CALIBRATION OF ULTRASONIC TRANSDUCERS - A COMPARATIVE STUDY OF DIFFERENT METHODS

KALIBRIERUNG VON ULTRASCHALL-AUFNEHMERN - EINE VERGLEICHENDE STUDIE VERSCHIEDENER VERFAHREN

CALIBRAGE DE DETECTEURS ULTRASONIQUES - UNE ETUDE COMPARATIVE DE METHODES DIFFERENTES

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SUMMARY

Three different techniques for a qualitative calibration of ultrasonic transducers were developed and tested extensively. In contrast to techniques for an absolute calibration, the transducers are tested without coupling to a test mass. In spite of this experimental simplification, the results are very satisfying and sufficient for most applications. Still they provide no basis for a proper deconvolution of ultrasonic and acoustic emission signals. This will be the subject of future work, considering also parameters like the phase information of the signals and the angle of incidence.

ZUSAMMENFASSUNG

Es wurden drei verschiedene Methoden für eine qualitative Kalibrierung von Ultraschall-Aufnehmern entwickelt und in umfangreichen Messungen getestet. Im Gegensatz zu absoluten Kalibriermethoden werden dabei die Aufnehmer nicht an einen Testkörper angekoppelt. Trotz dieser experimentellen Vereinfachung sind die Ergebnisse sehr zufriedenstellend und für die meisten Anwendungen hinreichend. Allerdings ist mit ihnen keine Dekonvolution von Ultraschall- und Schallemissionssignalen möglich. Dies wird das Thema der weiteren Arbeiten sein, wobei auch Parameter wie die Phaseninformation der Signale und ihr Inzidenzwinkel berücksichtigt werden sollen.

RÉSUMÉ

Pour faire un calibrage qualitatif de détecteurs ultrasoniques trois méthodes diverses ont été développées et étudiées. A l'encontre de méthodes de calibrage absolues, les détecteurs ne sont pas couplés à une surface avant le calibrage. En dépit de cette simplification experimentale, les résultats sont très bien et suffisant pour la plupart des applications. Mais il n'est pas encore possible de faire une déconvolution à l'aide de fonctions de transfert déterminées. Ce sera le but des travaux futurs. En plus, le spectre de phase et l'angle d'incidence seront aussi considerés.

KEYWORDS: ultrasonic, transducer, calibration, deconvolution

1. INTRODUCTION

Elastic waves are frequently used for non-destructive evaluation. To detect inhomogenities, faults or to determine elastic parameters, a well-defined signal (e. g. an US-pulse) travelling through a medium is investigated. In contrast to these active methods, acoustic emission technique deals with the problem of extracting source parameters from the time signal. Therefore, it is generally necessary to take into account the influence of the recording system. Especially the transfer function of the recording transducer significantly affects the frequency content of an US-signal. Only an ideal sensor would have no influence on the signal owing to a linear characteristic over a wide frequency range. The present paper covers the calibration of piezoelectric transducers in terms of the frequency and the phase response function. With these functions it is possible to extract the influence of the recording transducer completely by applying deconvolution techniques [BUTTKUS, 1991].

The detection of acoustic emission signals with low displacements at high frequencies requires transducers with a high sensitivity in a wide frequency range above the acoustic limits. Unfortunately, this can actually be achieved only using piezoelectric transducers used in resonance. To enlarge the range of increased sensitivity, so called *sandwich-transducers* are used. In this case the calibration of transducers is a serious problem due to the existence of several resonance peaks in the spectrum and the according zero points.

Some other problems arise:

- The sensitivity of a sensor is a function of the angle of incidence and sometimes of the azimuth.
- It cannot be described as a point receiver with respect to the most types of signals. Thus, the transducers always average the signals under their coupled area.
- Sensors subjected to shocks and changes in temperature may change their response functions.
- There is the question whether coupling the transducer to a surface is the appropriate set-up. On the one hand, this corresponds to the situation in reality. On the other hand, it is difficult to eliminate the influence the material when evaluating the spectra. The response of this system is not necessarily the same as that of a single transducer, especially when the mass of the sensor cannot be neglected to that of the specimen.

In all references found about calibration, the transducers are attached to the surface of a test block. Usually steel is used as material. Then, for step-force calibration, the surface displacement caused by a step-function force due to a lead pencil break [Miller et al., 1987] or due to breaking a glass capillary [ASTM E1106-86, 1986] is measured. Another possibility is the reciprocity calibration [DGZfP-SE2, 1992], where a stress pulse is generated by an identical transducer acting as a source. All methods have in common, that the transfer function or Green's function of the medium between source location and transducer location has to be known. This requires extensive calculations and a deconvolution of the signals. Nevertheless, it is not possible to compare calibrations carried out at different block materials with different mechanical impedances [Miller et al., 1987]. Moreover, a time window has to be set when recording the signal in order to cut reflections from the test block walls. This leads to a reduced resolution of the calibration curve and a lack of information at low frequencies.

However, for most of the ultrasonic and acoustic emission techniques it is neither feasable nor necessary to deal with all these fundamental problems. As a first approach to the problem, the results of different methods were investigated simply evaluating the frequency and the phase response of a piezoelectric transducer.

2. EXPERIMENTAL

In the present work, three different approaches were made to measure the transfer function of ultrasonic transducers. To avoid the disadvantages and problems stated above, the transducers were not mounted on any object. Thus, no absolute calibration in terms of voltage output per velocity or acceleration unit could be made. In spite of that, the procedures are a good compromise as far as accuracy and complexity of test system are concerned. For all the tests, the transducers are excited by a driving current and work as source, hence have to be reversible. This current can be a frequency sweep or a short pulse. Either a laser vibrometer or an identical transducer were used for measuring the vibrations of the transducer to be tested. A typical scheme for the calibration is shown in fig. 1.

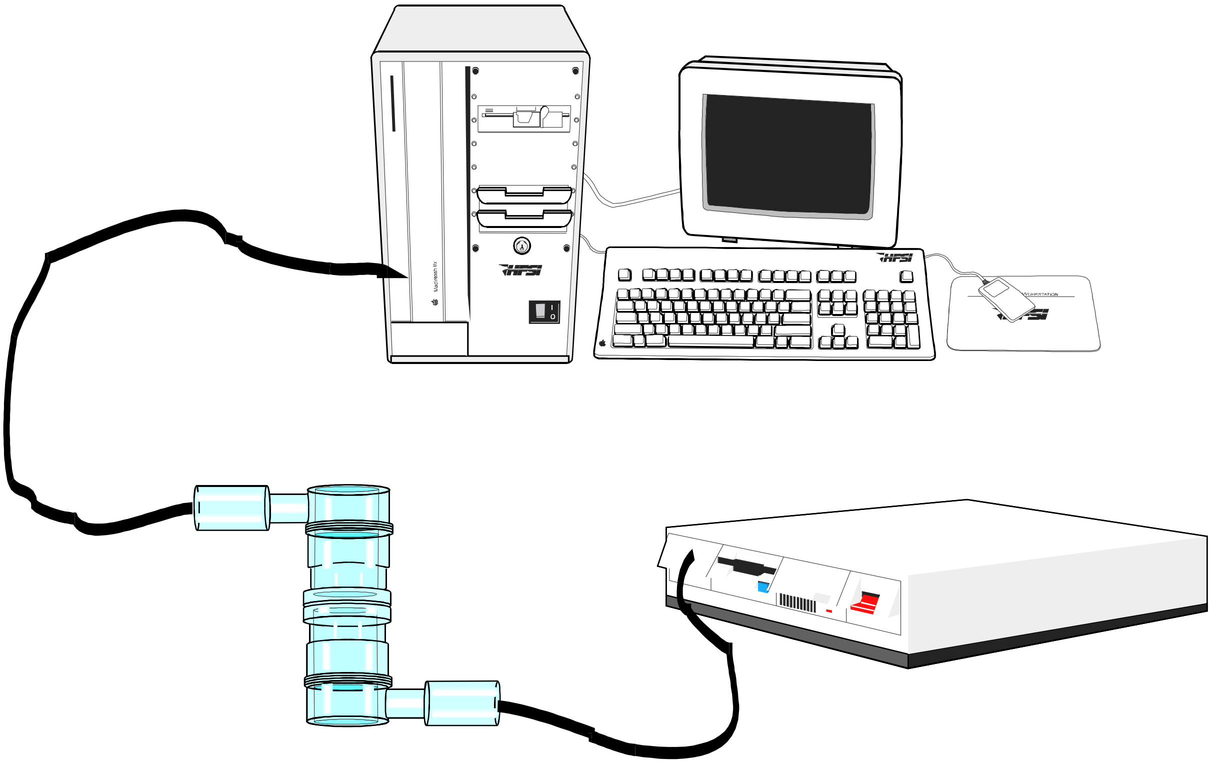

Fig. 1: *Calibration scheme for the reciprocity technique*

This figure refers to the method called *reciprocity technique*. A source-transducer is excited by a short electric pulse generated by a waveform generator. The mechanical pulse-response is detected by an identical receiver-transducer. A personal computer with an ADC-plug-in board converts the electric signal that is subsequently transformed into frequency domain. For the *laser-pulse technique*, the receiver-transducer is simply replaced by a laser-vibrometer for signal detection. Another method tested was the *laser-sweep technique*, where the driving current is a frequency sweep. The frequency of the harmonic waveform was sweeped slowly enough, enabling the transducer to follow the changes. A login-amplifier was used to amplify the signal detected by the vibrometer and to gain a better signal-to-noise ratio. In contrast to the piezoelectric transducers that measure accelerations, the laser vibrometer measures velocities. All three techniques were applied for a first test to the standard broadband transducer used at the FMPA for acoustic emission. In the following sections, the time and frequency functions of the transducer driving current as well as the achived sensitivities are presented for each technique.

2.1 Reciprocity technique

Due to the high sensitivity of the detecting piezoelectric transducer, the input current was limited to 5 V. At this range, it was possible to generate pulses with a duration of approximately 300 ns. The frequency content of this pulse is almost constant in the range of up to 1 MHz. The resolution of this technique is limited by the sampling time of 6 ms at a sampling rate of 10 MHz, according to a resolution of 160 Hz at a range of up to 5 MHz

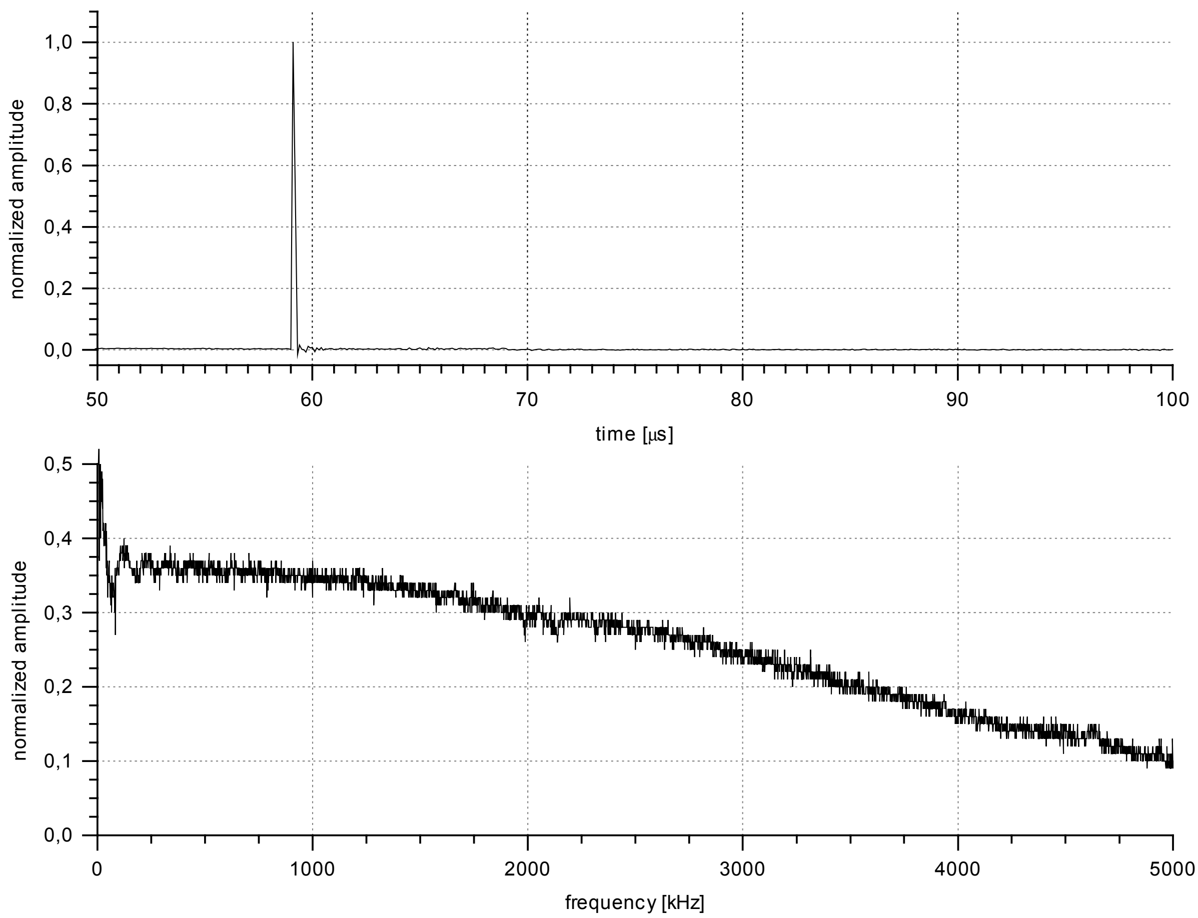

Fig. 2: *Driving current input for the reciprocity technique, time domain (top), frequency domain (bottom)*

2.2 Laser-pulse technique

In contrast to piezoelectric transducers, the sensitivity of a laser vibrometer for detecting displacements is rather poor. Hence, the source transducer had to be excited at a current of approximately 2000 V for getting displacements with a detectable magnitude. This was only possible with a rather long pulse of 7,6 µs duration. Thus, the frequency content becomes very weak above 250 kHz. In this case, the A-D conversion was oversampled with 6 ms at 5 MHz according to a resolution of 160 Hz between 0 and 2,5 MHz

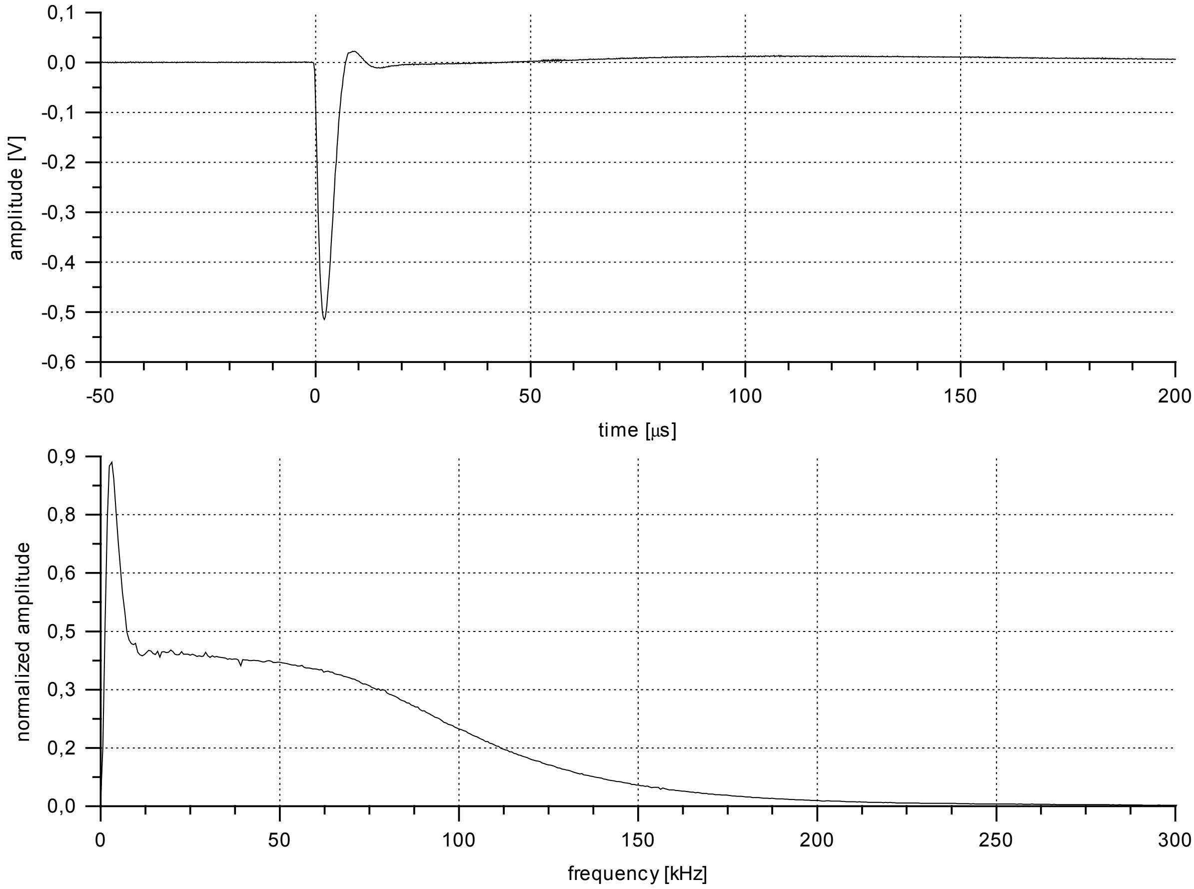

Fig. 3: *Driving current input for the laser-pulse technique, time domain (top), frequency domain (bottom)*

2.3 Laser-sweep technique

The laser-vibrometer in combination with the frequency-selective amplification of the login-amplifier provides an excellent sensitivity. That is why it was possible to run the waveform generator at a voltage of 5 V. Unfortunately, the current was not stable, but varied between 6 V and 3,5 V. The following figure shows the interpolation of some values that were read from a voltmeter.

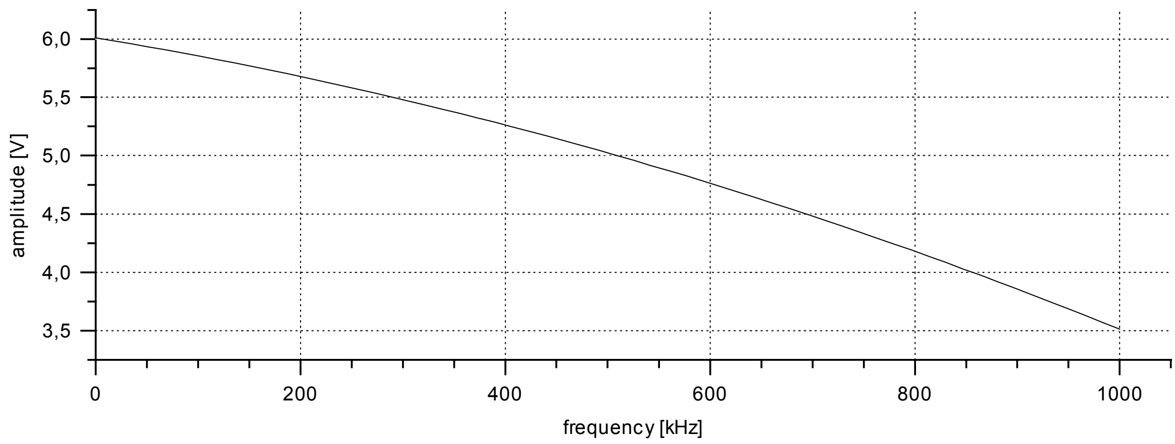

Fig. 4: *Driving current input for the laser-sweep technique, interpolated*

Other than for the previous techniques, the resolution is only limited by the number of measurements made within the frequency range in question. It was decided to make 4000 measurements in the range of 1 kHz to 1 MHz, according to a resolution of 250 Hz.

3. RESULTS

The spectra presented in the following sections are not deconvolved with respect to the input functions. This is subject of the discussion.

3.1 Reciprocity technique

Extensive tests were carried out applying the reciprocity technique. First, the spectra obtained with one receiver-transducer and different source-transducers were averaged in order to limit errors. But it turned out that the response spectrum does not depend considerably on the source-transducer. Thus, one transducer was used as reference source. Figure 5 shows the amplitude response functions of different transducers of one series using this reference transducer.

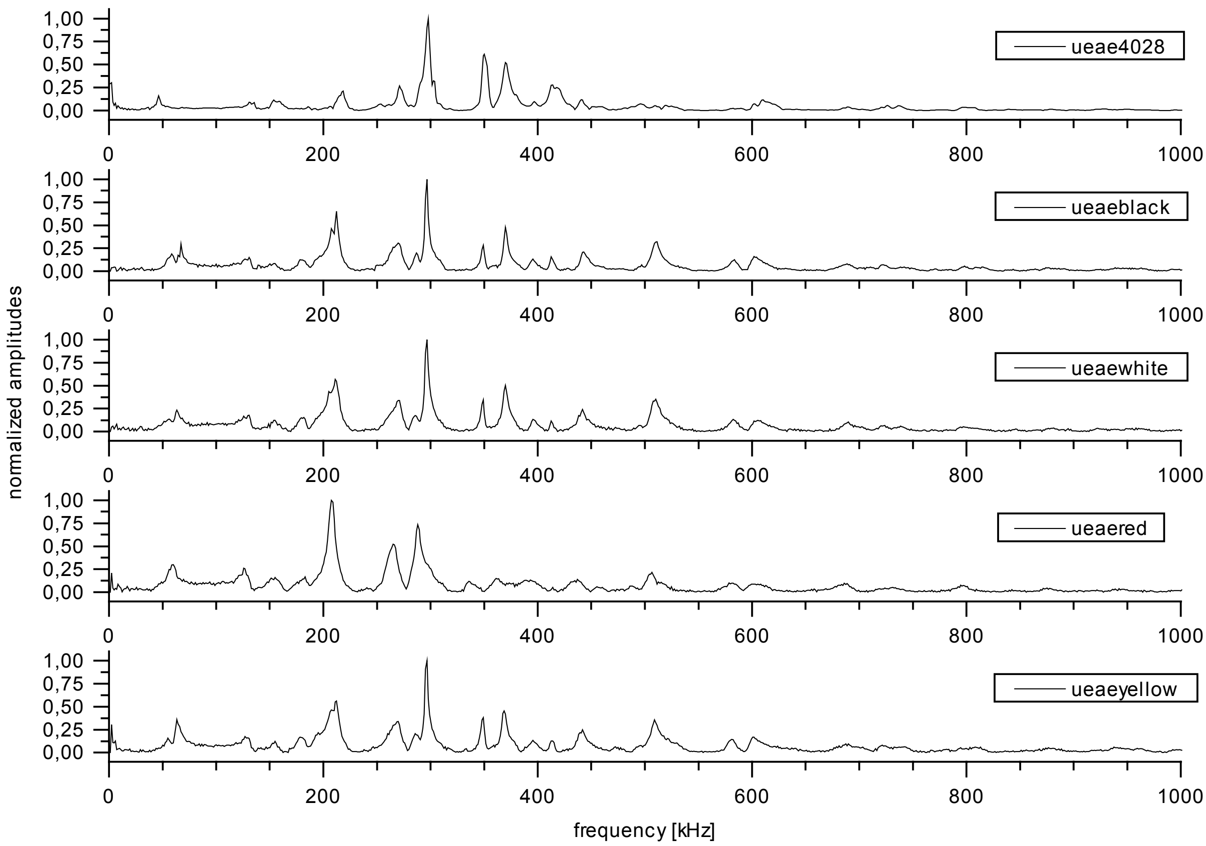

Fig. 5: *Reciprocity pulse response functions of different transducers of one type (UEAE)*

3.2 Laser-pulse technique

The vibrometer was working at two different sensitivities, and different low-pass filters were available. Tests with different combinations of these features are shown in figure 6. The tested transducer was the same as the first one of figure 5.

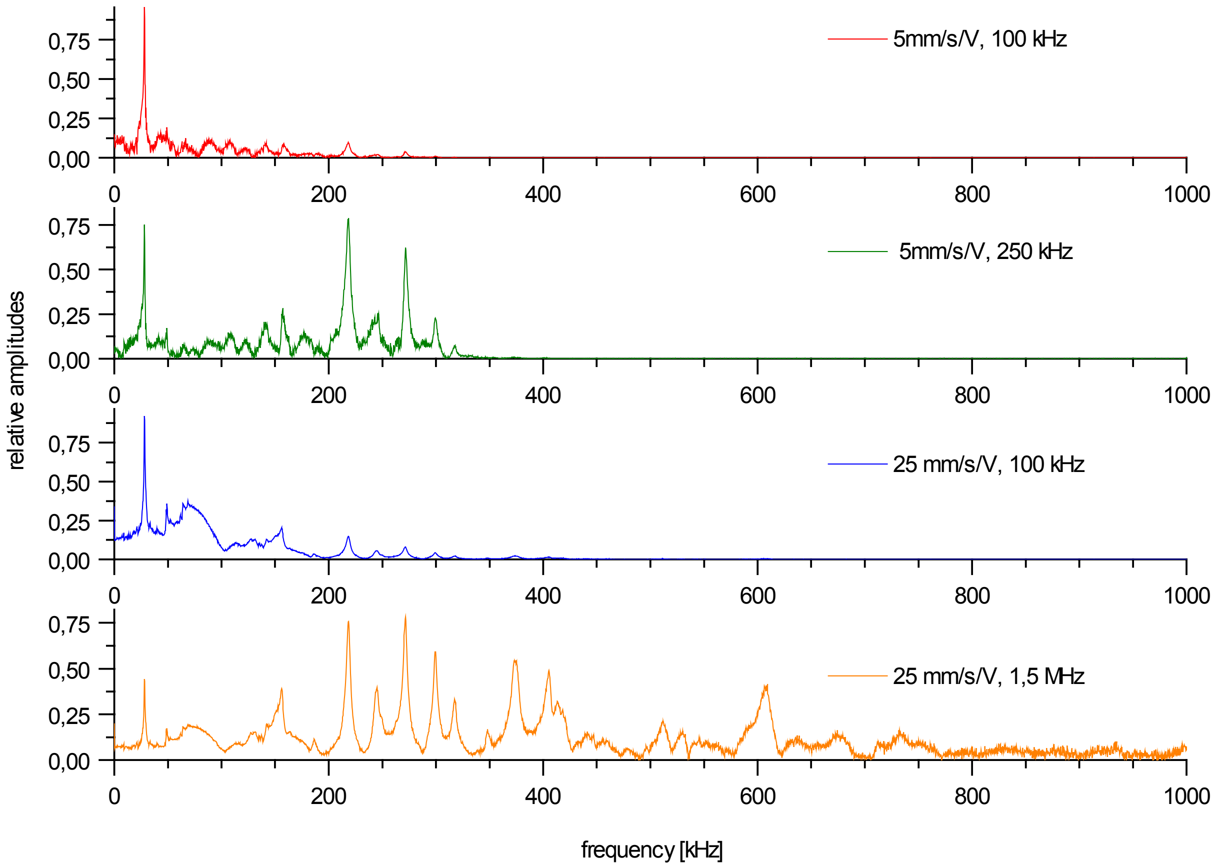

Fig. 6: *Pulse response function of one transducer (UEAE 4028) at different sensitivities and using different filters of the vibrometer*

The influence of the filters can easily be realize in the first and third spectrum. Although the frequency content of the input pulse is very poor above 250 kHz (figure 3), the fourth spectrum exhibits distinct peaks in this range. However, the electronic noise becomes predominant at higher frequencies.

3.3 Laser-sweep technique

Applying this technique to the same transducer (UEAE 4028), also the phase spectrum can be evaluated (figure 7).

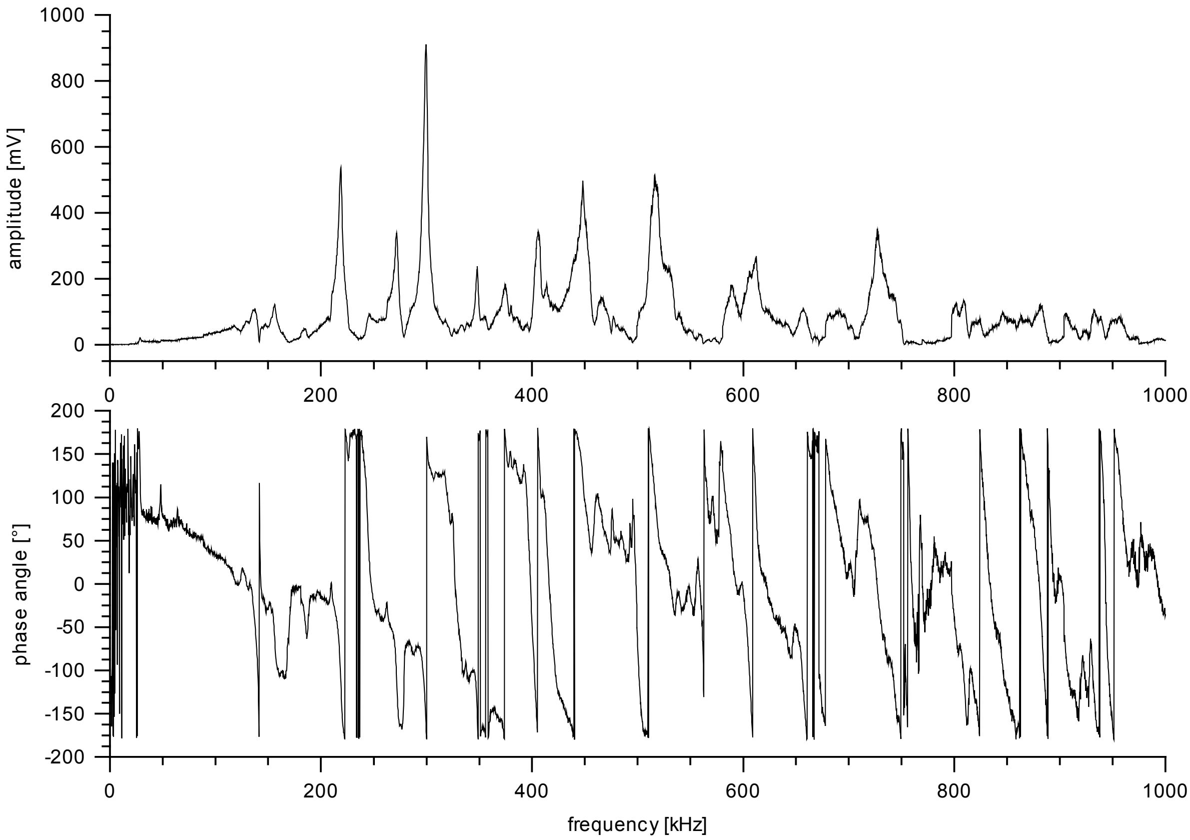

Fig. 7: *Amplitude (top) and phase (bottom) transfer function of transducer UEAE 4028 applying the laser-sweep technique*

Finally, a direct comparison was made between the three different techniques: laser-pulse technique at 25 mm/s/V filtered above 1,5 MHz, laser-sweep technique and reciprocity technique. The spectra for transducer UEAE 4028 are shown in figure 8. Except for frequencies of below 100 kHz, the spectra are in good agreement. Measurements at other types of transducers confirm these facts.

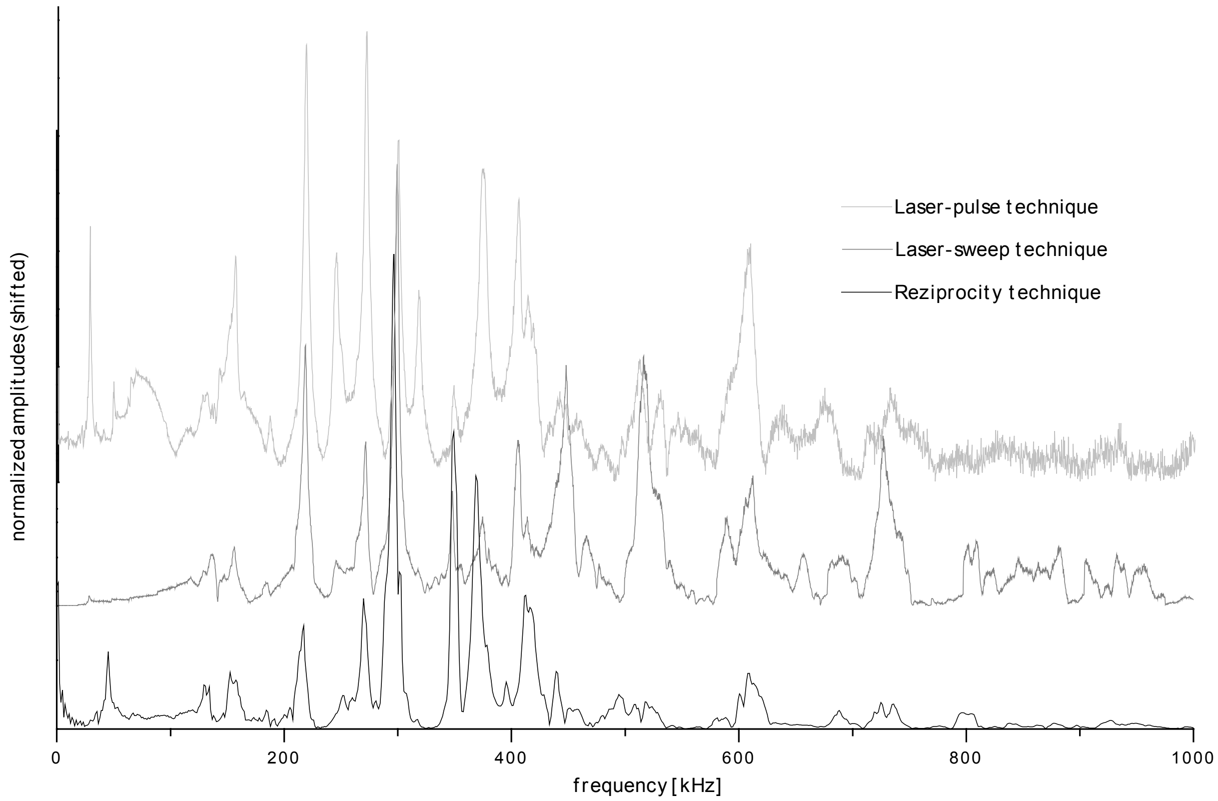

Fig. 8: *Comparison of the three different techniques*

5. DISCUSSION AND CONCLUSIONS

As expected, the frequency response function of the standard piezoelectric transducer used by the FMPA consists of a series of resonance peaks in the frequency range between 10 and 800 kHz. Therefore, the receiver shows a significant higher sensitivity than transducers developed, for instance, for modal analysis, but it exhibits also a remarkable non-linearity. Comparing the results of the frequency calibration achieved with three different methods, it becomes obvious that the peaks of the resonance's are more or less at the same frequencies irrespective of the stimulation or the recording method. In addition, the variation of the calibration curves for different transducers of the same series is in the limits of the measuring accuracy - the possibility of slight differences due to the manufacturing process cannot be excluded.

However, these very satisfying results have to be discussed by considering a couple of simplifications and uncertainties. The needle-shaped pulse as well as the frequency sweep that were used as input function are not at all comparable to the transient waves recorded by the sensor in practice. Moreover, in ultrasonic or acoustic emission tests the transducer is coupled to the surface of the specimen using a coupling agent and connected via cables to a preamplifier and then to a recording device. Hence, the measured signals have to be interpreted as a convolution of the mechanical and electrical properties of all these materials and instruments. Yet, the influence of every single part of this system is not completely understood.

As described the frequency and the phase response function of a transducer has to be well-known to extract the material or source parameters. For this reason, the evaluation of phase spectra is subject of future research. Moreover, the operation of piezoelectric sensors in resonance is assumed to cause nonlinearities which will rule out the application of deconvolution techniques. If there is no possibility to quantify the effects of coupling and nonlinearities, a proper elimination of the receiver characteristics will not be achieved.

6. CONCLUSIONS AND PROSPECTS

The frequency response functions of the FMPA standard transducers were investigated using different methods and a simplified approach. According to our experience in non-destructive evaluation of materials using piezoelectric transducers, the presented techniques provide a good tool for a smart but qualitative calibration of ultrasonic sensors. Nevertheless, a quantitative evaluation is required as basis for the application of the deconvolution technique. The physical effect of coupling the transducer to a surface as well as the nonlinearities connected with the resonance frequencies in the spectrum have to be understood. Last but not least the phase response of the system has to be investigated.

A problem closely connected to the discussed matter is the variation of the sensitivity of a transducer changing the incidence angle of a pulse. This is a subject of current research at the FMPA, using an aluminium half-cylinder for angle variation.

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