plate. This avoids unwanted bypass transmissions.

*Test object*

The test object is located between the impedance sensor and the force sensor.
For the measurements mentioned in this paper are used steel springs, hexagonal and ring-shaped elastomer elements as test objects.

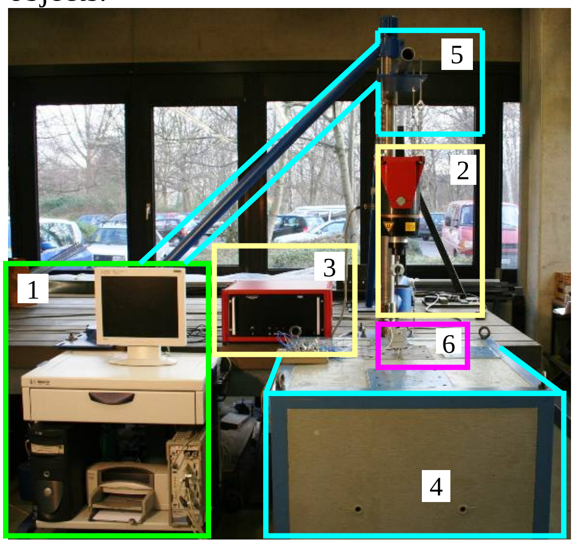



**Figure 4**: Test setup

1: Measuring and analysis equipment; 2: Electro-dynamic shaker and stinger; 3: Amplifier
4: Concrete block; 5: Gibbet; 6: Test object and sensors

## 4. SPRING TEST SETUP AND MEASUREMENTS

At begin of the preliminary tests the general accuracy of the results for the dynamic transfer stiffness, determined with the above described test setup shall be demonstrated. A possibility to do this is to make dynamic measurements of components with known static stiffness. The measured dynamic transfer stiffness has to correspond with the static stiffness for frequencies near zero Hertz [2]. In the present test steel springs are used for this. The steel springs with known static stiffness are measured dynamically.
The steel spring is fixed in the rig between the force sensor on the output side and the impedance sensor on the input side. Above the impedance sensor is mounted a cylindrical steel body. The function of the steel body is to apply a preload by its self-weight. The thereby generated preload is about 20 Newton. The preload avoids a complete unloading of the steel spring, which would lead to bad results. The steel spring is glued together with a small aluminum disk which is screwed into the sensor. In Figure 6 and Figure 7 the two used steel springs are shown. They have different stiffness's as can be seen by the different wire diameters and the numbers of windings.

**Fig. 6**: Hard spring

**Fig. 7:** Soft spring

**Figure 5:** Spring test setup

The measurements are made with different excitation signals and voltages. The best results are produced at measurements with white noise and five Volts. The correlation of the measured results and the known static stiffness is shown in Table 2. For the comparison the dynamic transfer stiffness at 145 Hz is chosen. Because resonances occur below this frequency it is not possible to use lower frequencies. By this comparison the general correctness of the measured results can be demonstrated.

**Table 2:** Comparison of static stiffness and measured dynamic stiffness

| | Soft spring | Hard spring |
|---|---|---|
| static stiffness | 28.5 N/mm | 73.2 N/mm |
| dynamic measurement at 145 Hz | 28.9 N/mm | 81.6 N/mm |

## 5. HEXAGONAL ELASTOMER ELEMENT TEST SETUP AND MEASUREMENTS

The quality of rig measurements is often negatively influenced by additional components like brackets or mounts. For this reason a test setup is chosen which has hardly any additional components. The test object has also a simple geometry. It is a hexagonal elastomer element (Figure 8). The measured results constitute the best possible ones for this test rig.
The test setup for the hexagonal elastomer element is basically the same like the test setup for the steel springs. Merely the cylindrical steel body and the steel spring are replaced by the elastomer element, which is screwed between two cylindrical aluminum blocks. Because of omitting the cylindrical steel body there is no preload attached to the test object. The elastomer element itself consists of two metal disks on which setscrews are mounted and the elastomer material between the metal disks. The elastomer element is vulcanized to the metal disks.
White noise is used for excitation to get a smooth excitation at a wide frequency range. In Figure 9 the result of the measurement is shown. There is no disturbance or unsteadiness at the whole frequency range for the dynamic transfer stiffness.

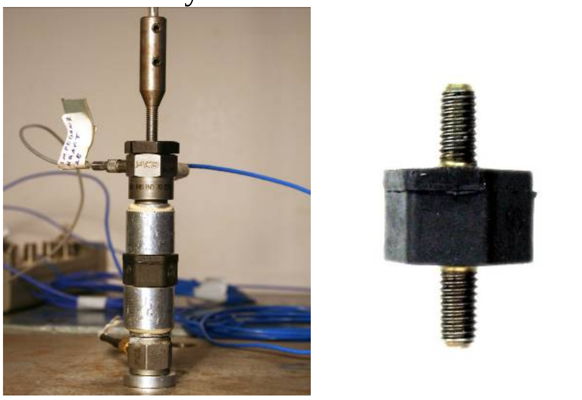


**Figure 8:** Hexagonal elastomer element & test setup

Such disturbances may occur by resonances of addition components. This shows the high potential of this test setup in comparison to conventional rubber mount testing machines which are usually limited to frequencies around 1000 Hz.

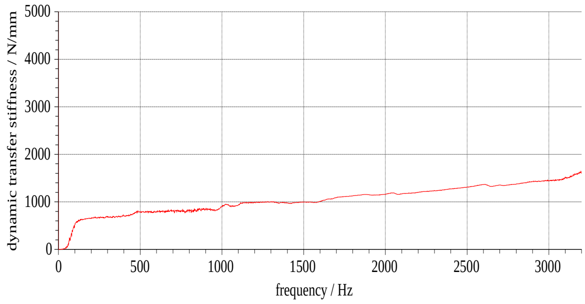



**Figure 9:** Dynamic stiffness of hexagonal elastomer element

## 6. RING-SHAPED ELASTOMER ELEMENT

The aim of the first two testing steps is to demonstrate the appropriateness of the test rig for dynamic measurements on elastomer elements. The following third step of the preliminary test is to clarify whether the requirements of the customer regarding the displacement can be fulfilled. For these measurements ring-shaped elastomer elements are used (Figure 10).

### 6.1 TEST SETUP RING-SHAPED ELASTOMER ELEMENT

There are two different test setups, a test setup for radial measurements (Figure 11) and one for axial measurements (Figure 12). For measurements in axial direction a preload about 20 Newton is attached. As mentioned before the preload is generated by a cylindrical steel body, which is mounted between the stinger and the impedance sensor. For measurements in radial direction no preload is required. The U-shaped bracket is made of aluminum. It is used to mount the elastomer element. The acceleration sensor at the output side and the three axial acceleration sensor at the input side are used for the measurements in chapter 6.3. The ring shaped elastomer element consists of an inner and an outer part. The inner part is a metal tube and the outer part is made out of elastomer. Both parts are vulcanized together.

**Figure 10:** Ring-shaped elastomer element - picture and CAD drawing

## 6.2 RING-SHAPED ELASTOMER ELEMENT MEASUREMENTS

The requirements of the customer are 25 µm constant displacements for the interesting frequency range. Because of the voltage regulated electro dynamic shaker is it not possible to adjust constant displacements on a direct way. The only possibility to achieve this is to use a sinusoidal signal of one frequency for excitation. With this signal it is possible to adjust the wanted displacement by the voltage. One after another measurement the target displacement can be adjusted for different frequencies. On that way it is possible to get a constant displacement for different frequencies. In present case the measurements are made in 100 Hz steps. In a first step the maximum possible displacements for each frequency step are measured. As result of these measurements occurred that it is not possible to achieve the required 25 µm constant displacement because of the capability of the amplifier.

In Table 3 the maximum achievable displacements for radial and axial measurements are listed. The comparison of the measured displacements at the test rig with data from in-vehicle testing shows that the test rig is capable to operate the mounts at the same displacement levels as in the vehicle.

**Figure 11&12:** Ring-shaped element radial/axial test setup

As conclusion the test rig is able to reach the real in vehicle displacements and according to this it fulfills the requirements. The customer requirement of a constant displacement over the whole frequency range is realized with displacements of 8 µm for radial measurement and respectively 0.9 µm for axial measurements. The results of these measurements are shown below.

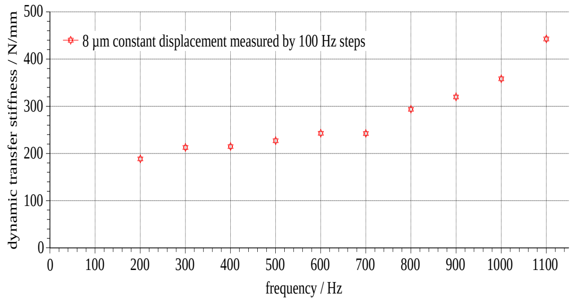



**Figure 13:** Ring-shaped elastomer element, dynamic transfer stiffness, radial excitation

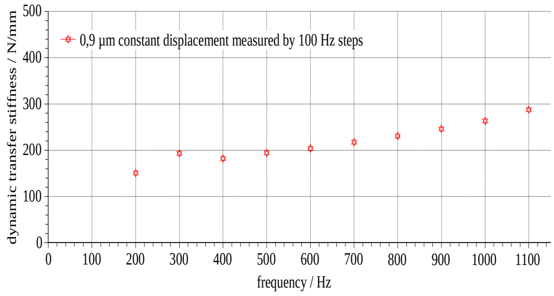



**Figure 14:** Ring-shaped elastomer element, dynamic transfer stiffness, axial excitation

**Table 3:** Maximum displacement for sinusoidal excitation

| | frequency / Hz | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| displacement /µm | radial | 110 | 46 | 27 | 18 | 13 | 11 | 9,3 | 8,6 | 8,4 | 8,5 |
| | axial | 24 | 12 | 8,2 | 7,2 | 11 | 9,7 | 8,9 | 2,7 | 1,1 | 0,88 |

## 6.3 MAIN CRITERIA FOR THE ACCORDANCE WITH DIN prEN ISO 10846-2

The norm DIN prEN ISO 10846-1 and -2 describe procedures for measurements of elastomer elements. For the customer the accordance of the measurements with the norm is a very important point.

By this means the customer is able to compare results which are measured on different test rigs. The DIN norm basically contains four criteria to check the capability of a test rig to measure dynamic stiffness. These are the frequency criterion, the force measurement criterion, the excitation acceleration criterion and the linearity criterion.

For the measurements to check the criterion a band noise excitation at a frequency range of 5 Hz - 1500 Hz is used. The maximum possible voltage is caused by the linearity criterion, equation (11&12). It is 0.9 Volt for radial and 1.7 Volt for axial measurements.

*Frequency criterion*

The frequency criterion compares the input side acceleration with the output side acceleration. The measurements for dynamic transfer stiffness are only valid for frequencies which fulfill the following equation.

$$\Delta L_{1,2} = L_{a_1} - L_{a_2} \geq 20\,\text{dB} \tag{8}$$

$L_{a_1}$ acceleration level input side

$L_{a_2}$ acceleration level output side

A reason for a too small level difference $\Delta L_{1,2}$ can be an insufficient stiffness difference of the test object and the ground plate (concrete block) [1].

In Figures 15 and 16 the results for the measurements in radial and axial direction are compared. The criterion is met the whole interesting frequency range.

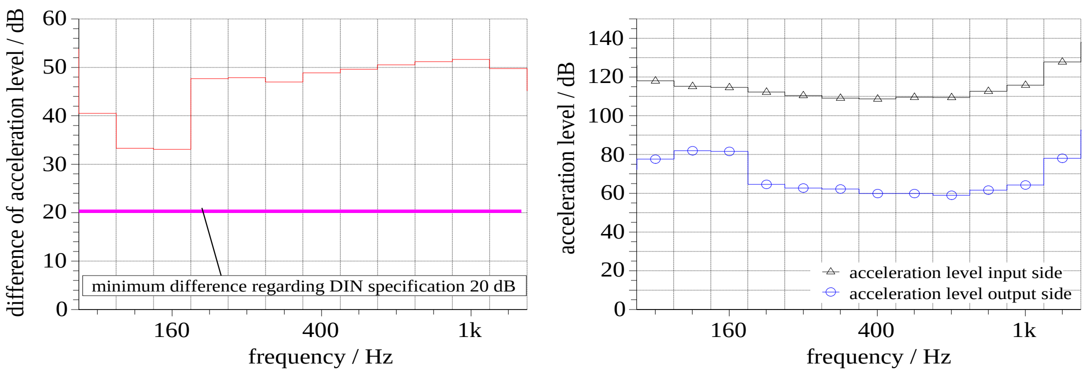



**Figure 15:** Ring-shaped elastomer element, frequency criterion, radial excitation

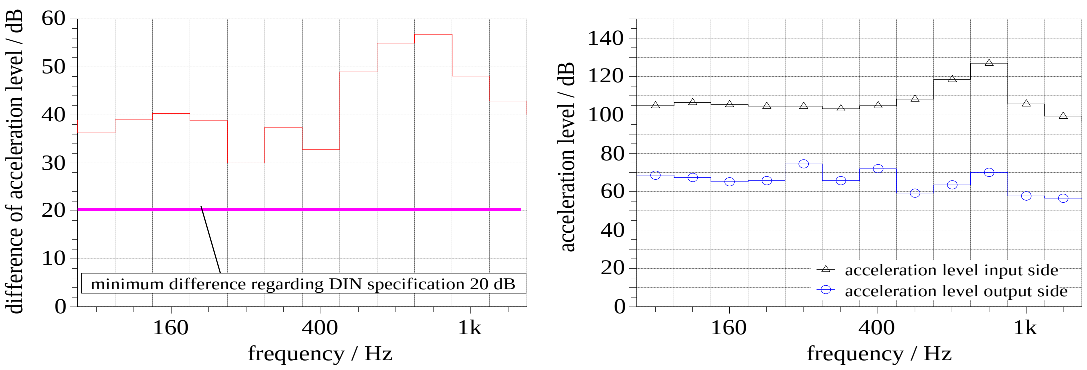



**Figure 16:** Ring-shaped elastomer element, frequency criterion, axial excitation

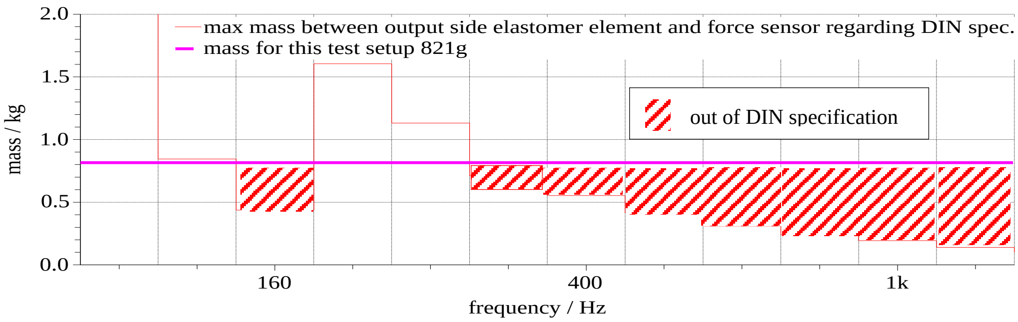



**Figure 17:** Ring-shaped elastomer element, force measurement criterion, radial excitation

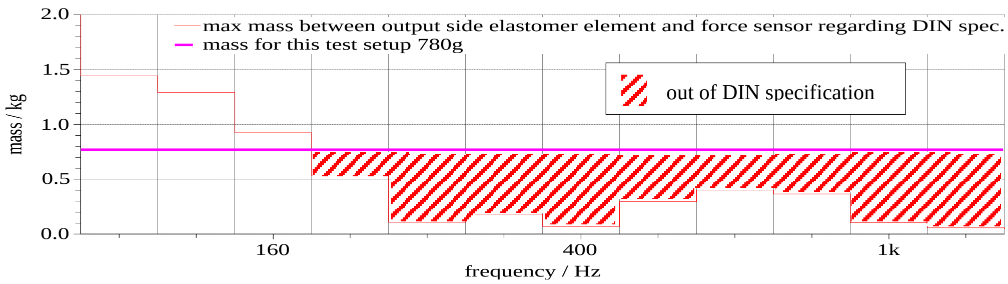



**Figure 18:** Ring-shaped elastomer element, force measurement criterion, axial excitation

*Force measurement criterion*

Between the force sensor at the output side and the output side of the elastomer element are mounted additional components like the U-shaped bracket. These additional components have a mass. If the addition of these masses is too big, the results of the measured force are falsified. To avoid a falsification the norm specifies a maximum weight for this mass.

Because of the frequency dependency of the measured data the maximum allowed weight is also frequency dependent.

$$m_2 \leq 0{,}006 * \frac{10^{L_{F_2}/20}}{10^{L_{a_2}/20}} \text{ kg} \tag{9}$$

$m_2$ Mass between output side elastomer element and force sensor

$L_{F_2}$ Force level output side

$L_{a_2}$ Acceleration level output side

The Figures 17 and 18 show clearly, that the mass $m_2$ is too big. This applies for both, axial and radial measurements.

*Excitation acceleration criterion*

Lacking symmetry of the excitation or the boundary conditions and the test object properties may generate disturbing vibrations, which are different to the wanted excitation direction. These disturbances can cause a high and unwanted vibration response at particular frequencies [1]. Corresponding to the norm, measurements are only valid, if equation (10) is fulfilled.

$$L_{a_z} - L_{a_{x,y}} \geq 15 \text{ dB} \tag{10}$$

$L_{a_z}$ Acceleration level in excitation direction

$L_{a_{x,y}}$ Accelerarion level cross to excitation direction

The evaluation of the measured results regarding the excitation acceleration criterion is shown in Figures 19 and 20. The Figures obviously display that the criterion is not fulfilled all over the interesting frequency range. A reason can be a bad shaker orientation above the elastomer element or a bended stinger.

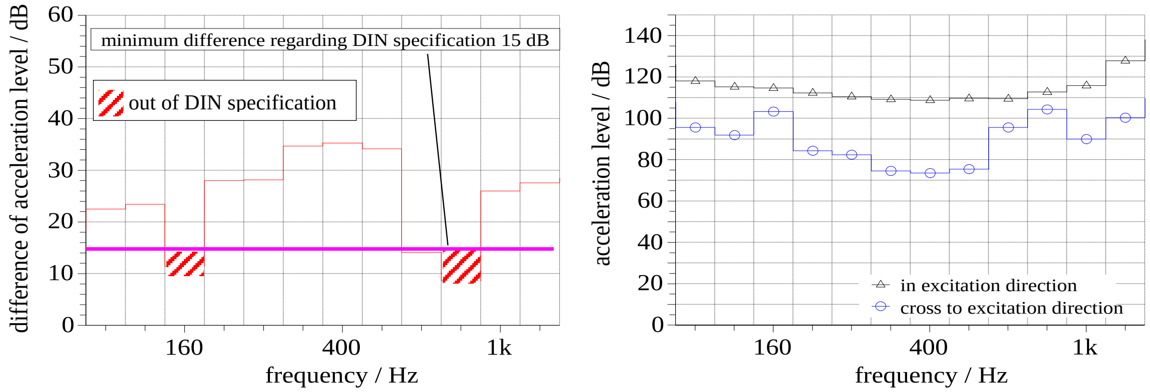



**Figure 19:** Ring-shaped elastomer element, excitation acceleration criterion, radial excitation, cross direction

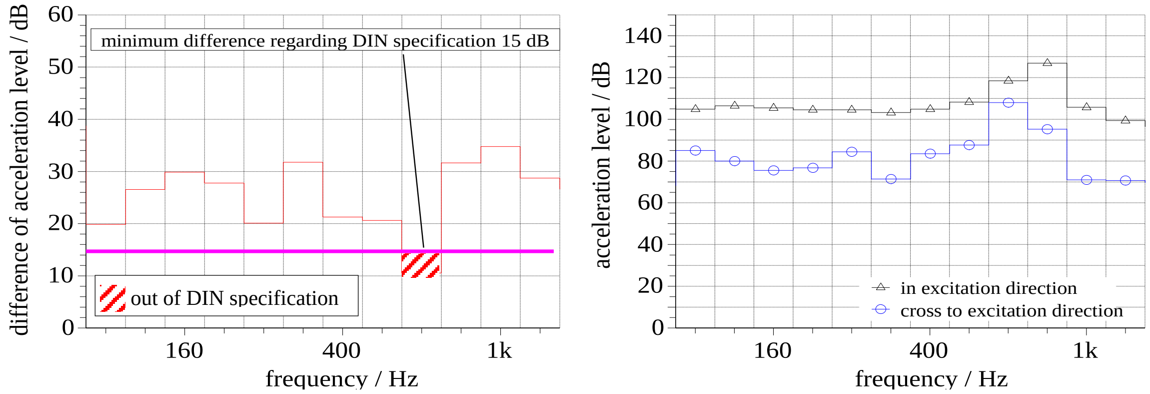



**Figure 20:** Ring-shaped elastomer element, excitation acceleration criterion, axial excitation, cross direction

*Linearity criterion*

In the norm ISO 10846 the definitions of the dynamic transfer stiffness and the measurement procedures for its determination act on the assumption of linear models for the vibration behavior of elastomer elements. In practice the elastomer elements show only nearly linear behavior [1]. The function of the equations (11) and (12) is to define the validation of the measured results for the dynamic transfer stiffness in dependence to the level of the excitatory vibrations.

$$A - B \geq 10\,\text{dB} \qquad (11)$$

$$\Delta_k = k_A - k_B < 1{,}5\,\text{dB} \qquad (12)$$

$A$ 1/3 - ovtave - spectrum input acceleration signal

$B$ second 1/3 - ovtave - spectrum

$\Delta_k$ difference of dynamic transfer stiffness

$k_i$ dynamic transfer stiffness

The Figures 22 and 23 show the measured results evaluated with the linearity criterion. Figure 21 displays the evaluation with the linearity criterion for a measurement with 0.9 Volt and 0.2 Volt in radial direction. In several measurements with different voltages it is identified that the linearity criterion is just fulfilled for 0.9 Volt. Only at one frequency band the difference of the dynamic transfer stiffness exceed the assigned maximum value by 0.2 dB.
Figure 22 shows the results for the axial excitation direction. In axial direction is the outcome of a multiplicity of measurements that for a maximum voltage of 1.7 Volt nearly linear behavior can be expected.

## 7. CONCLUSIONS

The preliminary tests show that the test rig and the test procedure are applicable for

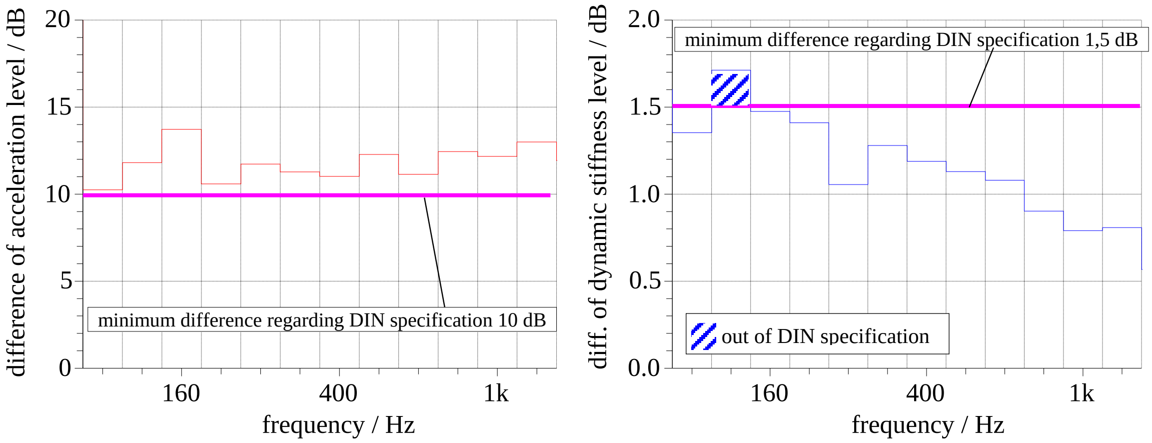



**Figure 21:** Ring-shaped elastomer element, linearity criterion, radial excitation

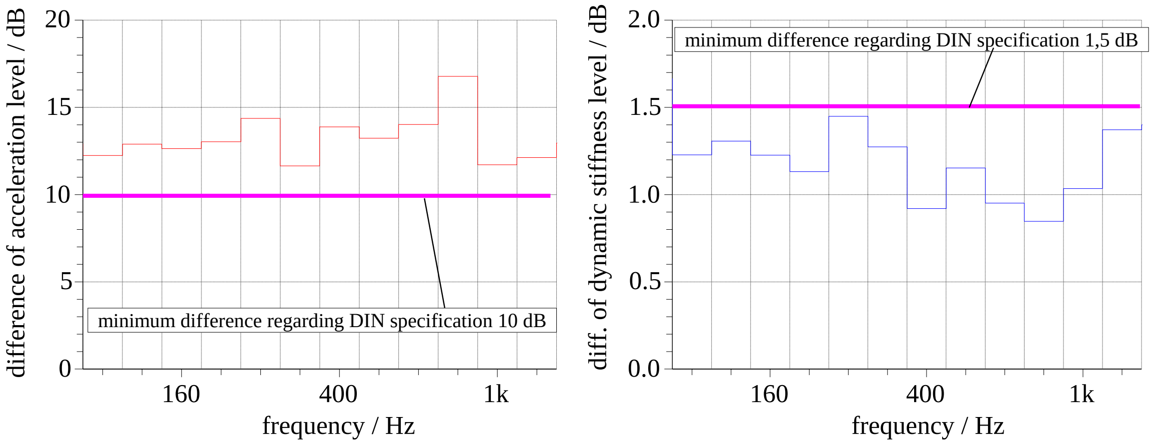



**Figure 22:** Ring-shaped elastomer element, linearity criterion, axial excitation

dynamic measurements at elastomer elements. The measurement results are repeatable and fit basically with the expectations. But there are still some improvements necessary to fulfill the requirements of the DIN prEN ISO 10846-1 and -2. These improvements are the reduction of the bracket mass as well as the avoidance of exceeding accelerations cross to the excitation direction.

## REFERENCES

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