Journal of Machine Engineering, 2023, Vol. 23, No. 1, 114–122
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *04 February 2023* / Accepted: *27 February 2023* / Published online: *03 March 2023*

nonlinearity, contact dynamics, clamping fixture, Hilbert transform

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DETECTION AND IDENTIFICATION OF NONLINEAR CONTACT DYNAMICS AT WORKPIECE CLAMPING POSITIONS

All mechanical systems behave nonlinearly to a certain extent since there are always reasons for nonlinearities, such as friction and slip effects, in the actual structures. It is important to detect and identify the nonlinearity due to friction and contact in order to investigate their effect on the global behavior of the workpiece-fixture system. That is a prerequisite for modeling the dynamic contact behavior at the interface between the workpiece and clamping elements. In this research, the workpiece-fixture system was excited with a shaker using the swept sine signal. The nonlinearities could be detected by comparing and analyzing the frequency responses of the structures in Bode plots. However, the nonlinearities behaved differently at various frequencies within the observation range. Different mechanisms such as nonlinear stiffness and damping, micro-slip friction, are responsible for that. Then the nonlinear contact behavior at the clamping positions was successfully identified by means of the Hilbert transform. In addition, the clamping force directly influenced the nonlinear stiffness of the workpiece-fixture system.

1. INTRODUCTION

A clamping fixture consists of various fixture elements that are connected to each other and to the workpiece in different ways. The connections are either force-, form- or material-fit [1]. The nonlinear behavior of the workpiece-fixture system can be caused by one or a combination of several factors. The nonlinearities occur not only in the individual fixture elements themselves but also in the joints of assembled structures. In the individual components, their dynamics depend on amplitude and frequency. In joints, the nonlinearities are usually clearance or friction, varying stiffness and damping [2]. Therefore, the joints are the primary source of damping compared to material damping, if no special damping treatment is added to the structure [3]. The static and dynamic stiffness of the structure is also strongly influenced by the position and the nature of its joints [4].

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https://doi.org/10.36897/jme/161718

In the field of continuum mechanics, nonlinearities are essentially divided into three. Large deformations or types: geometric nonlinearity, material nonlinearity, and boundary conditions [5–6]. Large deformations or deformations or displacements are known as geometric nonlinearity. Material nonlinearity occurs when the general Hook's law is not valid anymore, which is a linear relationship between strains and stresses [7]. Both nonlinearities mentioned above refer to describing a single body. On the other hand, the nonlinear boundary conditions take place due to the connection of different bodies. Since all types of nonlinear behavior always exist in workpiece-fixture systems, the question is not whether a clamping system is nonlinear or not, but how it behaves nonlinearly in the range observed by the user [8].

In order to detect and identify the nonlinearities due to contact and friction between the workpiece and the clamping elements (see Fig. 1), the present paper is limited to the non-linear boundary conditions only. An appropriate survey method is the experimental modal analysis (EMA), since it is inherently a linear theory and follows the principle of superposition [9]. If this principle is violated, the additivity and homogeneity of the systems are no longer valid. Moreover, this leads to errors in the results of the EMA [10].

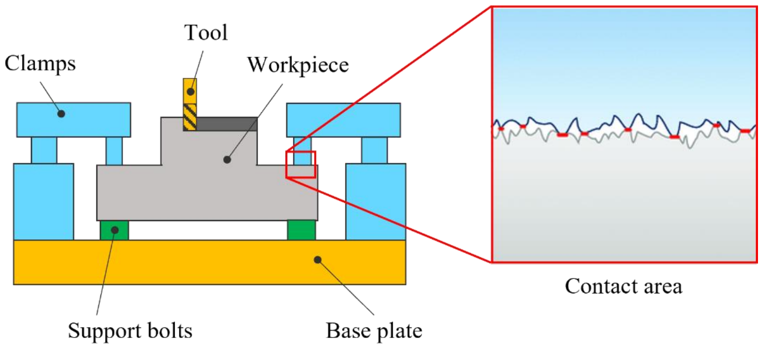

Fig. 1. Illustration of the contact area between the workpiece and clamping elements

The Hilbert transform is an integral transform in the frequency domain and can be used to investigate the causality, stability, and linearity of passive systems [11]. In the afore-mentioned paper, it was shown that the form of Hilbert transform distortions is characteristic of different nonlinearities. Comparing a frequency response function (FRF) and its Hilbert transform at a natural frequency of the system in the Nyquist plot allows to draw conclusions, such as which kind of nonlinearity is identified and how strongly it impacts the system.

A fundamental challenge in the modeling of workpiece clamping systems is especially the description of the friction and contact properties at the interface between workpiece and clamping elements [12–13]. Therefore, it is important to detect and identify the nonlinearities due to friction and contact in order to investigate their effect on the global behavior of the clamping system. For that purpose, an exemplary workpiece-fixture system was configured. Then an experimental modal analysis was carried out for it. Based on the eigenmodes, suitable measuring points were selected for investigating local nonlinearities. The detection and identification of the nonlinearities were realized by means of analyzing FRFs under different excitation force amplitudes in the Bode plot and comparing them with their Hilbert transforms in the Nyquist plot.

2. EXPERIMENT

As shown in Fig. 2a, a simple workpiece-fixture system is built up. The workpiece (an aluminum plate with dimensions of 420×150×60 mm) is clamped by three down-thrust clamps (provided by Erwin Halder KG), which are fixed on a base plate via T-slots. Fig. 2b shows the internal structure of the down-thrust clamp, which is adjustable for different clamping heights. The clamping force can be flexibly defined by the clamping screw and was kept constant as a constraint in the following experiments. All six support bolts have the same structural shape with flat surfaces. They are located between the base plate and the workpiece and also between the workpiece and the clamping claws as connecting elements.

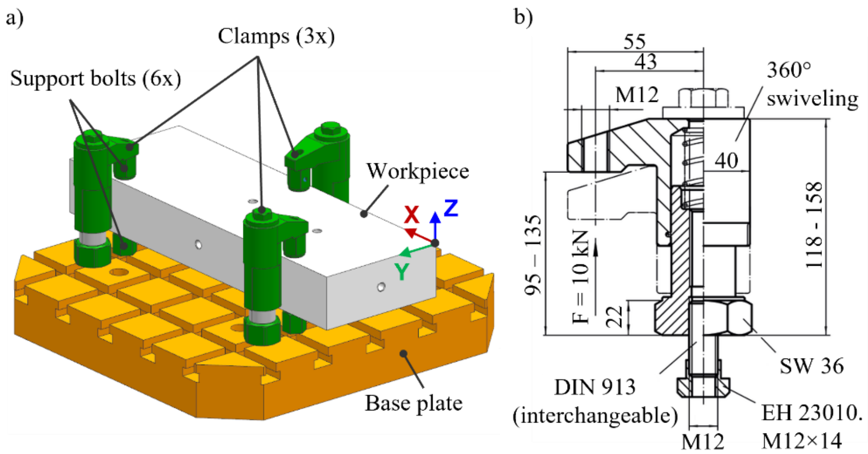

Fig. 2. a) Configuration of an exemplary workpiece-fixture system, b) dimensions of a down-thrust clamp

2.1. MEASURING EQUIPMENT AND TECHNOLOGY

For the experimental modal analysis, the impact or shaker test can be used to determine the frequency responses. In Fig. 3, the area circled in red shows the basic measuring setup of the impact test. The force stimulation on mechanical structures is realized by applying impacts with a hammer (Bruel & Kjaer, Type 8206-2). In this paper, a frequency range of up to 2 kHz is of interest and hence analyzed. To generate a medium excitation force spectrum, a PVC cap is selected for the impact hammer. The excitation signal is measured here by a piezoelectric load cell in the hammer. The response signal is acquired by two 3-axis accelerometers (Kistler, Piezostar Type 8766A), which are attached with wax to the desired locations on the clamping system. The two input signals are then fed to an FFT analyzer and recorded here, in order to calculate the transfer function or the frequency response.

In the shaker test, the force excitation is performed by an electrodynamic shaker system (see Fig. 3). A generator produces an electrical sine-sweep excitation signal, which is amplified and then converted into vibration by a shaker (TIRA, TV5200/LS). The alternating force acts on the fixture through another load cell (Kistler, Type 9321). Finally, the modal data from both measurements are imported into the Siemens Testlab System for a more efficient evaluation.

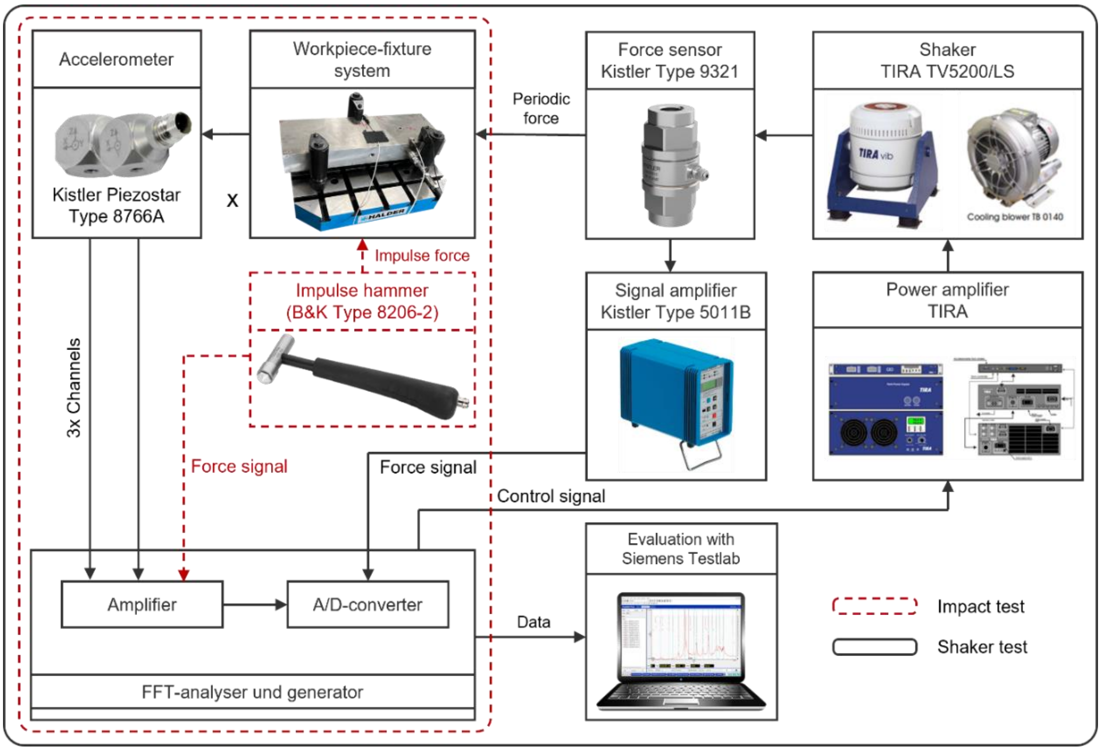

Fig. 3. Equipment for the experimental modal analysis: impact (circled in red) and shaker test (circled in black)

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2.2. EXPERIMENTAL MODAL ANALYSIS

Figures 4a and 4b show the experimental setups for the impact and shaker tests. In the actual operating condition, the clamping fixture should be mounted (positioned and fastened) on the worktable of a machine tool. For this reason, the workpiece-fixture system here is not freely suspended but fixed as rigidly as possible on a T-slot table by means of screw connections, aiming at reducing the influence of connection structures on the clamping system in the observed frequency range. The shaker is also fixed on the T-slot table. Using a shim plate made of wood, it is possible to adjust the height of the shaker. This ensures that the periodic force acts horizontally (in the *Y*-direction) on the object structures.

Figure 4d shows the acceleration frequency responses of both measurements. The clamping force is set identically to 8,500 N for all three clamps. As usual for a multi-degree-of-freedom system, many natural frequencies are present in the observed range. A few natural frequencies of both measurements are similar, for example at 780 Hz, where the max. inertance amplitude occurs here. However, the difference between both frequency responses cannot be neglected. One reason for the difference is that the structures have to be coupled with a force exciter in the shaker test. The inherent dynamics of the stinger and the excitation signal used here have a significant influence on the clamping system [2]. In addition, the base structures under the clamping system including two T-slot plates are strengthened by four clamping claws (see Fig. 4b). In this way, clean response signals can be better captured.

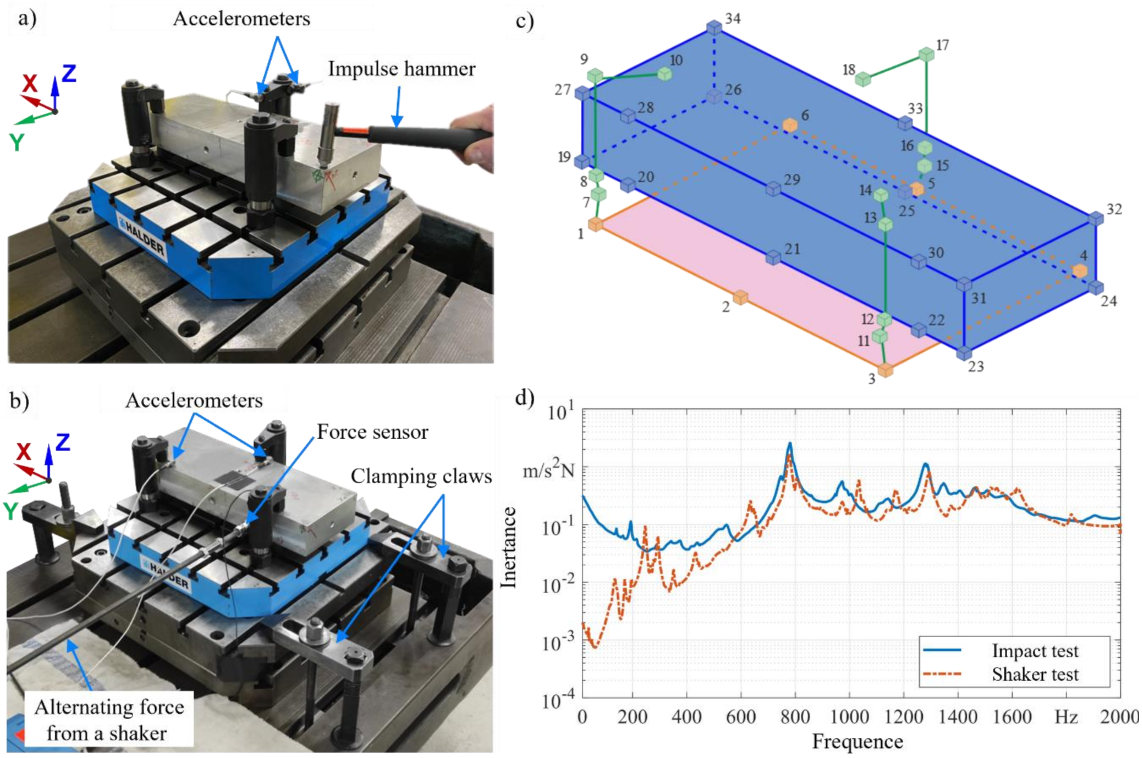

Fig. 4. a) Experimental setup of the impact test, b) setup of the shaker test, c) measuring points (1-34), excitation points (21/29 and 22/30 for the shaker test, 31 for the impact test), d) comparison of the frequency responses up to 2 kHz

Although the transient impulse excitation with the impact hammer has a broad force spectrum, the energy associated with an individual frequency (over the observed range from 0 to 2000 Hz) is too small to effectively excite nonlinearities from the structures [14]. Moreover, it is nearly impossible to repeat the hammer impact with ascending or descending excitation amplitudes at the same position. The excitation with a shaker, however, avoids such weaknesses and is therefore chosen for the following investigation.

3. DETECTION AND IDENTIFICATION OF NONLINEARITIES

3.1. SELECTION OF THE EXCITATION SIGNAL

In experiments, it was found that the current excitation force generated by the shaker depends on the varying operating temperature despite a cooling fan. To avoid this problem or at least to reduce the influence of temperature, the measurements under different excitation force amplitudes should be performed in short time intervals.

The swept sine signal is selected for the measurement of FRFs, because this harmonic excitation can detect nonlinearities as effectively as the stepped-sine sweep but much faster [2]. The frequency of the swept sine signal behaves linearly between an arbitrary initial angular frequency ω_a and a final angular frequency ω_e with a sweep duration T:

$$x(t) = X\, sin\left(\omega_a t + \frac{\omega_e - \omega_a}{T} t^2\right), \tag{1}$$

where the frequency increases for $\omega_a > \omega_e$ and decreases for $\omega_a < \omega_e$. At each instant, the transient frequency of the excitation signal is:

$$\omega(t) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\omega_a t + \frac{\omega_e - \omega_a}{T} t^2\right) = \omega_a + 2\frac{\omega_e - \omega_a}{T} t, \qquad 0 \leq t \leq T. \tag{2}$$

The results show that this excitation signal is valid for the detection and identification of nonlinearities.

3.2. RESULTS

As mentioned above, the inherent dynamics of the shaker as well as of the stinger have a direct influence on the dynamic behavior of the workpiece-fixture system. Therefore, its vibration form could be asymmetrical. Fig. 5 shows the distortion of the structures at a low natural frequency of 295 Hz. The front end of the workpiece moves back and forth in the *Y*-direction. At the same time, both clamps at the front and in the middle slide in the opposite direction. Thus, it is assumed that it could be promising to detect the friction or at least the microslip effect at the front clamping point (measuring point 28 in Fig. 4c). To detect the local nonlinearity at point 28, we continued utilizing the setup of the shaker test in Fig. 4b. Then five different excitation amplitudes $\hat{F}_{exc} = \{0{,}2; 0{,}4; 0{,}6; 0{,}8; 1{,}0\}$ were employed.

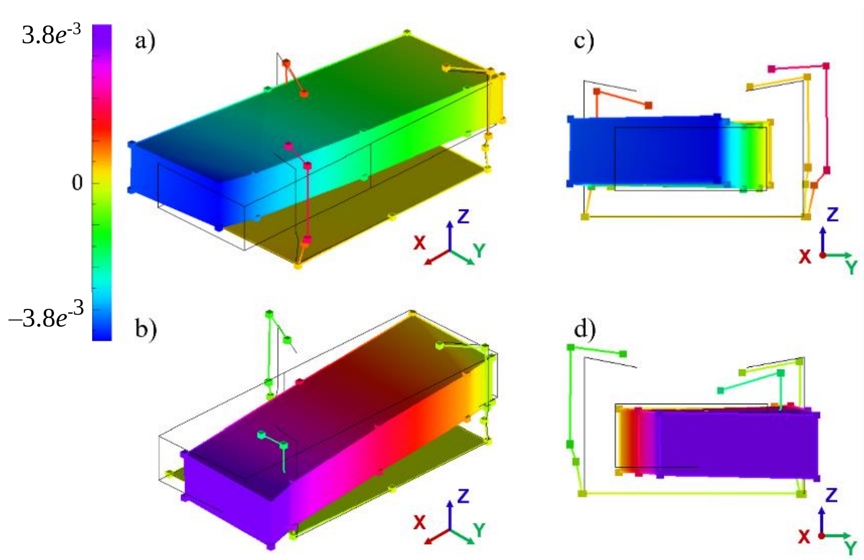

Fig. 5. Eigenmode at 295 Hz with 0.92% modal damping: displacement in ±Y direction in the isometric view (a, b) and the side view (c, d), undeformed (black contour) and deformed (color)

In Fig. 6, their frequency responses from 200 to 800 Hz are given. Looking at several natural frequencies with the highest amplitudes, it is possible to already recognize typical characteristics of local nonlinearities due to contact and friction.

Roughly speaking, the acceleration frequency responses behave almost linearly according to the principle of superposition (see Fig. 6). But at some natural frequencies, for example at 295 Hz and 730 Hz, the FRFs show an obvious sensitivity to the excitation amplitude. At 295 Hz, the inertance decreases significantly with increasing excitation force and shows the characteristics of progressive damping. On the contrary, the responses of the system become significantly larger at 730 Hz, which indicates degressive damping. Furthermore, a slight drift of both natural frequencies towards the lower range can be easily found. This corresponds to degressive stiffness. We can conclude that the nonlinearities behave differently in various frequency ranges and that different mechanisms are responsible for that.

When further analyzing the Nyquist plots of the FRFs and their Hilbert transforms and comparing them, it is possible to identify some specific nonlinearities. Note that the Hilbert transform can only be executed for a limited number of samples from the measured frequency response. This means that the truncation error was unavoidable. Hence, more data points smaller and greater than the natural frequency of 295 Hz are selected for the Hilbert transform so that the truncation error do not strongly affect the observed frequency range, as shown in Fig. 7b. The distortion of the Hilbert transform at 295 Hz resemble the one of a micro-slip friction element, because the characteristic curve is rotated anti-clockwise and elongates to a more elliptical form and the damping effect decreases with growing excitation amplitude [11]. It can be concluded that the Hilbert transform have a considerable sensitivity to nonlinearity, even though the distortion is low in this case.

Besides the influence of the excitation amplitude, the clamping force generated by tightening the clamping screws plays a significant role in nonlinearity as well. The magnitude of the clamping force has a direct impact on the friction force in the tangential direction and further on the dynamic stiffness of the workpiece-fixture system.

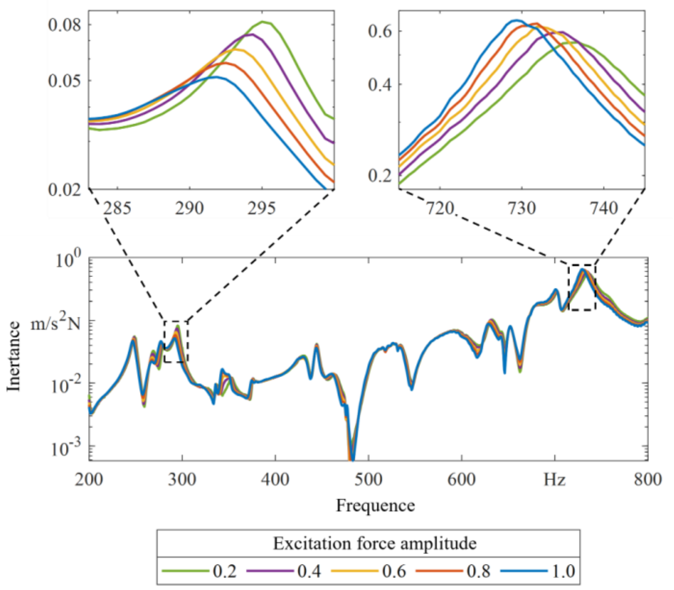

Fig. 6. Inertance for different excitation force amplitudes (excitation points 22/30, measuring point 28)

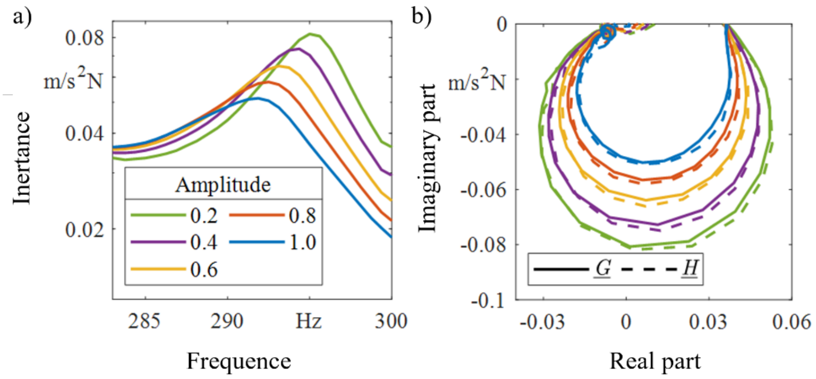

Fig. 7. Nonlinear measurement at 295 Hz: a) inertance for different excitation amplitudes in the Bode plot, b) comparison of the FRF (***G***) with its Hilbert transform (***H***) in the Nyquist plot

Figure 8 shows the dynamic compliance frequency responses (receptance) under different clamping forces. With increasing tightening torque, the stiffness and damping in the lower range (frequency $f < 600$ Hz) do hardly change. For $f > 600$ Hz, the natural frequencies drift towards the higher range, which means an increase in the dynamic stiffness of the system.

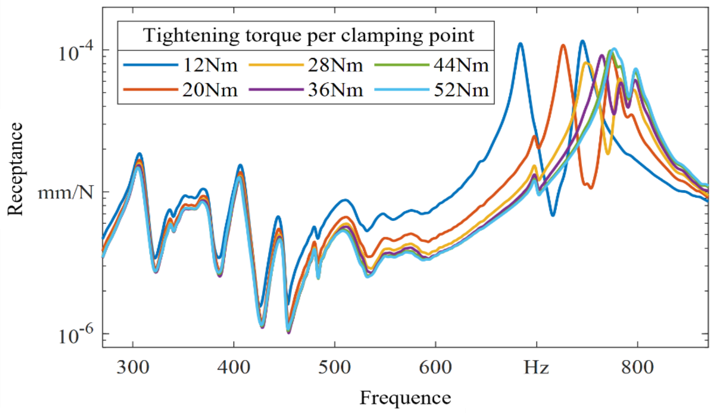

Fig. 8. Receptance for different tightening torques of the down-thrust clamp (excitation point 21/29, measuring point 28)

4. SUMMARY AND OUTLOOK

In this research, the nonlinearities were successfully excited from structures with a shaker using the swept sine signal. By comparing and analyzing the frequency responses of the structures in Bode plots, it is possible to detect the nonlinearities. By means of the Hilbert transform, the nonlinear contact behavior at clamping points was identified. Moreover, the clamping force has a significant influence on the dynamic stiffness of the workpiece-fixture system. The presented experimental results show that local nonlinearities in clamping points can affect the overall dynamics of the clamping system.

In future research, a direct measurement of the contact and friction properties will be carried out in order to build up different models for various contact behaviors. Then the models should be implemented into an FE analysis to generate more realistic results as training data for machine learning. A clamping concept will be optimized by the intelligent method of machine learning with the intention of increasing the dynamic stiffness of workpiece-fixture systems, reducing manufacturing errors and improving the machining accuracy.

ACKNOWLEDGEMENTS

This work was funded by the German Research Foundation (DFG) within the Excellence Initiative GSC 262 and by the Baden-Württemberg Ministry of Science, Research and Arts within the sustainability support for the projects of the Excellence Initiative II. The authors would like to thank Erwin Halder KG for providing a base plate and three down-thrust clamps, and thank Han Huang for the support during his student thesis.

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