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SEISMIC TEST OF PIPE SYSTEM SUPPORTING ANCHORS BY A LINEAR SHAKER

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ABSTRACT

Seismic testing is one of the possibilities to proof the seismic resistance of components installed in nuclear power plants. Usually base excitation is used for these tests. This means the structure to be tested is mounted on a shaking table reproducing the required seismic motion. This paper presents another approach to perform a seismic test. The investigated structure is a mock-up consisting of a piping system which is vertically suspended by a strut. The strut is fixed by two anchors to a concrete slab. In a research project Kerkhof (2015) especially the behaviour of anchors during a seismic is investigated. For this purpose a seismic excitation has to be generated. As the mock-up is fixed to the ground concrete slab as well as to a rigid support, the seismic excitation is achieved by mounting a shaker system to the free cantilevered end of the pipe. The main seismic loading of the mock-up's anchors is due to vertical seismic excitation, so the linear shakers are working in this direction. The paper describes the mock-up and the used shaker system. The derivation of seismic design spectra based on numerical calculations of the building structure as well as of the mock-up itself is presented. The determined force time history signal is the target signal which has to be induced by the shakers during a test. The method to gain to appropriate drive signal of the shakers is presented. An example shows the results. By scaling the drive signal, other loading levels can be achieved, for this purpose global linearity of the mock-up behaviour is essential.

INTRODUCTION

Earthquake loading is one of the load cases which have to be regarded for the design of Nuclear Power Plants (NPP). The building structures as well as the installed components have to resist the site specific earthquake loading. Depending on the seismic classification of the structures / components, their stability, integrity or even operability during / after a seismic event has to be proved (KTA 2201.4). For piping systems the proof of stability and integrity is required. These proofs are usually established for the pipe itself as well as for its supports by using analysis based on common standards. Considering post-installed supports, these often consist of anchor plates which are fixed to building structures by e.g. (undercut) anchors. The transient loading of these anchors depends strongly on their interaction with the supported component (anchor plate, strut, piping system), building structure and the local fastening situation considering crack opening of the concrete around the anchor. To get a basic understanding of the mentioned interaction as well to investigate the load-bearing behaviour of anchors during earthquake loading, within a research project Kerkhof (2015) a mock-up was established. This mock-up is used to perform seismic tests. Usually shaking tables are used for seismic testing providing a base excitation. Instead of base excitation another approach is used. A linear shaker is mounted on the supported pipe structure to provide a transient seismic excitation.

In this paper the steps to establish the shaking test as well as the results of the test with respect to seismic loading are presented. Firstly the mock-up is described. Based on response spectra describing the earthquake motion at the anchors and a finite element (FE) model of the mock-up, acceleration time histories of the vertical force acting on the anchors were generated. A selected acceleration time history is afterwards used to implement the transient shaker drive signal. The method to get the drive signal is described. Results of an example are presented.

MOCK-UP

Mechanical Setup

The mock-up is a vertical / horizontal piping system (~13 m long, nominal diameter DN200, wall thickness 17.5 mm) as shown in Figure 1. On the lower left side of Figure 1 a finite element model of the mock-up is shown, the lower right side shows a frontal view of the mock-up, the top shows the top view of the concrete slab the anchors are fastened to. The shown hydraulic cylinders can be used for a defined cyclic crack opening within the research project Kerkhof (2015). One end of the pipe is fixed to the ground; the other end is freely suspended. At the free end the shaker system is installed. An additional pipe strut is fixed by two anchors to the bottom side of the concrete slab. When performing tests, the supporting jack depicted Figure 1 is removed. Besides this loading by dead load, the system is supposed to be seismically loaded by driving the shaker system.

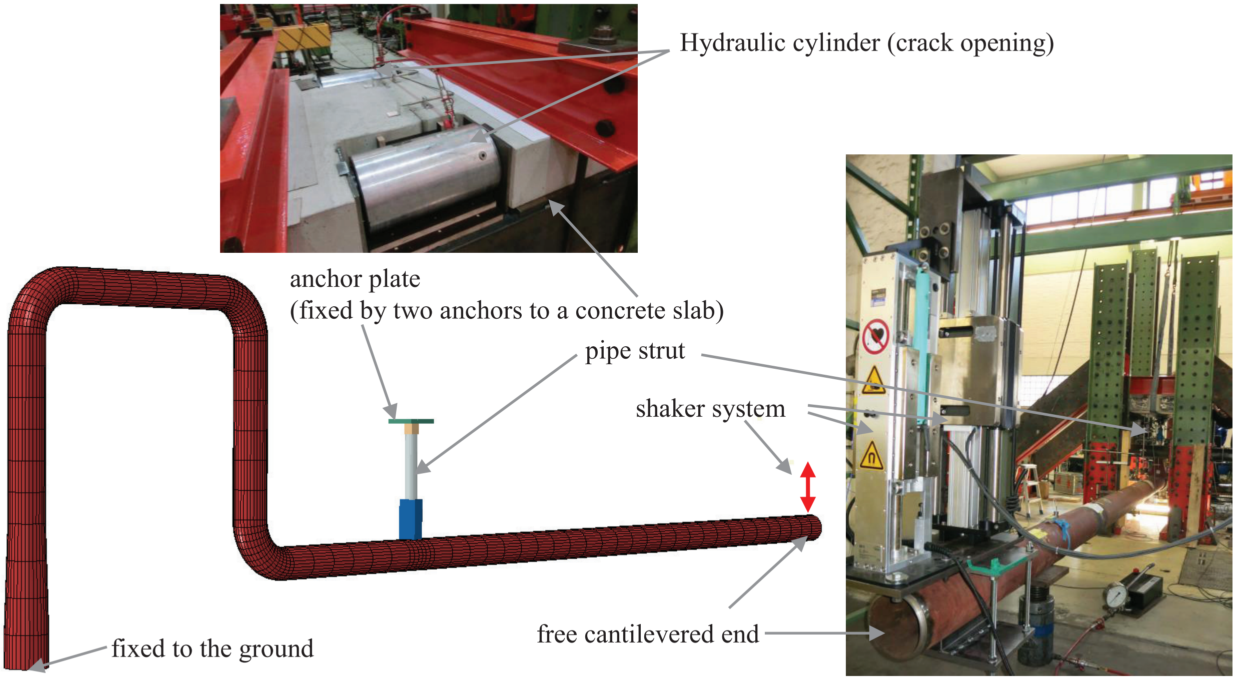

Figure 1. Mock-Up: Finite Element-Model (bottom left); Frontal view (bottom right); Concrete slab with additional hydraulic cylinders for defined crack opening (top).

The mock-up is equipped with several acceleration and displacement sensors. As the investigations are focused on the transient vertical loading of the two anchors, the measurement of the force experienced by the anchors is essential. For this purpose a strain-gauge was applied to the pipe strut. After calibration the measuring of the vertical force experienced by the strut / anchors is possible.

Seismic Loading of Mock-Up at its Fixing Points

Figure 2 shows the finite element model of the building structure of the assumed NPP. The site specific design basis earthquake (DBE) is defined by the free-field response spectrum based on deterministic and probabilistic seismic hazard analysis using a recurrence period of 10^{-5}/a (KTA 2201.1). For the considered typical German seismic site the DBE shows peak ground acceleration (PGA) of 2 m/s² in horizontal directions and 1 m/s² in vertical direction. The spectra are shown in Figure 2 (right).

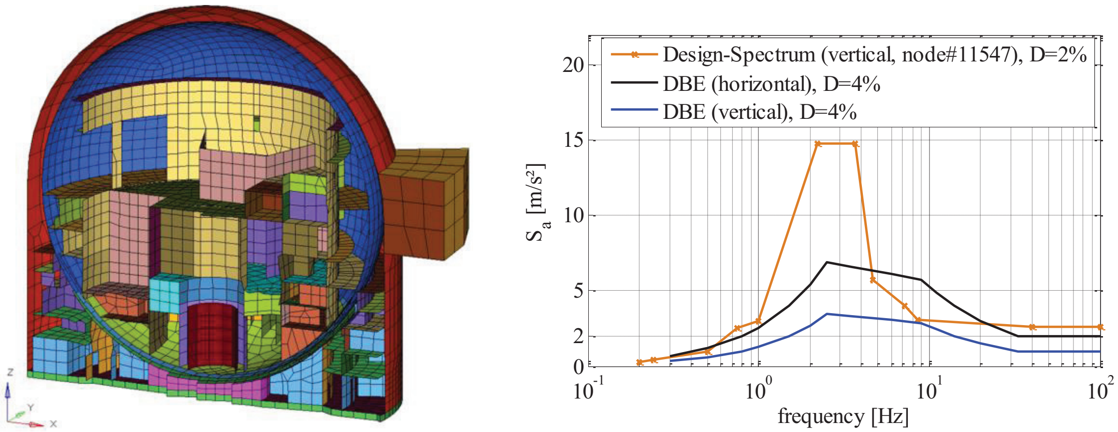

Figure 2. Finite Element-Model of NPP (left); DBE (right).

From the DBE spectra artificial acceleration time histories of 10 s duration are created to calculate the responses of the building. The variation of soil parameters was considered. The resulting design spectra were determined. The design spectrum in vertical direction of the regarded installation location is shown in Figure 2 (right).

If a test on a shaking table would have to be performed, the design spectra would serve as seismic loading for the base excitation at the mock-up's fixing points. Due to German standards additional tests at lower levels (e.g. operating basis earthquake) are not required. Since the mock-up will not be base excited, but a shaker system will be used, additional calculation have to be made to get the anchor/strut loading during the seismic event.

Seismic Loading of Mock-Up: Strut Force

For this purpose a separate FE model of the mock-up is used to determine a time history signal of the force in the strut during the earthquake. The idea behind this approach to look at the strut force is, that the (vertical) force transmitted in the strut should be quite equal to the sum of the normal forces on the two anchors which behaviour is investigated. The used FE-model of the mock-up from Dwenger (2015) for this decoupled simulation is shown in Figure 1. The total mass is approx. 1.5 tons. The mass of the shaker system is respected in the calculations. The first vertical eigenfrequency is found to be 3.55 Hz, the corresponding eigenform is shown in Figure 3.

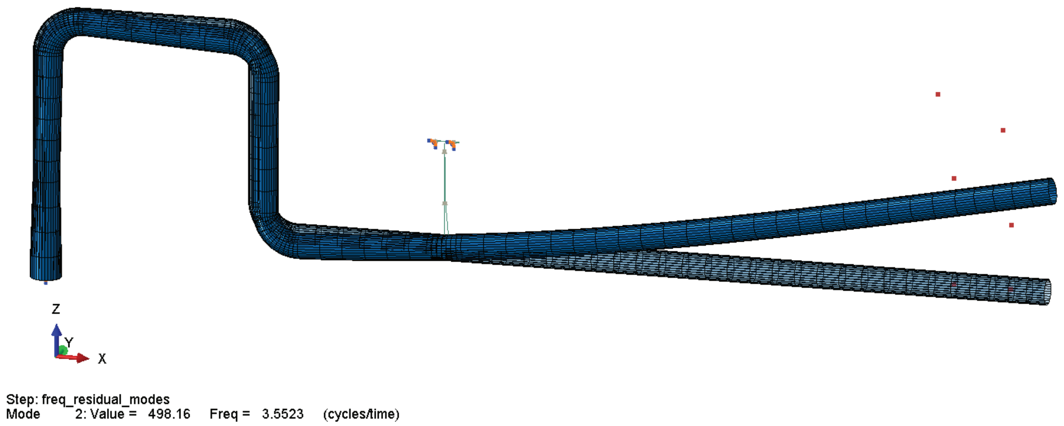

Figure 3. First vertical eigenform of FE model of the mock-up

It can be seen, that in this eigenform the shakers at the end of the free cantilevered pipe experience a significant motion.

The transient response of the mock-up is determined by applying artificial time histories matching the design spectra at the mock-up's base (fixed end of pipe and anchor plate). Modal transient calculation is used. Superpositioning of the transient results in both horizontal and in vertical direction give the most unfavourable transient loading of the strut. The resulting vertical force is plotted in Figure 4.

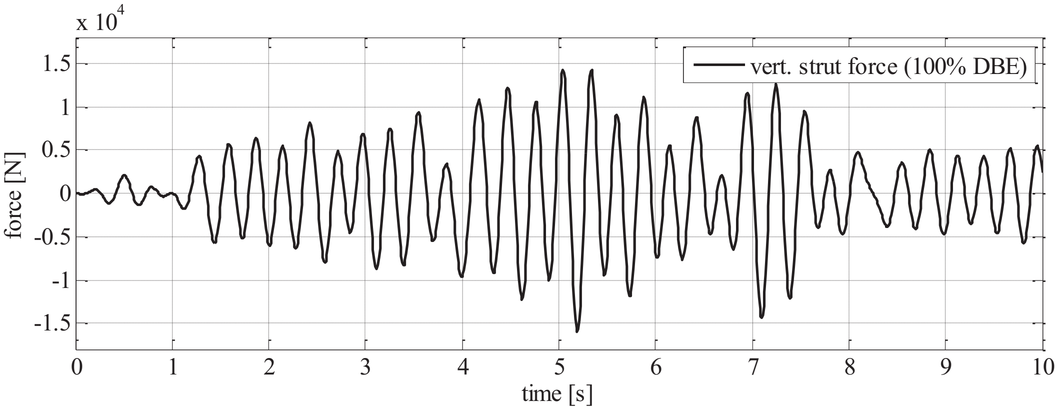

Figure 4. Strut force (vertical) due to seismic loading of mock-up.

Maximum force amplitude of approx. 16 kN appears for the considered 100% DBE. It can be clearly see, that the vertical response of the structure is dominated by the first vertical eigenfrequency.

SEISMIC TESTING

Goal of the seismic testing is to apply a force time history signal as shown in Figure 4 to the strut of the mock-up by driving the shaker system with an appropriate voltage drive signal u_{drive}. This drive signal has to be in the range of +/-10 V. It is generated by a digital programmable realtime PC equipped with analog input and output interfaces. The drive signal u_{drive} is fed into the amplifiers of both shakers, see illustration in Figure 5.

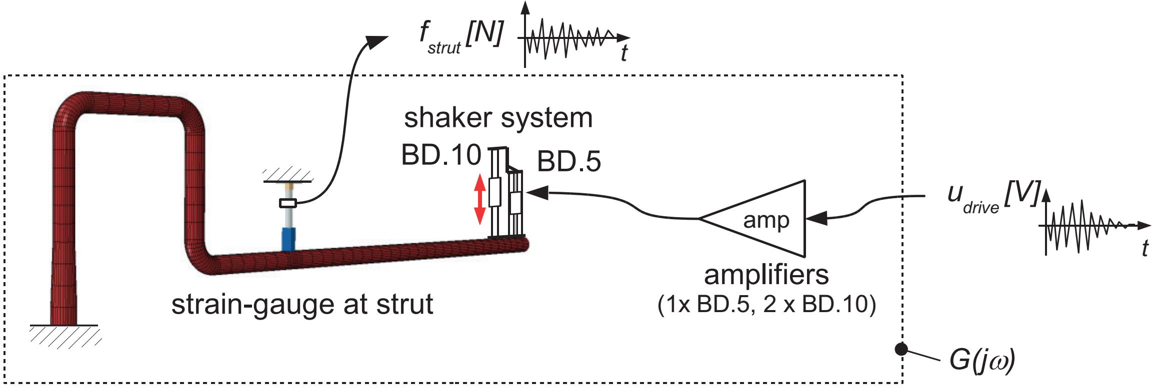

Figure 5. System sketch of mock-up

The several sensors like e.g. the strain-gauge at the strut provide signals (strut force f_{strut}) of the system response due to the external loading (dead load, shaker excitation) of the mock-up. The sensor signals are digitally sampled by the realtime PC at a rate of 500 Hz.

Shaker System

To induce forces to the pipe, a shaker system is attached at the free end of the pipe by clamping (see Figure 6). The shaker system consists of two shakers ‘BD.5’ and ‘BD.10’ in vertical operating direction. The shakers are actuated in parallel as their amplifiers are driven by the common drive signal. Both shakers use linear bearings and electrodynamic linear actuators driving a reaction mass for force generation. The reaction masses are vertically suspended by mechanical springs (BD.5) or a rubber band (BD.10). Typical parameters of both shakers are given in Figure 6.

shaker:	BD.5	BD.10
nominal max. continuous force:	+/-500N	+/-1000N
max. amplitude (peak-peak):	290 mm	600 mm
reaction mass:	27,5 kg	70 kg
shaker resonance:	~1.5 Hz	~1.1 Hz

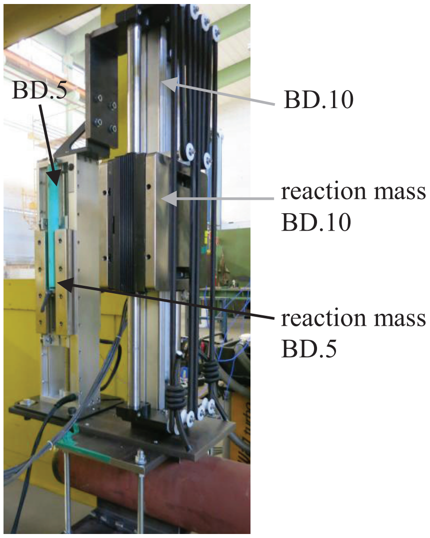

Figure 6. Shakers: individual shakers (left), shaker system for pipe (right)

After accomplishing preceding tests using only one BD.5, there as a demand for additional force, so a more powerful BD.10 shaker was added to the mock-up.

Frequency Response Function (FRF)

Assuming linear system behaviour, the system dynamics is given by the frequency response function $G(j\omega)$ as illustrated in Figure 5. The FRF $G(j\omega)$ can be measured by driving the actuators with a known signal u_{drive} while measuring the response i.e. strut force f_{strut}. During the tests the frequency response function was determined by using broadband noise (frequency range up to 50 Hz, amplitude 3 V) as well as sine sweep signals (e.g. 1.5 to 50 Hz, amplitude 0.2 V, sweep rate ~2.5 oct/min).

Figure 7 shows the determined transfer functions $G(j\omega)$ for both types of excitations. Both excitations give approximately the same result. Up to 50 Hz four obvious resonance peaks are identified. The lowest identified resonance is 3.4 Hz, which is approx. 4% lower than the numerical result found in Figure 3. Using half power bandwidth method the damping for the first resonance can be determined in the range 2.2 to 3 %. Looking at the mock-up’s vertical design spectrum in Figure 2 (right) it can easily be seen that only the first vertical resonance of 3.4 Hz is significantly excited by the earthquake. As the higher resonances starting at ~26.5 Hz are located in the rigid-body-range of the spectrum, nearly no contribution from these resonances to the total response of the pipe takes place. Thus only the first vertical resonance is contributing to the seismic response of the pipe.

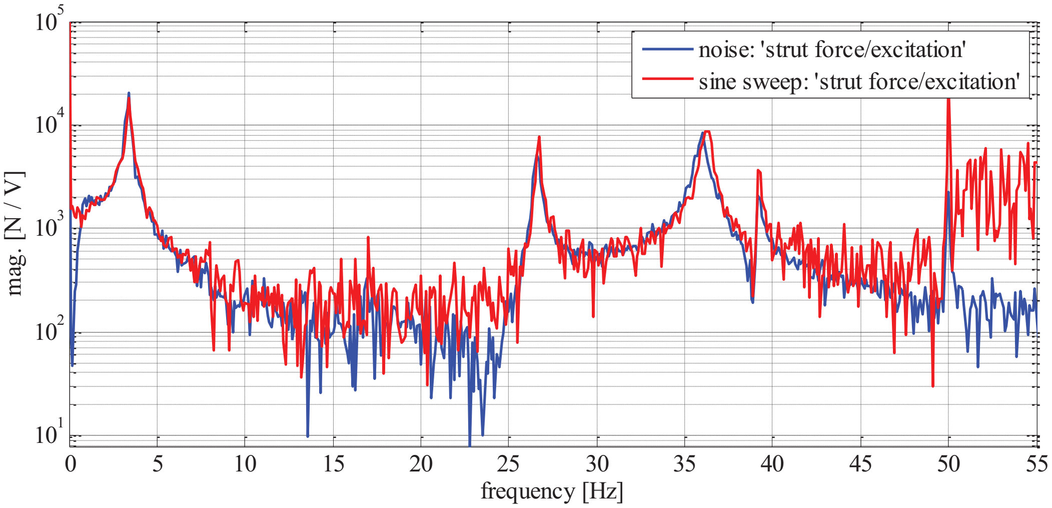

Figure 7. Frequency response function *G(jω)*: strut force (vertical) / drive signal.

Shaker Constants

To determine the force ‘constants’ of each shaker the transfer function from the drive signal to the acceleration sensor placed on each reaction masses is evaluated. By multiplying the measured accelerations with the reaction mass the generated force can be determined. Figure 8 shows the transfer functions of both shakers determined by using broadband noise excitation.

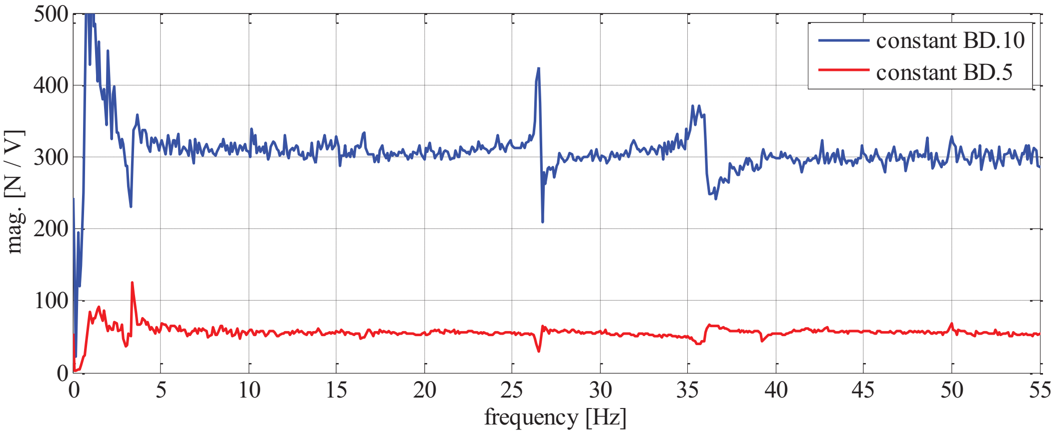

Figure 8. Force ‘constants’ of both shakers.

Away from its own and additional structural resonances a force constant of approx. 55 N/V is achieved for the shaker BD.5. The bigger shaker BD.10 reached due to its adjusted and more powerful amplifiers a force constant of approx. 310 N/V. By driving them in parallel a summed constant for the shaker system of approx. 365 N/V is reached.

Drive Signal Generation

Looking at Figure 5, for a linear system the relation between system response f_{strut} and the drive signal in frequency domain is given by the following formula

$$f_{strut}(j\omega) = G(j\omega) \cdot u_{drive}(j\omega) \tag{1}$$

As the strut force is known, the most direct approach is to solve this equation to get the drive signal

$$u_{drive}(j\omega) = G(j\omega)^{-1} \cdot f_{strut}(j\omega) \tag{2}$$

In this formula $f_{strut}(j\omega)$ is determined by the Fourier transform of the desired strut force signal. $G(j\omega)^{-1}$ is determined by inverting the FRF shown in Figure 7. To get the time domain signal $u_{drive}(t)$ an inverse Fourier transform of $u_{drive}(j\omega)$ is established. Before doing so, an additional filter in the frequency domain is regarded: only frequency content from 2.5 Hz up to 40 Hz is considered for the inverse Fourier transform. This filter was chosen for three reasons. First the FRF was determined only in the frequency range up to 50 Hz, higher frequencies with low amplitude in $G(j\omega)$ would lead due to inversion to contamination of the drive signal with high frequencies noise. Second, too much low frequency content would lead to too high displacements of the shakers reaction masses which would make them run into their end stops. The third reason is that the seismic event will only excite frequencies in a limited frequency band as given in the response spectrum (e.g. see Figure 2).

Example: Seismic Loading at 50%DBE

The procedure described in the previous section was applied to the mock-up. The example will show the results for a strut force signal which is 50% of the signal depicted in Figure 4, additionally a fade-out beginning at 9 seconds was applied to the signal. This targeted strut force signal is shown in Figure 10.
To generate the drive signal the FRF $G(j\omega)$ based on the noise excitation (see Figure 7) was used. The drive signal for this example is shown in Figure 9.

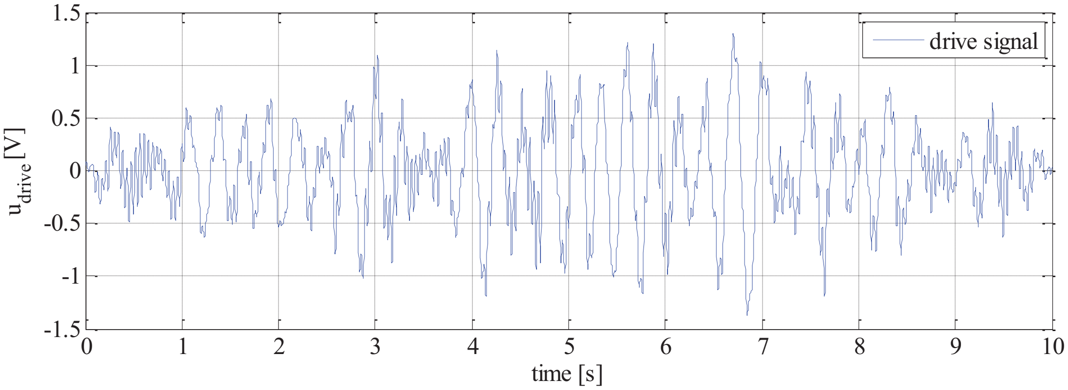

Figure 9. Example, drive signal

A comparison of the targeted strut force signal and the measured signal is depicted in Figure 10.

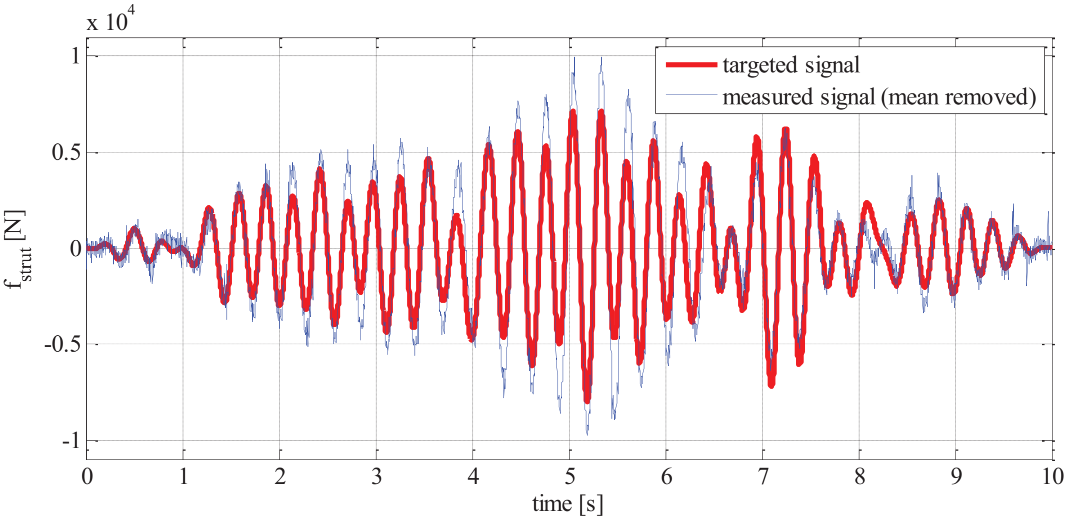

Figure 10. Example, strut force: targeted signal and measured signal

During test the weight of the pipe suspended from the strut is also measured by the strain-gauge sensor, in order to compare the measured signal with the targeted signal, the mean value of the measured signal is removed. From the comparison it can be seen that in the time interval from 2.5 s to 6.5 s the measured signal is noticeably higher than the targeted force signal. Furthermore some high frequency content seems to be constantly present throughout the whole duration of the signal. Although both signals represent forces, a response spectrum for D = 2 % is calculated (see Figure 11) to get an additional comparison based on frequency domain considerations.

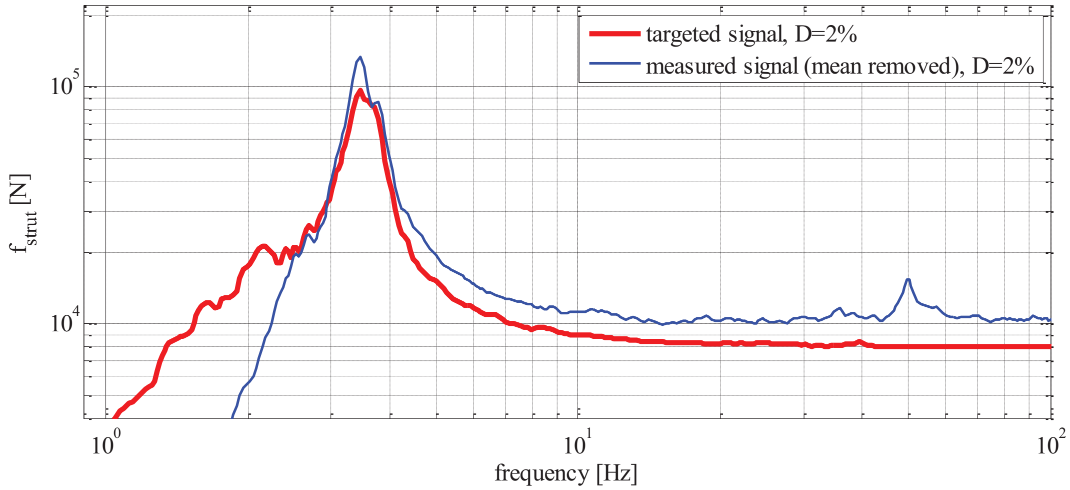

Figure 11. Example, strut force: targeted signal and measured signal, response spectrum, D = 2%

It can be seen from Figure 11 that in the frequency range below the first dominant eigenfrequency and above, the spectrum of the measured signal is conservatively enveloping the spectrum of the targeted signal. The reason for the significant undercoverage in the lower frequency range is because of the chosen frequency filter start frequency of 2.5 Hz preventing significant motion amplitudes of the shakers' reaction masses.

CONCLUSION

The presented work showed an approach to seismically test a pipe system and its anchors. Instead of the typical base excitation which is accomplished by shake tables, the seismic loads were induced vertically by a shaker system consisting of two different linear shakers attached to the free cantilevered end of the pipe. Besides the determination of the design spectrum of the mock-up, the method of generating an appropriate drive signal is shown and results of an example are presented. The achieved results are used to perform seismic tests within the research project Kerkhof (2015). Within this project the presented results were later linearly scaled to achieve higher seismic loads. Based on the results of the presented example a theoretical maximum scaling of factor 7.3 is possible, as the limits of the drive signal are +/- 10 V (compare Figure 9). To keep the presented seismic characteristics during seismic loading using a scaled drive signal, linear behaviour of the mock-up to a certain degree is essential, otherwise adaptions of the drive signal with respect to changed mock-up behaviour could become necessary. Based on the earthquake loading at the assumed installation location, the 100 % DBE tests or even higher loads did not lead to any stability issues of the examined mock-up.

ACKNOWLEDGEMENTS

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