Physikalisch-Technische Bundesanstalt

Short Report for CCAUV, June 2012

1. Organisation

PTB is the National Metrology Institute of Germany and the highest technical authority for the field of metrology and certain sectors of safety. PTB comes under the auspices of the Federal Ministry of Economics and Technology. PTB has several fundamental tasks for example to realise and maintain the legal units in compliance with the International System of Units (SI) and to disseminate them. Another task is type approval and calibration of devices that are covered by national or international regulations. In addition PTB is active in many basic and applied research fields and included into the European metrology research program (EMRP).

The PTB work in acoustics and vibration is done in two departments. The department "Acoustics and Dynamics" combines the activities in applied acoustics, vibration, dynamic force and dynamic torque. Microphone calibration, audiometry, ear simulator tasks, and sound level meter type approval as well as ultrasound are carried out in the department „Sound".

2. Activities in acoustics, ultrasound and vibration at PTB

PTB is active in a variety of fields in acoustics, ultrasound and vibration. One of the main duties and responsibilities is the realization and maintenance of units, and several calibration and standard measurement set-ups are available:

- pressure reciprocity calibration of laboratory standard microphones between 2 Hz and 25 kHz
- free-field calibration of microphones between 25 Hz and 20 kHz
- measurement of ultrasound power between 5 mW and 300 W
- calibration of hydrophones in amplitude and phase between 400 kHz and 60 MHz
- primary calibration of accelerometers with sinusoidal excitation in the range of 0.4 Hz to 20 kHz and 0.01 m/s² to 100 m/s² in both, magnitude and phase of the complex sensitivity coefficient
- primary calibration of accelerometers with shock shaped excitation in the range of 50 m/s² to 100 km/s²
- primary calibration of angular accelerometers with sinusoidal excitation in the range from 0.4 Hz to 1.6 kHz and 1 rad/s² to 1400 rad/s²
- primary calibration of laser-vibrometers with sinusoidal excitation

Another important task concerns legal metrology issues. PTB is responsible for a number of type approvals and safety investigations:

- type approval and calibration of sound level meters
- type approval and calibration of sound calibrators and pistonphones
- calibration and testing of mechanical couplers

- testing of acoustic couplers and ear simulators
- testing of free-field and diffuse field environments
- supervision of building acoustic test facilities
- testing of ISO tapping machines and loudspeakers for building acoustics
- free-field and diffuse field calibration of reference sound sources.

Scientific research plays an important role at PTB, and many ideas and projects are currently under consideration. The maintenance, improvement, and the extension of calibration capabilities attract constant attention, for example by the use of broad-band signals for the testing of directional response of sound level meters or the complete modernisation of primary ultrasound pressure standard which is represented by an interferometer. New measurement techniques for high-intensity ultrasound fields were investigated and developed within national and international research collaborations. This includes the development of new sensors which were transferred into industrial use via a technology transfer procedure. The development of cavitation indicator measurement methods for technical ultrasound applications was successfully finished.

PTB is increasingly active in the improvement of accuracy and reliability of objective audiometry which is coming more and more into clinical practise, in particular for the screening of newborns. A currently running national research project deals with the improvement of calibration techniques for otoacoustic emission audiometry.

The two acoustic departments are strongly engaged in the EMRP-program. Three projects are currently running or in the starting position and two are coordinated by PTB staff members. The topics come from the complete AUV region: the first covers the traceable dynamic measurement of mechanical quantities like force, torque or pressure and relies heavily on the developments in field of vibration metrology. The second deal with the measurement and assessment of non-audible sound and the development of a universal ear simulator and the third develops a dose concept for therapeutic ultrasound.

A major task in applied acoustics is the uncertainty determination of different quantities like sound power levels, airborne sound insulation or impact noise levels. These activities are based on the compilation of many round robin data. The results will be used in international and national standardisation. Further current research topics in applied acoustics are the development of a standard for airborne sound power, the qualification of highly absorbing measurement chambers, the development of a test method for walking noise and the measurement and prediction of installation noise in buildings.

3. Current status of standards

PTB operates a couple of acoustic and vibration standards in agreement with international regulations. Many of them are included in the appendix C of the Mutual Recognition Arrangement as CMC entries and can be found in the on-line database. Other special services that are also covered by a quality management system following ISO/IEC 17025 were offered to meet requirements of our customers. A summary list of all services can be found on the web site of PTB (www.ptb.de). Here only several quite new aspects will be highlighted.

3.1 Broadband measuring station for the extended testing of the directional response pattern of sound level meters and the calibration of measuring microphones

One of the numerous tests performed for type approvals is the directional response pattern test in which the tested object has to show that sound coming from all possible directions of incidence is equally evaluated. It is common practice to use sinusoidal sound signals as an excitation signal to reach the low measurement uncertainties required for the testing of the directional response pattern of sound level meters and for the calibration of measuring microphones. By using broadband signals, it has now become possible to reduce the time needed for a measurement, to considerably increase the spectral resolution and to facilitate the identification of distorting reflections. Instead of performing 30 to 40 individual measurements over several hours for just as many frequencies, the determination of a spectrum with 800 or more frequency lines only takes a few minutes. In addition, the reproducibility of the measurement is improved so that the corresponding contribution to the measurement uncertainty turned out to be much lower than when using the time-consuming sinusoidal sound signal method. Although various hypotheses are necessary in the broadband method which bring about additional contributions to the measurement uncertainty, the low total uncertainty can be maintained in the case of microphone calibration and even be reduced to some extent in the case of SLM directional response pattern testing.

3.2 Characterization of high intensity focused ultrasound (HIFU) fields using a broadband membrane hydrophone and numerical modeling

The acoustic output characterization of medical ultrasound devices is important in terms of quality assurance and the safety of the patients. The measurements are usually performed in water using hydrophones to determine local pressure and intensity parameters. However, hydrophone measurements are difficult in the case of HIFU fields used, for instance, for tumor ablation. At the high intensity levels, the combined effects of nonlinearity and diffraction lead to the generation of higher harmonics in the wave spectrum and the formation of asymmetrically distorted waveforms with steep shock fronts. Direct measurements of such high amplitude waves thus require a hydrophone that is robust to mechanical damage, has a large bandwidth to capture the sharp shock fronts and a small diameter to accurately describe the small focal beam profiles. As an alternative to the hydrophone-based technique, numerical modeling can be used to predict ultrasound fields from medical devices.

The measurement possibilities of HIFU fields using particularly broadband membrane hydrophones developed at PTB have now been demonstrated. Waveforms with fundamental frequencies of about 1 MHz and 3.3 MHz were measured. The peak rarefactional and peak compressional pressures detected so far were 13 MPa and 56 MPa, respectively. For comparison, the nonlinear propagation of HIFU fields in water was described using the Khokhlov-Zabolotskaya-Kuznetsov (KZK) nonlinear parabolic equation. It was solved numerically with the boundary conditions given at the source for a focused beam with an initial harmonic waveform and uniform pressure distribution. The results of the nonlinear sound field modeling and the experimental results show good agreement. The numerical modeling performed has proven to be an effective method for the characterization of HIFU transducers. The experiments show both the favorable applicability of the hydrophones for HIFU field characterization in principle, as well as the technical limitations seen so far.

4. Research areas

PTB is active in a wide range of research activities summarised in the annual reports that can be found at the PTB web site (www.ptb.de). In the field of acoustics some projects should be highlighted:

4.1 First steps towards a quantitative characterization of ultrasonic cleaning vessels

Ultrasonic baths are widely used in industry, in manufacturing and in the domestic field. The construction of an instrument for a specific application has to this date, however, been based on long test series and on individual empirical values of the manufacturers. The reason for this is that the underlying physical effect – cavitation – is, by nature, highly stochastic and depends on a whole series of ambient parameters. PTB has now succeeded in bringing some order into the chaos.
Ultrasound is used for the most diverse applications in medicine and technology. In liquid media, these are often based on cavitation processes. Due to the stochastic nature and the many influence parameters, it is extremely difficult to check, to control and to optimise all application processes. This hinders especially the manufacturers – who are usually small- and medium-sized companies – from developing and designing ultrasonic baths for the broad range of application possibilities. To overcome this problem, a project tried to improve the quantitative description of the phenomena occurring in ultrasonic baths of the small and the medium performance classes with the aid of simple measurements of physical quantities.
The most essential approach hereby was the measurement of the sound field quantities. The objective of this project was to develop this approach further and to complement it with new measurement techniques by which the cavitation effects can be determined. For this purpose, different model processes were investigated and suitable indicators for cavitation were developed – among these, indicators for the erosion, for the chemical effect and for sonoluminescence. The indicators serve to describe possible applications quantitatively, that is to determine the actual effect. For this purpose, the relationships of the indicators among each other were investigated and their dependence on the operating parameters was determined. An essential element of this was multivariate data analysis. By means of a factor analysis, statistical analyses were carried out and a general procedure was developed by which indicators – or other output quantities of a cavitation process – can be described as a function of easily measurable input quantities.

4.2 A new way to elicit otoacoustic emissions

The human ear is not a passive sensory organ: If a healthy ear is stimulated by two pure tones that are a musical minor third apart, it responds by producing the fundamental of the major triad. This inaudible tone which originates from the inner ear is called a distortion product otoacoustic emission, or simply a "DPOAE", and can be both elicited and recorded by a small probe inserted into the ear canal. Conventionally, the two miniature loudspeakers in the ear canal probe are used to elicit DPOAEs. In an innovative study, we investigated a combined stimulation of otoacoustic emissions, with one tone presented as is usual by a miniature loudspeaker and the other applied by a bone vibrator placed on the cranial bone of the test person. This combined stimulation yielded detectable DPOAEs.
In our study, DPOAEs were stimulated by air and bone conduction in a combined procedure, which has not been performed before. The f_1 tone was presented by one of the probe loudspeakers and the f_2 tone by means of a bone vibrator placed behind

the same ear of the test person. The first tone (f_1 via air conduction) travels through the ear canal and the middle-ear chain towards the inner ear. On the other hand, the second tone (f_2 via bone conduction) reaches the inner ear directly and is not affected by the calibration errors which arise in the ear canal.
With the combined stimulation of DPOAEs, it is possible to present the pure tones via the alternative acoustic pathway (bone and air conduction, respectively) and to repeat the measurement with the same position of the probe. This provides a simple way to assess the effective stimulus levels in the inner ear. The presence of a DPOAE in one configuration and its absence in the other (after swapping the signal delivery pathways) does not indicate a pathologic inner ear but is rather evidence of an unfavourable adjustment between the stimulus levels. This caused the suppression of the DPOAE despite a healthy inner ear.

4.3 Monitoring of the formation of lesions in HIFU treatments on the basis of radiated shear waves

HIFU is mainly used to destroy tumour tissue, but increasingly its use is being studied for fields of application in neurology, too. By locally heating up an area by means of HIFU, tissue is necrotised in a clearly delimited area (ellipsoid). Besides the temperature increase, also cavitation and boiling bubbles can occur which also contribute to the formation of lesions. In the occurrence of such bubbles, the ultrasound is reflected by them and the area lying beneath the bubbles is shielded. This leads to a shift of the treatment zone – i.e. a "migration" of the focus towards the HIFU transducer. Furthermore, the ellipsoidal lesion assumes a shape resembling a tadpole. This irregularity must be detected early to avoid uncontrolled necrotisation due to shifting and deformation. When the HIFU is switched on, the tissue is shifted away from the HIFU transducer due to the acoustic radiation force. The tissue relaxes again as soon as the HIFU is switched off. In both cases, a shear wave radiates into the neighbouring tissue. It was recently shown that the denaturation of proteins is clearly reflected by a change in the elasticity of the tissue. Since the deflection – and, thus, the magnitude of the shear waves – depends on the elasticity of the treated and of the neighbouring tissues, a change in the radiated shear wave in the course of the necrotisation process is also to be expected.
In ex vivo measurements on porcine tissue, lesions were induced by means of a HIFU transducer. Thereby, the HIFU exposure (8 kW/cm²) was periodically intermitted for 4 ms each time, so that the interrupted radiation force caused a shear wave. During this relaxation time of the tissue, high-frequency echo signals (A-scans) were recorded by a single-element transducer at a distance of 5 mm from the HIFU focus (pulse repetition frequency: 8 kHz). Using a correlation procedure, the displacement of the tissue was determined from the successive A-scans.
If the tissue displacement is plotted over time and tissue depth, it is possible to represent the shear wave which passes through the area of the A-scan. Based on this, the magnitude of the shear wave in different tissue depths and the corresponding propagation times in the course of the lesion formation were analysed. It was demonstrated that a focus shift leads to a decrease of the shear wave magnitude in deeper tissue areas. A deformation of the lesion is accompanied by considerable changes of both, the magnitude and the propagation time of the shear wave. These results prove that it is possible to obtain information on the formation of lesions from the radiated shear waves. Since this method can be realised with minimum equipment, it is a good alternative to real-time monitoring.

4.4 Characterisation of measuring amplifiers

Within the EMRP project IND09 "traceable dynamic measurement of mechanical quantities" one issue addressed is the dynamic characterisation of conditioning amplifiers, namely charge, ICP and bridge amplifiers. The goal is to derive a parametric model, which describes the transfer function of the respective amplifier over a large frequency range in terms of a digital filter design, including the consistent handling of uncertainties.
With respect to charge amplifiers (CA) a new model of the dependence of the CA to its source impedance has been developed, and methods to model the CA as a sequence of parametric high-pass and low-pass filter have been successfully tested. The latter was done in cooperation with a guest scientist from the Japanese NMIJ.
The results will be published during the IMEKO World Congress 2012.

4.5 Calibration of Impulse Hammers

In the area of shock force calibration a new device for the calibration of impulse hammers has set-up. The device comprises an airborne horizontally aligned 8 kg stainless steel cylinder, with an accelerometer mounted on its back side. The front side could than be hit by the DUT, i.e. the impulse hammer. The force generated by the impact of the hammer tip is calculated as product of mass times acceleration, where the first is known from calibration of the mass body (weighting) and the latter is traceable to primary standards by a primary calibration of the mounted accelerometer according to ISO 16063 parts 11 and 13.
This device is still currently under validation.

4.6 Proposal for single number descriptors in building acoustics

The insulation of airborne sound depends strongly on frequency. To communicate and declare product properties and to predict sound insulations, quantities are needed which describe the airborne sound insulation as one number. The necessary rating of sound insulation spectra is described in ISO 717 which is now being revised under the auspices of PTB. Originally, only frequencies between 100 Hz and 3.15 kHz were considered. Some current investigations show that an extension to frequencies between 50 Hz and 5 kHz increases the correlation between the single number descriptor and the subjective response significantly. Before the frequency range could be extended it had to be clarified how the uncertainties of the single number values will be affected. A comprehensive data base with interlaboratory test results is available at PTB which could be used to investigate this. It turns out that the uncertainties remain largely unchanged by extending the frequency range. Thus, the extension of the frequency range has been proposed by PTB which is discussed now among national and international experts.