Application of operational test data and transfer path analysis to a test bench for optical systems

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Abstract
In this paper the application of operational test data analysis and transfer path analysis to a test bench for optical systems is presented. Especially data of vibration and acoustic measurements are investigated and spectral analysis is employed next to TPA in order to identify the driving sources of occasional failures of test runs.

1 Introduction

Carl Zeiss SMT GmbH is known for high precision optics. In order to assure the required high level of fidelity of its products, various quality assurance steps are employed.

A special test bench is utilized to verify certain performance parameters of a specific optical product. Occasionally, under distinct environmental conditions, non-expected performance was determined during performance tests, that has subsequently been attributed to external perturbations rather than to performance deviations of the product. In these cases, a repetition of the performance tests yielded results as expected proving the conformity of the investigated system.

Since a repetition of performance tests is both time and cost consuming and reduces the overall throughput of the test bench, vibration and acoustic measurements have been conducted as a basis for identifying the driving sources for deviations of the test runs. Especially operational data were investigated with the help of spectral and transfer path analyses.

This paper highlights the main results and outcome of the test campaign and shows how an intelligent combination of state of the art experimental techniques can aid in optimizing the performance of modern technical systems.

2 Conducted Tests

Vibration (acceleration) and acoustic (sound pressure) measurements were taken at and in the vicinity of a test bench for specific optical components in a clean room environment. The test bench itself is comprised of a heavy, resiliently mounted, base granite that carries a test item next to measurement appliances. During the conducted vibration and acoustic tests the test bench was under operation and performance parameters (e.g. control errors) were measured synchronously.

In addition to defined transfer path measurements (see e.g. [1]) by means of force (modal hammer) and airborne sound excitations (two sound sources, one for low frequencies up to about 400 Hz – LFM – and one for higher frequencies – HFM, see also [3]), realistic operating vibration tests were also carried out. Figure 1 shows typical force and sound source excitations while figure 2 highlights a representative operational excitation scheme with a loaded lifter traveling back and forth along the path passing by the test bench.

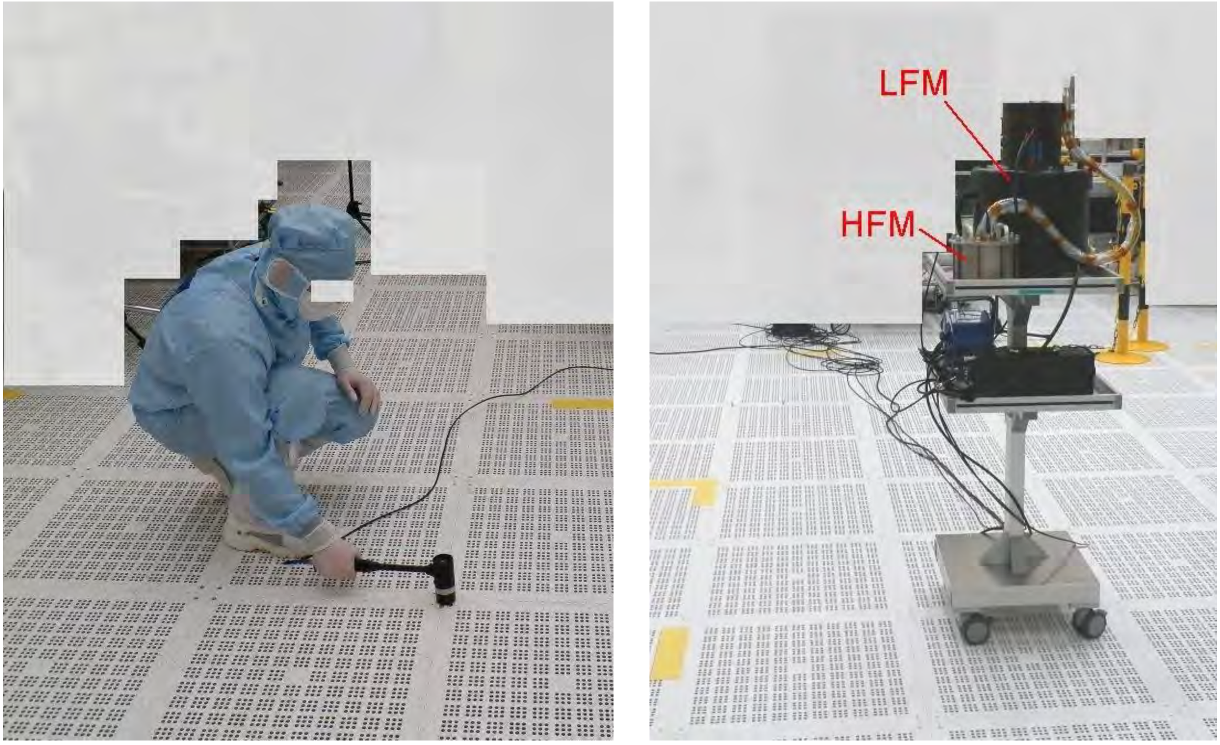

Figure 1: Excitation with modal hammer (left) and sound sources (right)

Figure 2: Operational excitation (lifter with loaded pallet)

3 Data Analysis

Due to the high complexity of the relations between force and sound excitation as well as to the resulting structural responses and performance parameters, the evaluation of the obtained data was divided into three phases:

1. General assessment of time data and spectral information
2. Level and Spectral Analysis
3. TPA

The general evaluation of time data and spectral information is dealt with in Section 3.1 and is used for the basic analysis of the signal contents for the operational tests on the basis of selected measurement signals. On one hand, a first evaluation of the interference effects resulting from the mocked-up operating conditions was carried out directly on the basis of the time signals. On the other hand, a global screening of the spectral contents was done on the basis of averaged power spectral densities (PSD).

Level and spectral analyses according to Section 3.2 were subsequently carried out for the defined excitations and for the operational measurements respectively in order to be able to further assess the vibration behavior. In particular, temporal changes of the signal contents were identified and related to the mocked-up operating situations. Specifically, level analyses over time, third-octave analyses as well as Campbell diagrams over time for the respective signals were generated.

In addition to the level and spectral analyses, a TPA was performed, which is presented in Section 3.3. For TPA a matrix inversion technique was applied (see e.g. [1], [2]). Here, frequency response functions of selected potential transmission paths (or "paths" for short) are measured first, from which excitation forces can subsequently be identified (via an inversion of the frequency response function matrix) with the aid of measured operational responses. Based on these forces, it is possible to determine individual response components, finally allowing an assessment of the significance of individual paths.

3.1 General assessment of time data and spectral information

Figure 3 shows the time responses of two representative acceleration sensors (one on the floor in the vicinity of one foot of the test bench support frame and one on the granite base of the test bench itself that is resiliently decoupled from the floor), one microphone, and a typical performance parameter (control error, measured over 100s only instead of 152s) enforced by operational excitation from a moving lifter with loaded pallet.

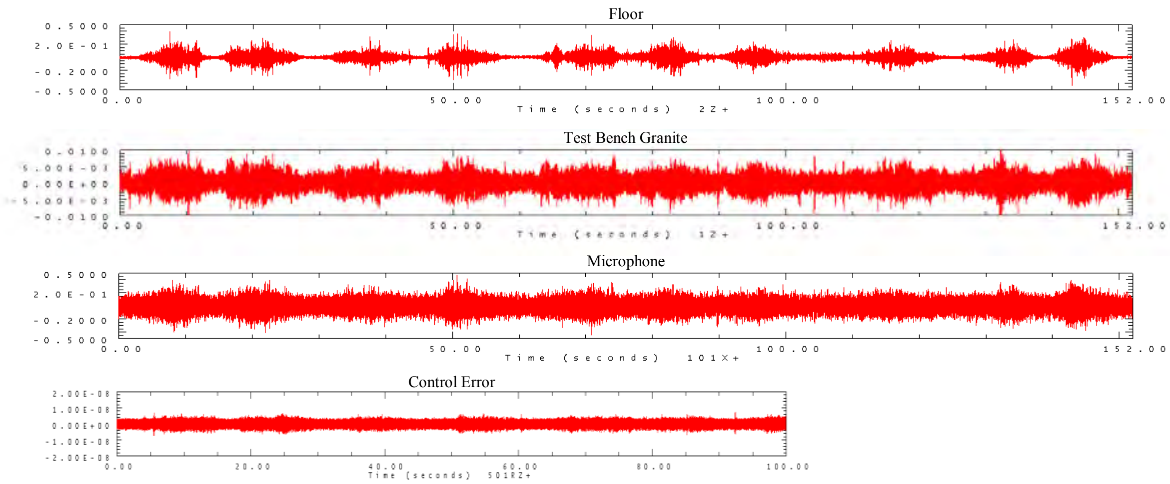

Figure 3: Time responses enforced by loaded lifter operation

It can be noted that on the ground and on the granite as well as at the microphone significant responses can be seen that can directly be correlated to the disturbances by the lifter passing by back and forth. For the control error similar behavior can be noticed, however, less pronounced due to the noise level.

In Figure 4 a comparison between an idle measurement and two lifter excitation runs is shown. It is particularly observable here that in the lower frequency range a clear increase in the spectrum takes place due to the lifter motion (see also marking in red).

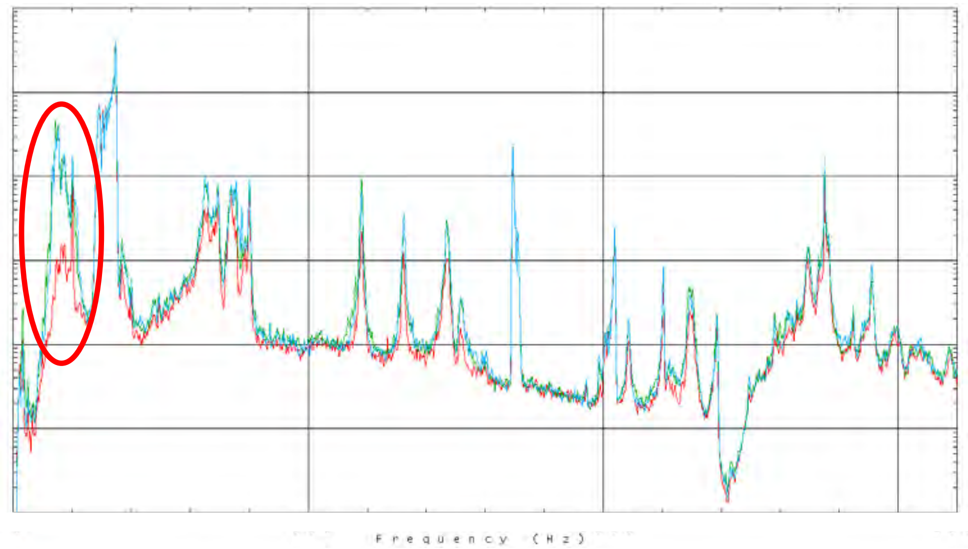

Figure 4: Control error PSDs of idle measurement (red) vs. moving lifter (green/blue)

3.2 Level and Spectral Analysis

To obtain further insight, dedicated level and short time spectral analyses were conducted. In a first step, the measurements with known excitation (force excitation with hammer on the ground and sound excitation with sound source in the area of the travel path) were compared to idle measurements in order to assess the basic effects of both excitation variants (force excitation see Figures 5-10, sound excitation see Figures 11-16). Here, the following observations can be made:

For force excitation, the hammer impulses are clearly visible on the ground in the vicinity of the test bench (Figure 5) and still – in a weakened manner – on the base granite of the test bench (Figure 6). On the test item mounted on the test bench effects can rather be noted for sensor 1 than for sensor 2 (Figures 7, 8). For a representative microphone (Figure 9) practically no effects can be observed. The control error (Figure 10), however, again shows the hammer pulses relatively clearly.

The effects of sound excitation are only weakly recognizable on the ground (Figure 11). The main elevation occurs in the lower frequency range, as already noticed above from the general spectral information (see also PSD in Figure 4). The granite of the test bench (Figure 12) shows practically no effects. For the test item mounted on the test bench effects can rather be noted for sensor 2 than for sensor 1 (Figures 13, 14), in contrast to force excitation. For the microphone (Figure 15) and the control error (Figure 16), however, the sound excitation leads to relatively clear interferences in the complete frequency range.

A closer look reveals that a signature of residual controller noise in the upper frequency range can also be recognized at sensor 2 on the test item (compare pictures 8 and 10 as well as 14 and 16). There is thus a recognizable transmission path. As a result, disturbances on the test item due to base excitation over the granite or via sound excitation over air are in principle possible.

Figures 17 to 22 finally show a comparison of an idle measurement with the operating measurement with loaded lifter passing by. Here, the signatures of the lifter passing by are more or less clearly visible on all measured signals.

Hammer Excitation (Ordinate: Frequency in Hz, Abscissa: Time in s):

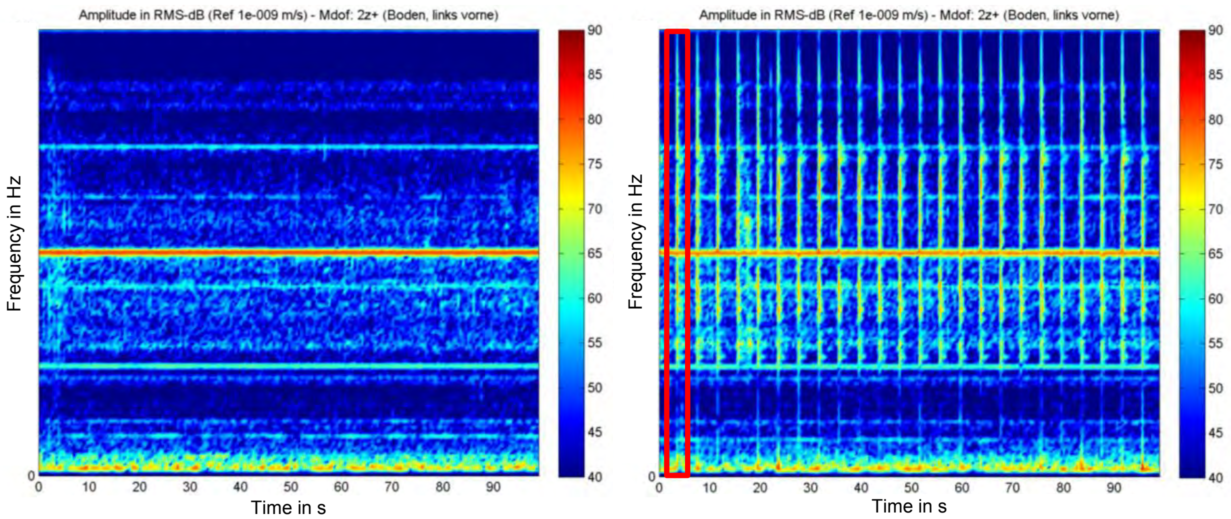

Figure 5: Sensor on ground, left: idle measurement/right: hammer excitation on ground

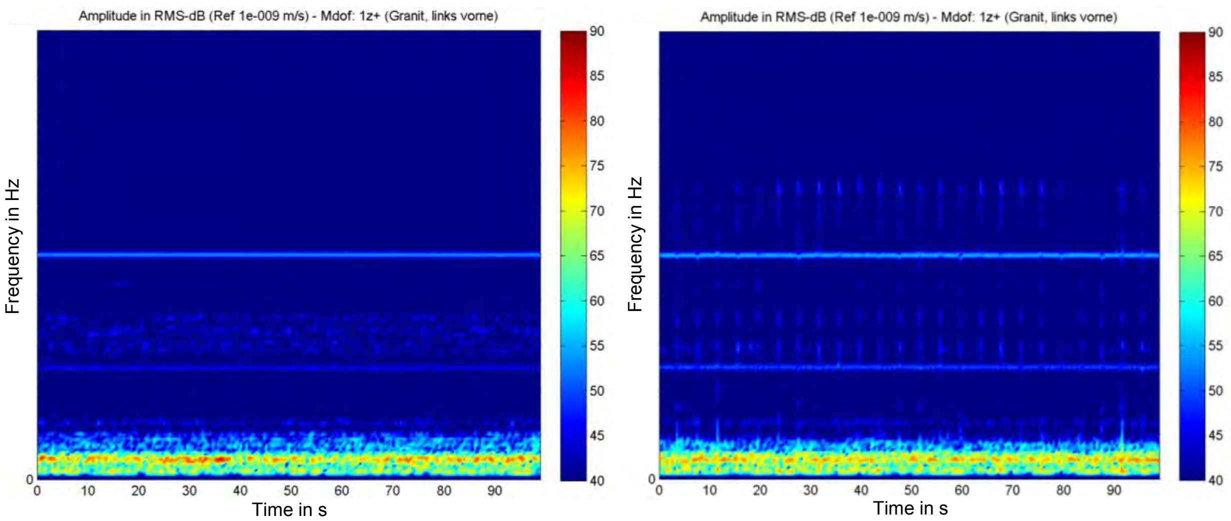

Figure 6: Sensor on granite, left: idle measurement/right: hammer excitation on ground

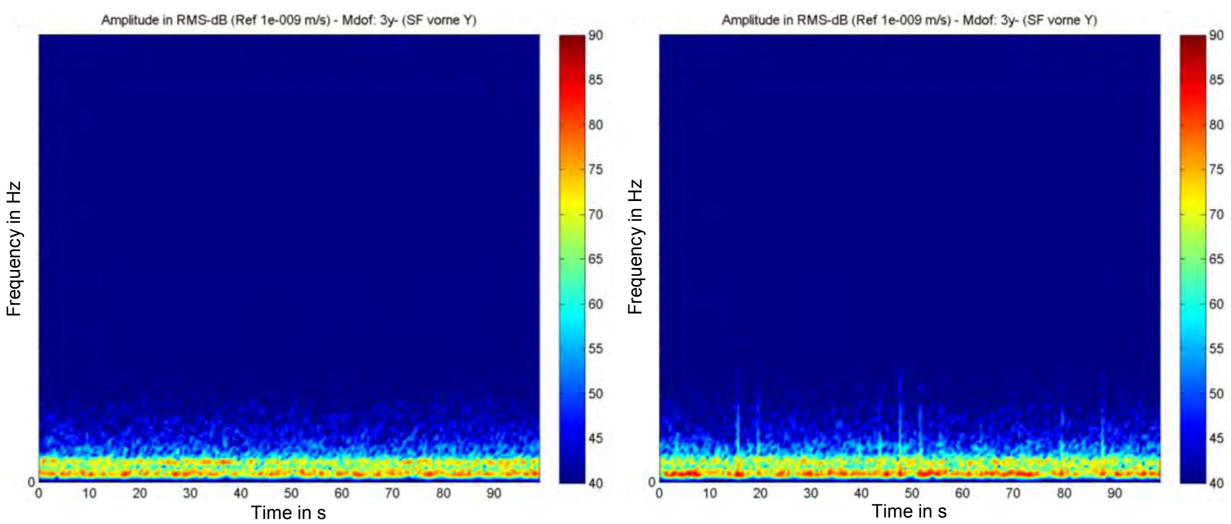

Figure 7: Sensor 1 on test item, left: idle measurement/right: hammer excitation on ground

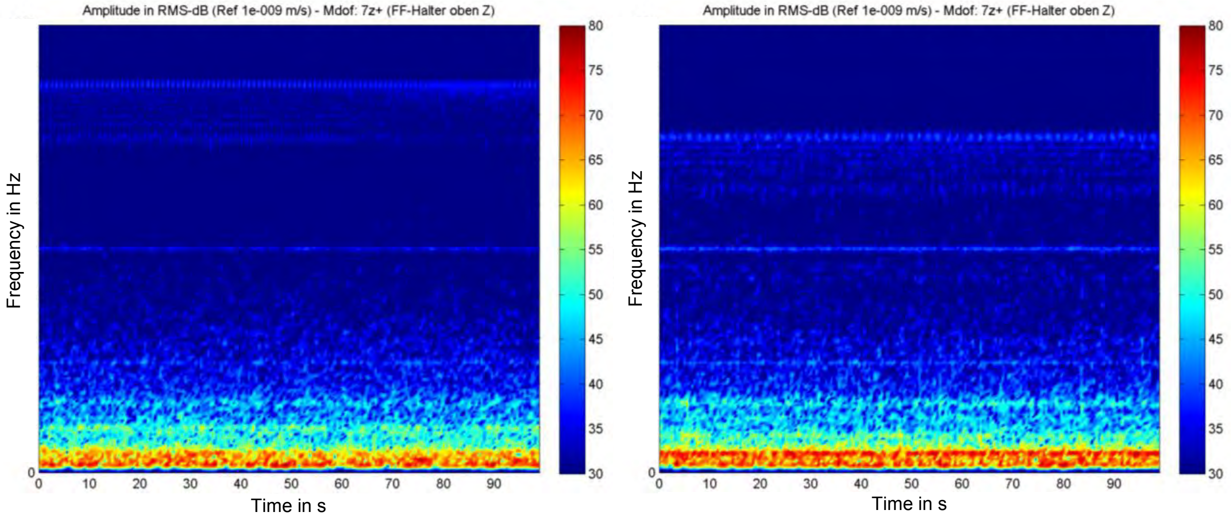

Figure 8: Sensor 2 on test item, left: idle measurement/right: hammer excitation on ground

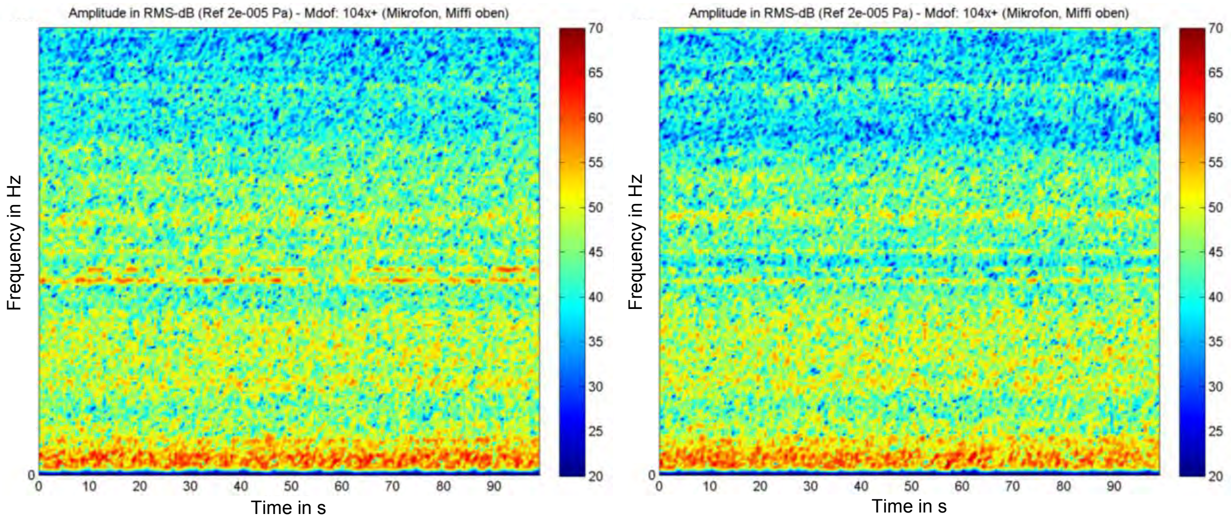

Figure 9: Microphone, left: idle measurement/right: hammer excitation on ground

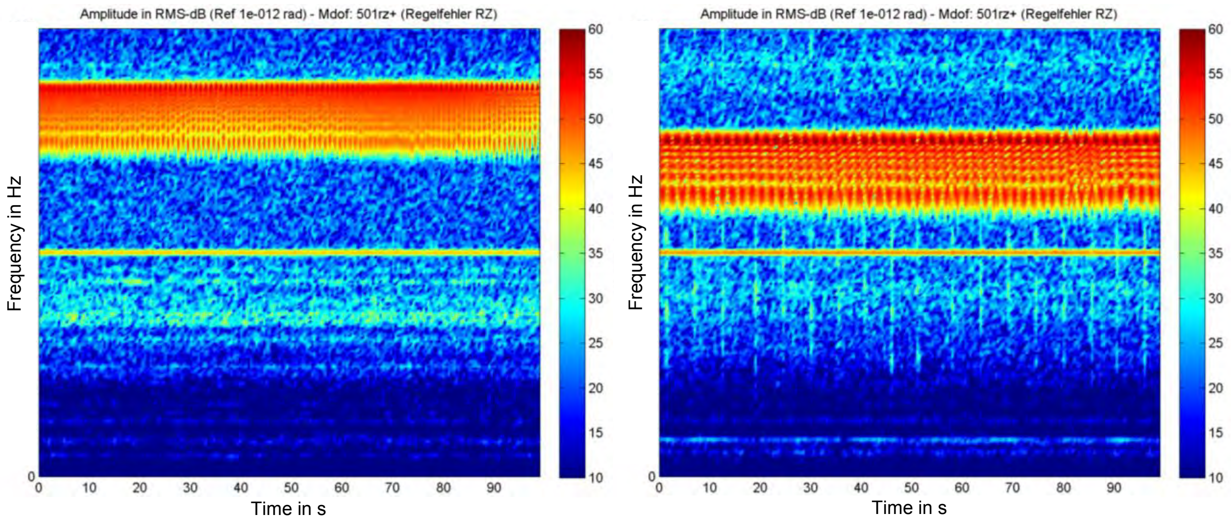

Figure 10: Control Error, left: idle measurement/right: hammer excitation on ground

Sound Excitation (Ordinate: Frequency in Hz, Abscissa: Time in s):

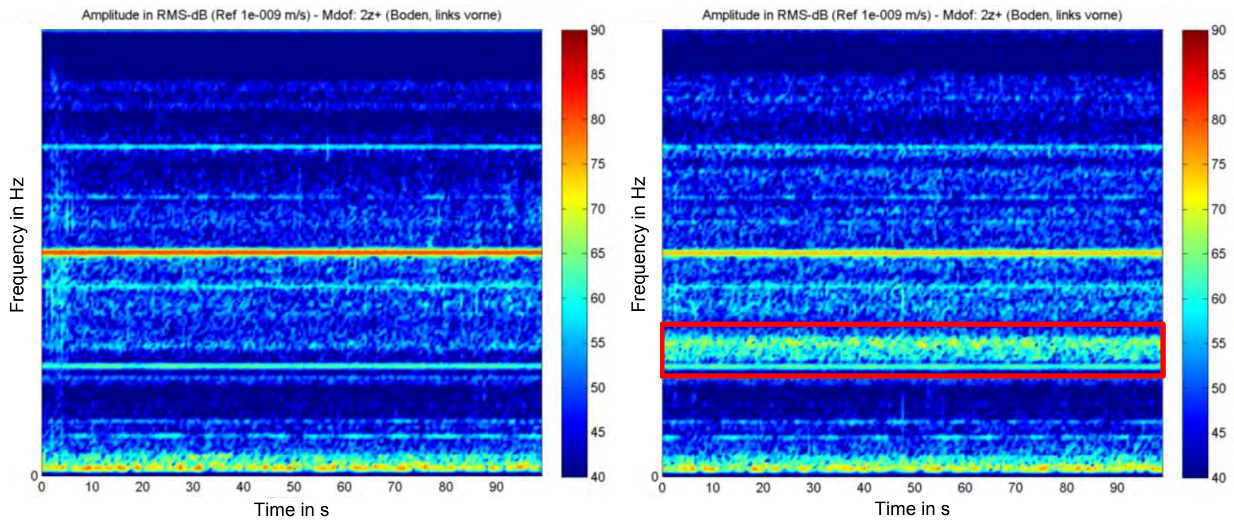

Figure 11: Sensor on ground, left: idle measurement/right: sound excitation

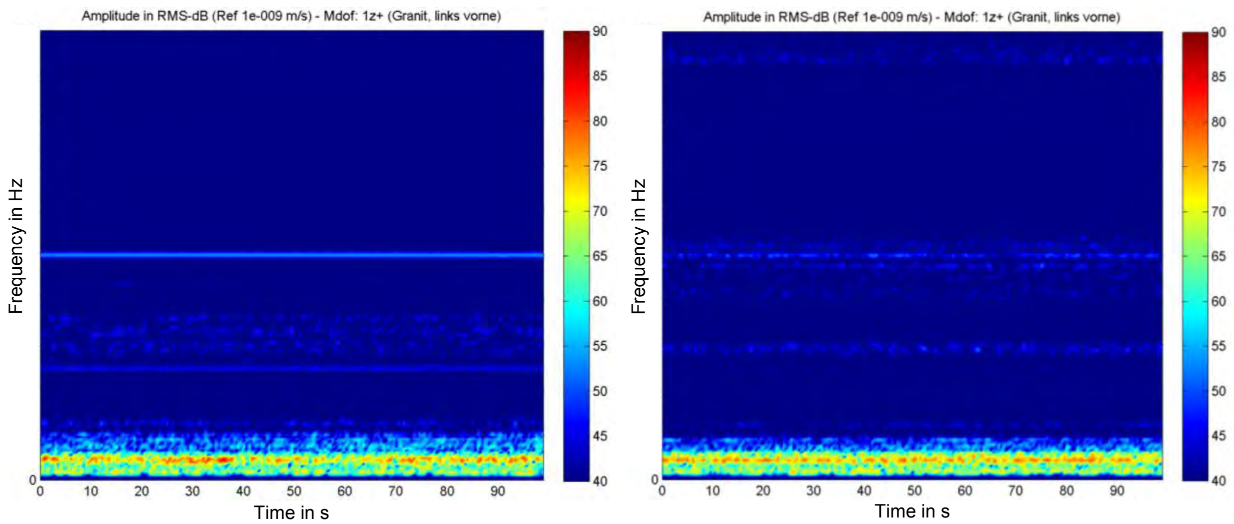

Figure 12: Sensor on granite, left: idle measurement/right: sound excitation

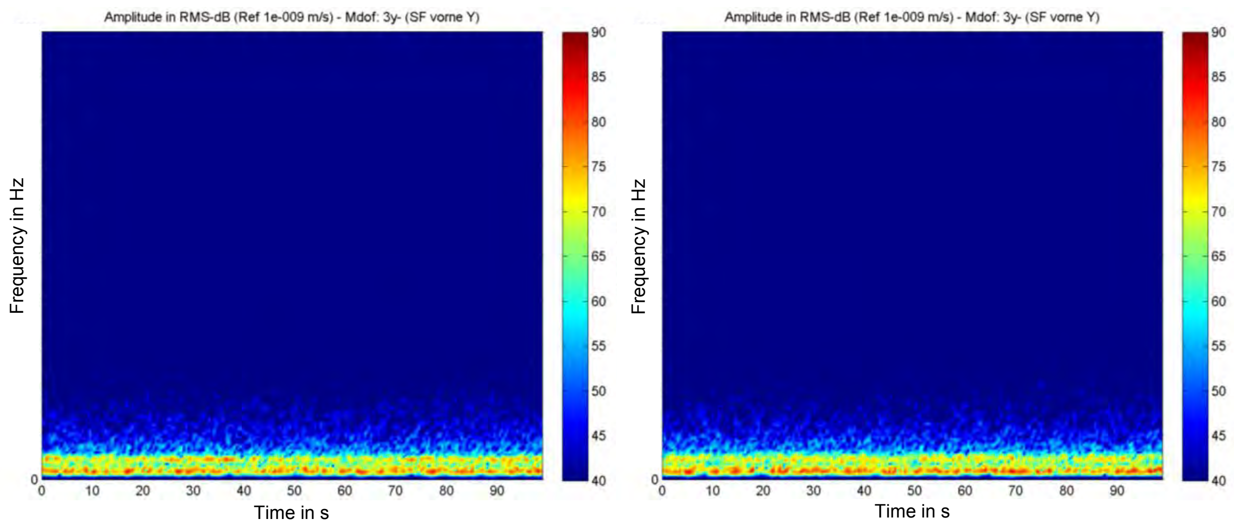

Figure 13: Sensor 1 on test item, left: idle measurement/right: sound excitation

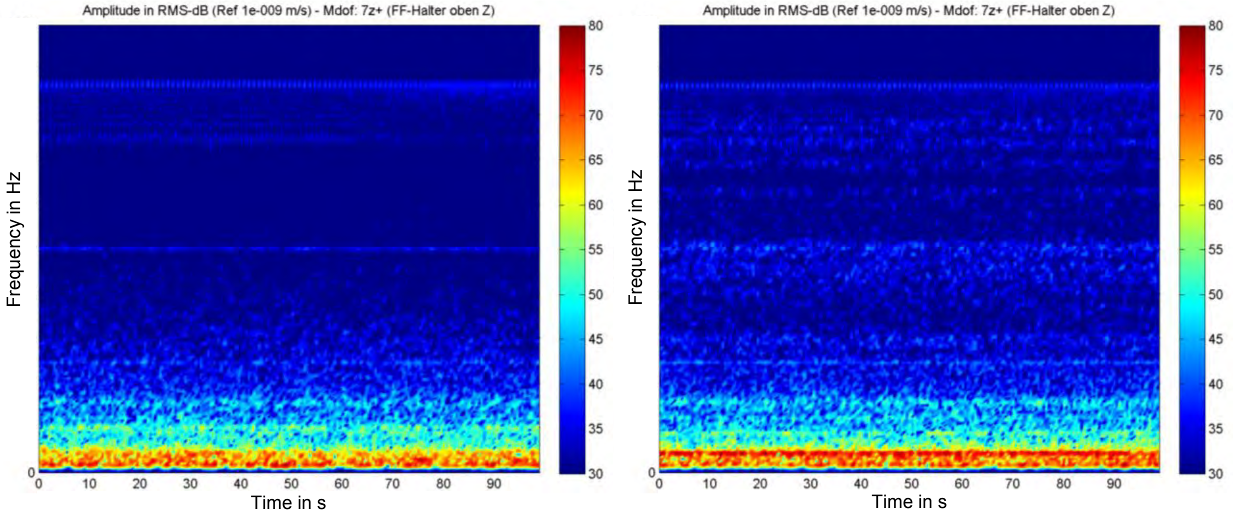

Figure 14: Sensor 2 on test item, left: idle measurement/right: sound excitation

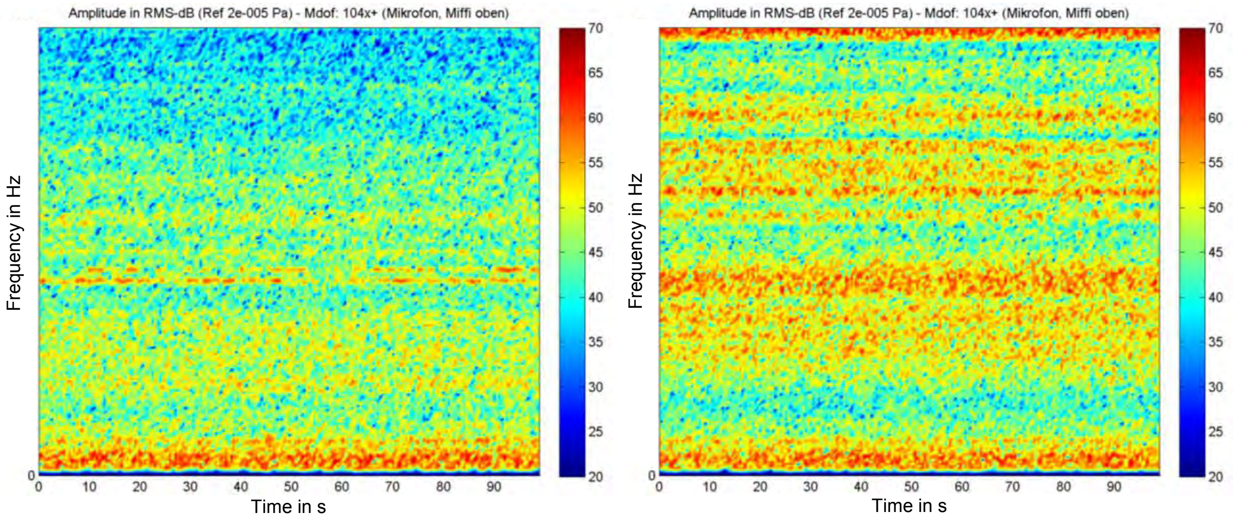

Figure 15: Microphone, left: idle measurement/right: sound excitation

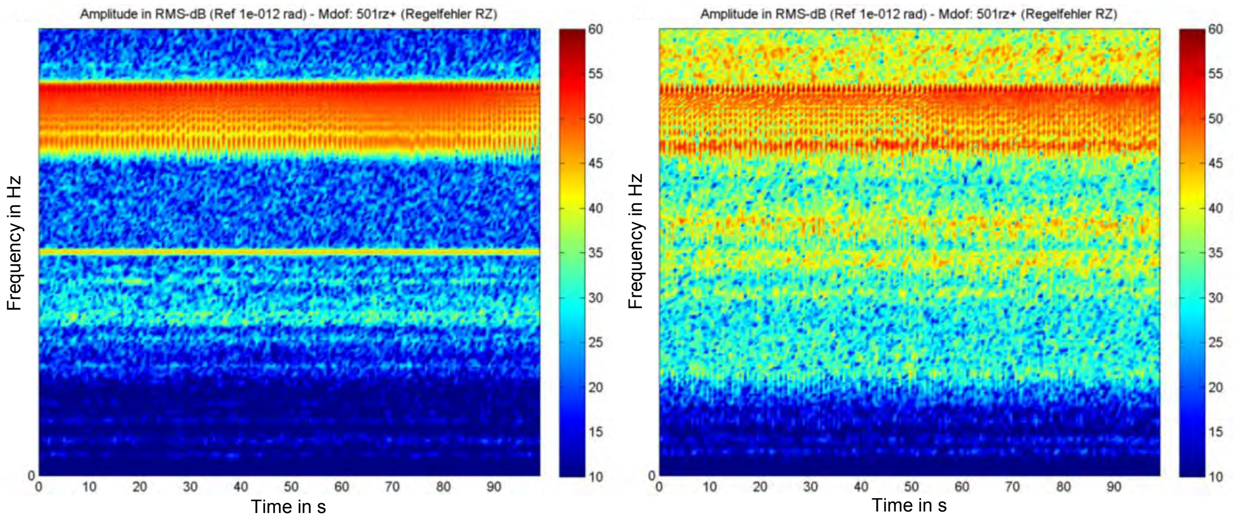

Figure 16: Control Error, left: idle measurement/right: sound excitation

Operational Excitation (Ordinate: Frequency in Hz, Abscissa: Time in s):

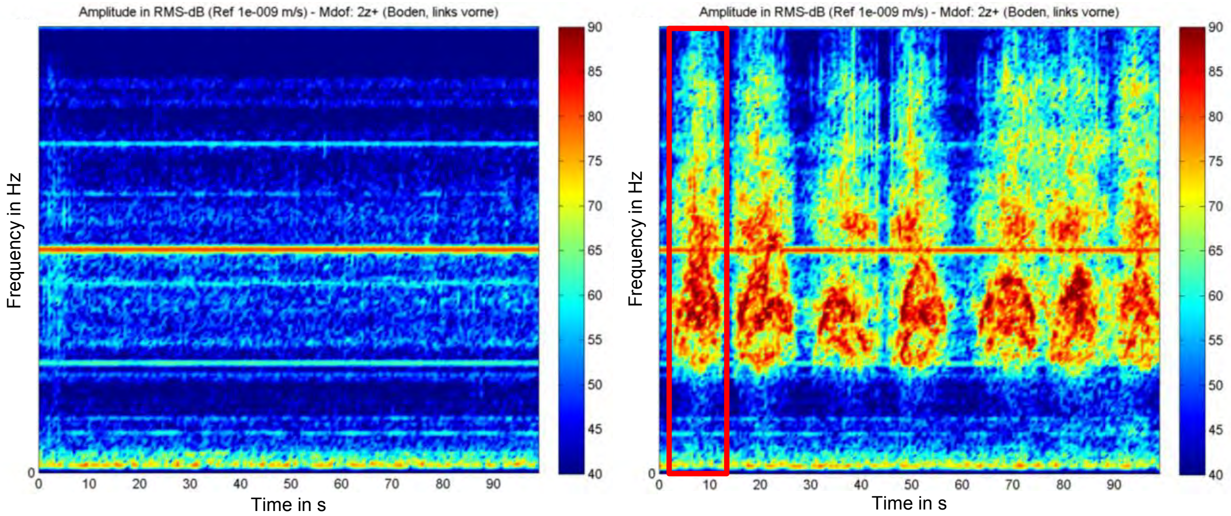

Figure 17: Sensor on ground, left: idle measurement/right: operational excitation with loaded lifter

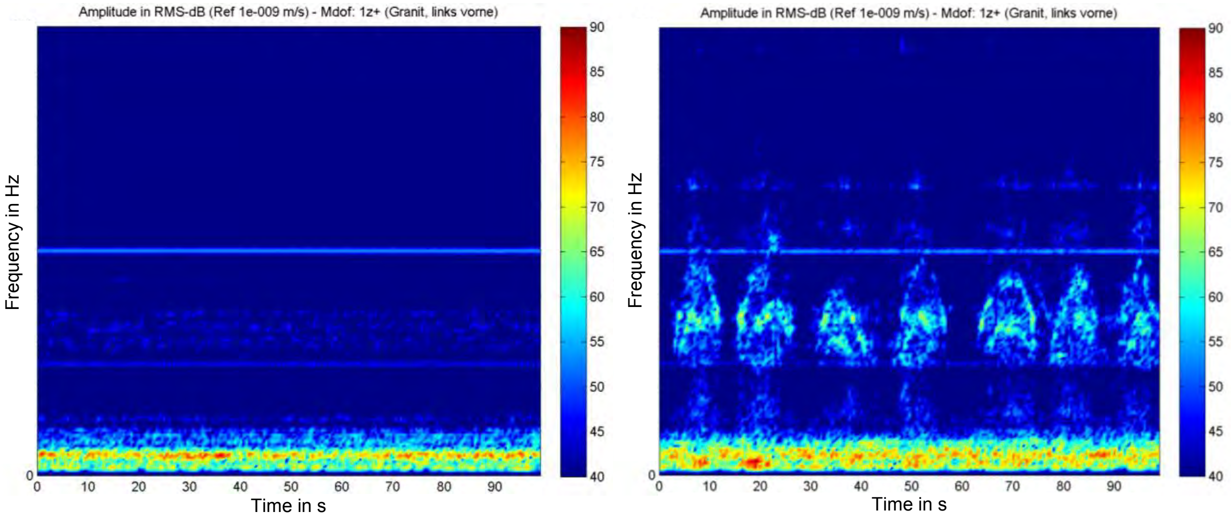

Figure 18: Sensor on granite, left: idle measurement/right: operational excitation with loaded lifter

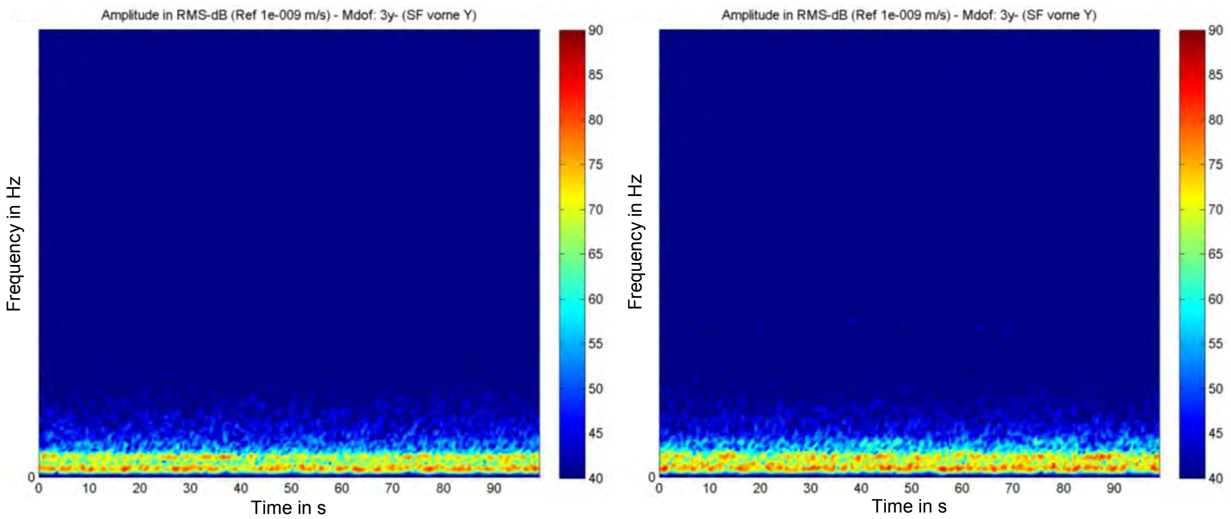

Figure 19: Sensor 1 on test item, left: idle measurement/right: operational excitation with loaded lifter

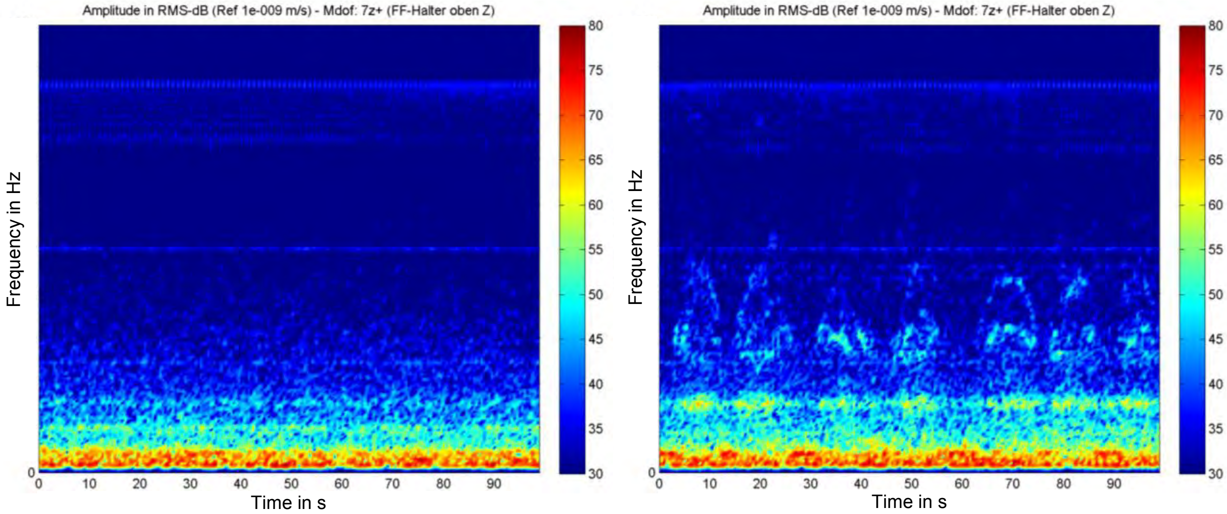

Figure 20: Sensor 2 on test item, left: idle measurement/right: operational excitation with loaded lifter

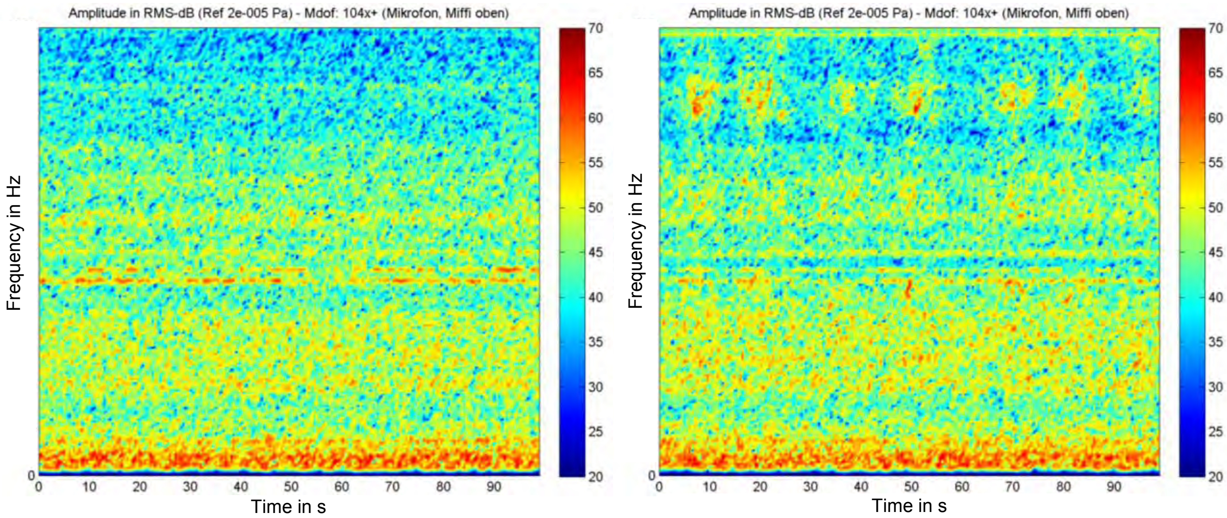

Figure 21: Microphone, left: idle measurement/right: operational excitation with loaded lifter

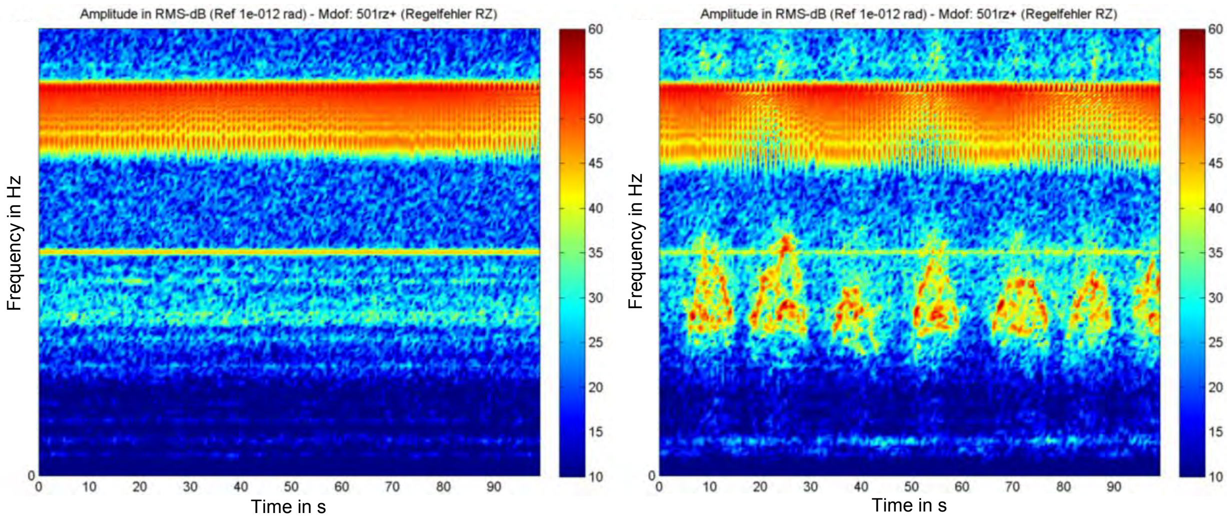

Figure 22: Control Error, left: idle measurement/right: operational excitation with loaded lifter

3.3 TPA

For TPA of the test bench, paths and operating data according to section 2 were used. The challenge was here that not all planned sound excitation paths could be measured because of failure of the sound source particle sensor before the end of the test campaign. Thus only a reduced base of paths was available. From the finally available paths, the following subset was selected for the TPA:

1. Hammer excitation, ground near left front foot of test bench support frame
2. Hammer excitation, ground near right front foot of test bench support frame
3. Hammer excitation, ground on travel path left
4. Hammer excitation, ground on travel path right
5. Sound Source, on travel path
6. Sound Source, in front of test bench
7. Sound Source, on left side of test bench
8. Sound Source, behind of test bench

As operational input data for the TPA force identification, a subset of the measuring points and directions ("indicators") was selected from the measurement with loaded lifter. The recalculation of the measured input data by means of the path frequency response functions and the identified forces was finally conducted for selected target measurement points and directions.

Figure 23 shows the forces identified with the TPA model described above. The recalculations for the targets sensors 1 and 2 on the test item and the control error are presented in Figures 24 to 26. For the control error Figure 27 additionally illustrates the individual path contributions to the overall response.

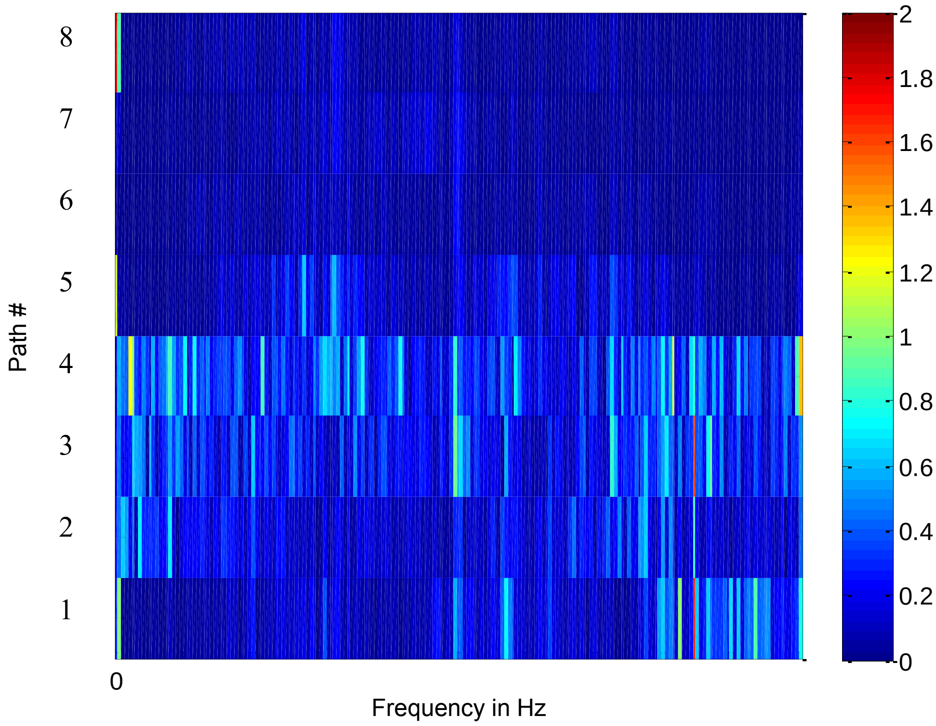

Figure 23: TPA results – identified forces

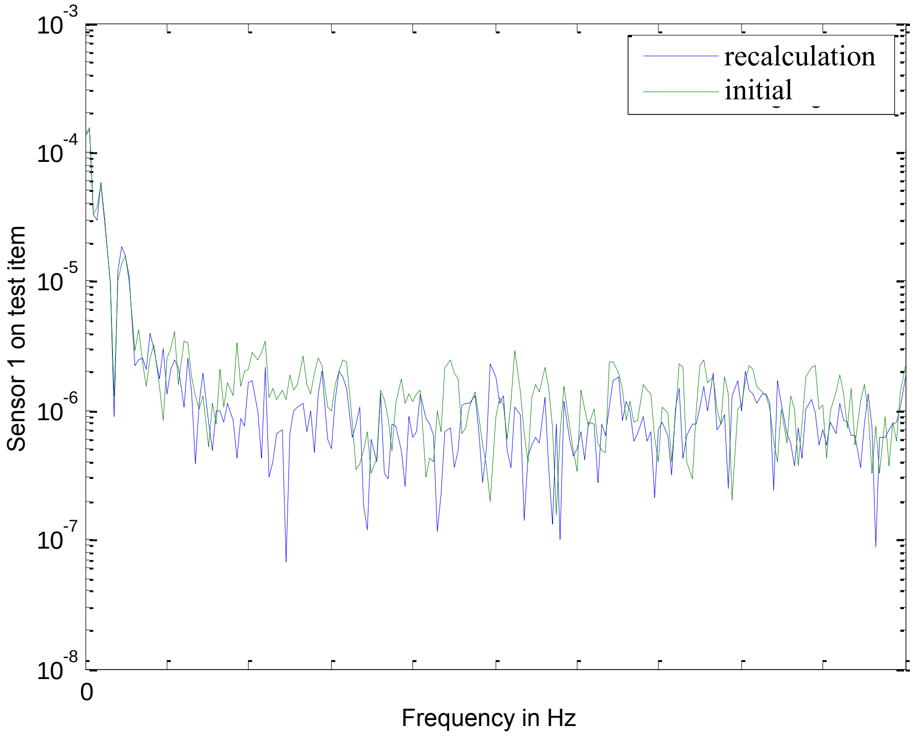

Figure 24: TPA results – comparison measured vs. recalculated signal for sensor 1 on test item

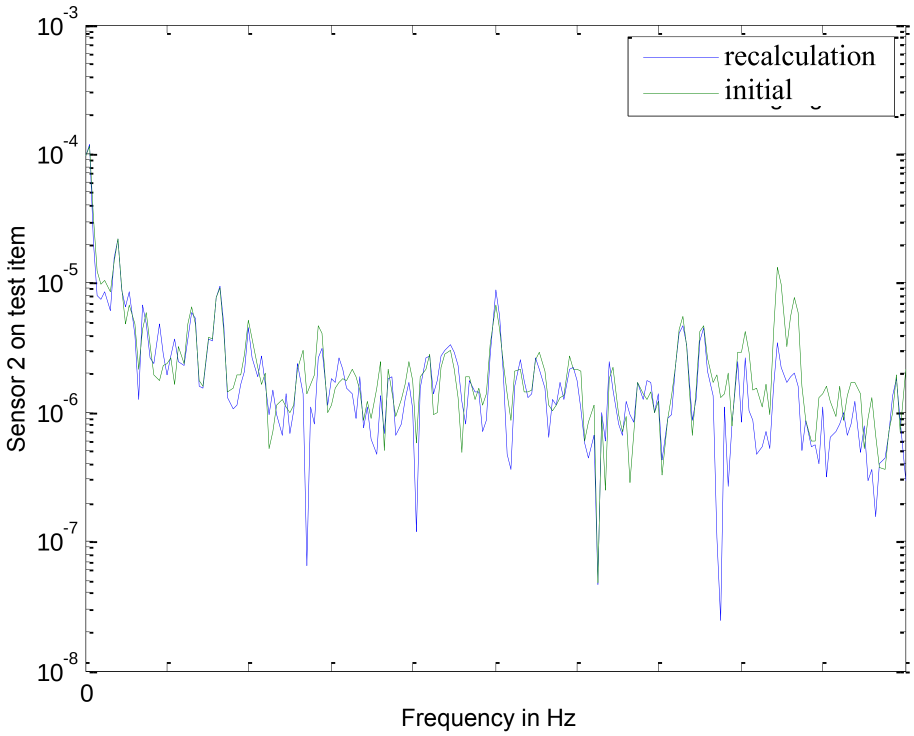

Figure 25: TPA results – comparison measured vs. recalculated signal for sensor 2 on test item

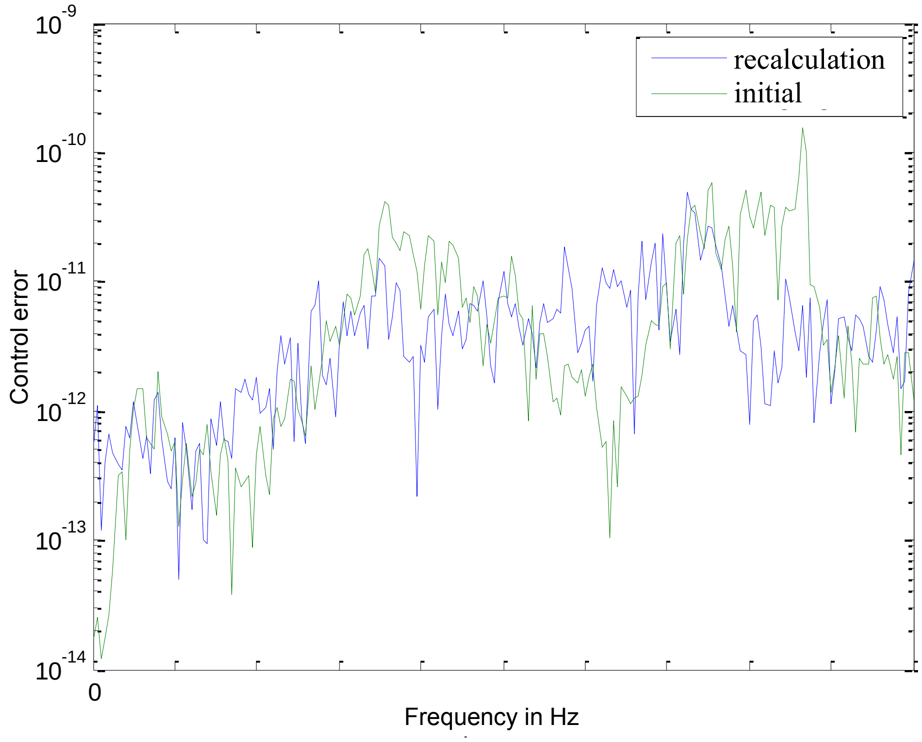

Figure 26: TPA results – comparison measured vs. recalculated signal for control error

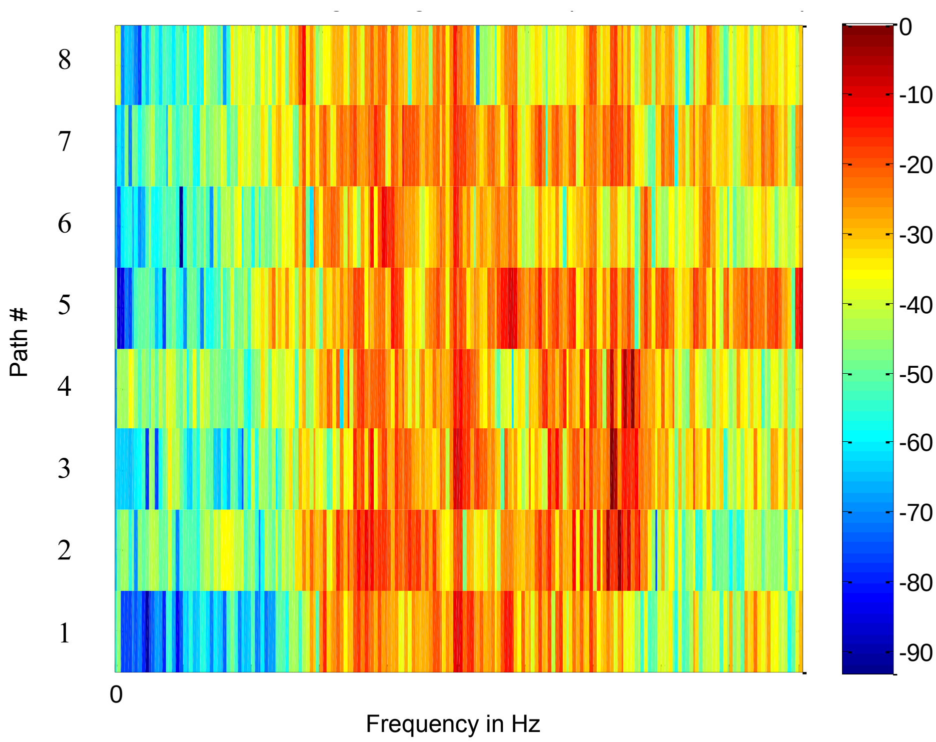

Figure 27: TPA results – path contributions to overall signal

First of all, it should be noted that the recalculations reproduce the characteristics of the initially measured signals very well. For the control error according to Figure 26 larger deviations can be observed in the upper frequency range that can be explained by the residual controller noise in this frequency range. Since the controller noise can be regarded as non-structural, it cannot be mapped by the TPA model.

Furthermore, it can be observed that none of the paths stands out from the others in particular. From this no preference for either structural or sound excitation can be concluded. One reason could be that both excitation variants can lead to control errors, which is why they can – in principle – be excited in either case via corresponding paths and associated forces (→ non-unique force identification).

Finally, it should be noted that a force excitation with hammer always produces a (pulsed) sound excitation as well and that sound excitation can always cause a structural vibration. Thus, in both cases, in case of doubt, energy is transmitted via both transmission paths, albeit with different intensity.

4 Test Results

To summarize, it can be stated that control errors can be triggered by typical operating situations in the vicinity of the test bench. This can clearly be seen on both time and spectral data, e.g. in case of pass-bys with a loaded lifter. Especially in the lower frequency range significant PSD increases occur.

Furthermore, by temporal resolution of the signal contents using short-term spectral analyses, typical operating signatures can be identified. These signatures can, depending on the type of excitation, be observed with varying intensity on the individual components of the test bench itself as well as on sound pressures, and, finally, on the control errors.

With predominant force excitation disturbances seem to be transferred primarily over the foundation in the test bench. Since the excitation signatures can also be detected on test item at location 1, this can have a direct effect on the control errors. With predominant sound excitation the disturbances are to be recognized first of all on the test item at location 2 as well as on the microphones. The assumption is therefore obvious that the disturbances, which can also be found on the control errors, can result from an excitation of the test item via air.

With combined force and sound excitation, as it occurs for example when passing by with a lifter, in principle both phenomena described above are basically recognizable. However, the disturbance signatures on the test item at location 1 are virtually undetectable (as for pure sound excitation), whereas they stand out clearly in the test item at location 2. From this, a primary disturbance due to sound excitation may be concluded.

5 Summary and Conclusions

Vibration and acoustic measurements were carried out on a test bench. Accelerations on the ground and on the test bench, sound pressures in the immediate vicinity, and control errors were measured. In particular, the control errors can be regarded as a measure of the impact of external disturbances. The excitation was carried out successively both by defined force and sound excitation at several points, as well as by typical operating loads.

It was found that day-to-day operation in front of the test benches can cause clearly detectable effects on the control errors. These disturbances are also found on the measured structural accelerations and (partly) on the sound pressures. In this case, a clear separation of the individual excitation pathways (structurally or by air) via TPA is not completely possible – in principle, both path variants have the potential to cause the disturbances individually and also in combination. However, a certain preference on the airborne path can be concluded.

Therefore, for a reduction of the occurring disturbances primary measures for decoupling the test stand from the acoustic environment may be required. To achieve this, an enclosure for the test bench with sufficient acoustic decoupling of external disturbances is currently under development. Later, to check the effectiveness of the enclosure, additional measurements are planned.

Acknowledgements

The authors wish to thank the Carl Zeiss SMT GmbH for the support of this work and the permission to present the results.

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