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The development of a shock-tube based characterization technique for air-coupled ultrasonic probes

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ABSTRACT

The present paper proposes a new characterization technique for air-coupled ultrasound probes. The technique is based on a shock tube to generate a controlled pressure wave to calibrate transducers within their operating frequency range. The aim is to generate a high frequency pressure wave (at least up to 200 kHz) with the low energy levels typical of commonly used air-coupled ultrasound probes. A dedicated shock-tube has been designed and tested to assess calibration performances. The sensor transfer function has been measured by using a pressure transducer as reference.

1. Introduction

Non-contact ultrasound (air-coupled) probes offer many advantages, such as high installation flexibility and no need of coupling fluids, which is why the industrial interest for this NDT technique has increased over the last years in several fields [1–6], particularly where porous materials like wood [7,8], ceramics [9–12], concrete [13,14] and composite materials, [15] also on sandwich panels [16], need to be inspected. In conventional ultrasound systems either a coupling medium like gel, oil or water must be used between probes and samples or both probes and samples must be immersed in water. However, when investigating porous material (e.g. green ceramics) this coupling could be a problem, because it could damage the sample inspected. Other limitations of contact methods may be represented by the use in automated inspection systems and by the problems of removing the coupling fluids especially for delicate surfaces (e.g. art works [17,18]). However, a major issue for non-contact probes is the large difference of acoustic impedance between air and the material to be inspected. This causes most of the energy to be reflected at the interface between the two media and thus the energy transmitted is very small. A quantitative characterization of these phenomena is therefore of paramount importance for assessing the feasibility of such non-contact inspections on specific components and choosing the best probes to use. In particular, from the knowledge of the pressure field generated by a certain ultrasound probe and the combination of this information with numerical models and simulations, it is possible to assess the suitability of a probe for a specific application, as demonstrated also in [19]. In addition, in many cases different probes and materials are used to improve performances. The main objective of the work presented in this paper is to develop a method for the calibration of ultrasound probes providing quantitative information on the generated pressure levels. Different methods for the characterization of air-coupled ultrasound probes have been presented in the literature, which follow two main approaches.

The first one is based on the measurement of efficiency (defined as $20\log_{10}(V_{\text{reception}}/V_{\text{excitation}})$ [20], where $V_{\text{reception}}$ and $V_{\text{excitation}}$ are the voltage measured and the excitation voltage respectively acquired in reference conditions). This method provides an important overall parameter, but it is not suitable to separately assess the performance of the electrical part and that of the mechanical part.

The second approach for ultrasound transducer characterization is based on 3D pressure field reconstruction. Several methods have been developed for this purpose. The most simple one is based on pinhole measurement [21], but this method is quite limited since only a qualitative evaluation can be done, because of the conversion factor needed to derive the pressure, which is usually not available, and the pinhole itself, which may be intrusive for the beam (creating harmonic distortions and secondary echoes). Other quantitative methods are based on the use of a balance for measuring the radiation force [22–25], but they are usually used for

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waveform propagation in water, where the pressure values are higher. The uncertainty in the direct measurement by balance in water is in the order of 7% and even higher in air (expected below 20%) due to the low pressure generated by air coupled ultrasound transducers.

An interesting method is based on the measurement by laser vibrometry of the effect of the acoustic pressure field created by the emitter on a thin membrane. Once the emitted acoustic field is known, it is used to calibrate the receiver [26]. This method is suitable for quantitative calibration, however it uses a model to derive the calibration results, therefore it is not traceable and may have some (not specified) degrees of uncertainty, and it requires the use of a high-frequency laser vibrometer, which is a very expensive instrument for everyday use.

Another technique is tomography reconstruction based on laser interferometry measurements [27,28]. Laser interferometry measures the density gradient generated by the pressure field and has been used for the specific characterization of ultrasonic probes with high resolution e.g. in [29]. Another powerful method is based on the use of laser Doppler vibrometry techniques with high frequency demodulation systems (20 MHz). Once the vibration is measured directly on the active surface of the transducer, it is possible to reconstruct the pressure field by finite or boundary element models. In the works by Benny and Hayward et al. [30,31] such techniques were applied to piezoelectric composites, piezoelectric polymers and electrostatic transducers in order to qualitatively estimate the acoustic beam field. In [21] the method was extended to perform a quantitative characterization from a metrological point of view, showing also how this result can be used to predict transducer transfer functions.

A widely used (e.g. for the characterization of microphones up to 100 kHz) and standardized method is free-field reciprocity calibration [32]. The reciprocity method has also been extended to ultrasonic transducers that operate in air at frequencies above 100 kHz, but in these ranges the calibration expression must be corrected by taking into account diffraction, diameter of transducer, attenuation, etc. [33,34]. However, these corrections may be complicated and introduce some uncertainties in the calibration procedure.

In conclusion, the methods described in the literature often require extremely complex measurement set-ups, rarely provide direct quantitative measurements, in particular for use in air above 100 kHz. It is therefore extremely important to further develop this evolving metrological sector.

In this paper an innovative characterization method is proposed which uses a dedicated shock tube able to generate an air shock wave and to create a sub-microsecond pressure step necessary to excite the operating frequency range of air-coupled ultrasound transducers. The shock tube technique proposed produces a direct traceable pressure reference and it does not require parameter corrections.

Shock tubes are well-known devices used for many different applications ranging from aerodynamics to gas phase combustion reactions, for which a wide the literature is available. Examples are chemical kinetics studies [35], structure excitation [36] and determination of mechanical properties of materials under dynamic loads [37]. Shock tubes are also commonly used for the dynamic calibration of pressure transducers with fast response [38].

The application proposed requires dedicated developments, as reported in our paper. In fact, usually in calibration a shock tube is used to generate a high-amplitude fast pressure perturbation, whilst in the present case the aim is to generate low-amplitude shock waves with high frequency content in the ultrasonic range. The main topics of the paper are therefore mainly related to:

- Development of a new method for quantitative calibration of air coupled ultrasound probes using a shock tube and a reference pressure probe (Section 2).
- Customization of the shock tube to generate low-amplitude, but high-frequency pressure shock waves (Section 3).
- Development, application and validation of the proposed method (Section 4).

2. Shock tube development

The proposed technique for ultrasound probe characterization consists in generating shock waves (unsteady motion) through a shock tube (Fig. 1). The shock tube is a tube closed at both ends with a diaphragm which separates a region with high pressure gas, on the left (region 4), from a region with low pressure gas, on the right (region 1), as shown in Fig. 1. The gases in regions 1 and 4 can be at different temperatures and can have different molecular weights (in this work the air used in both the chambers was at the same temperature). When the diaphragm bursts (for example, by electric current or mechanical action), a shock wave propagates in region 1 and an expansion wave propagates in region 4, as illustrated in Fig. 1. While the shock wave propagates towards the right at a velocity W, the pressure of the gas behind increases (region 2), generating a motion with velocity u_p. In the high pressure chamber behind the expansion wave the pressure becomes $p_3 = p_2$. The motion field in the shock tube after the burst of the diaphragm is completely determined by the conditions given in regions 1 and 4 before the burst of the diaphragm.

This behavior can be described by the equation given in the literature [39]:

$$\frac{p_4}{p_1} = \frac{p_2}{p_1}\left\{1 - \frac{(\gamma_4 - 1)(a_1/a_4)(p_2/p_1 - 1)}{\sqrt{2\gamma_1[2\gamma_1 + (\gamma_1 + 1)(p_2/p_1 - 1)]}}\right\}^{-\frac{2\gamma_4}{\gamma_4 - 1}} \tag{1}$$

a_1 and a_4 are respectively the sound speeds of gas in the two chambers. γ_1 and γ_4 are respectively the specific gravities of the gas in the two chambers. p_2 is the pressure of the low pressure chamber after the passage of the shock wave.

In the low pressure tube the initial air pressure is atmospheric. The conditions of relative pressure, temperature, density, sound

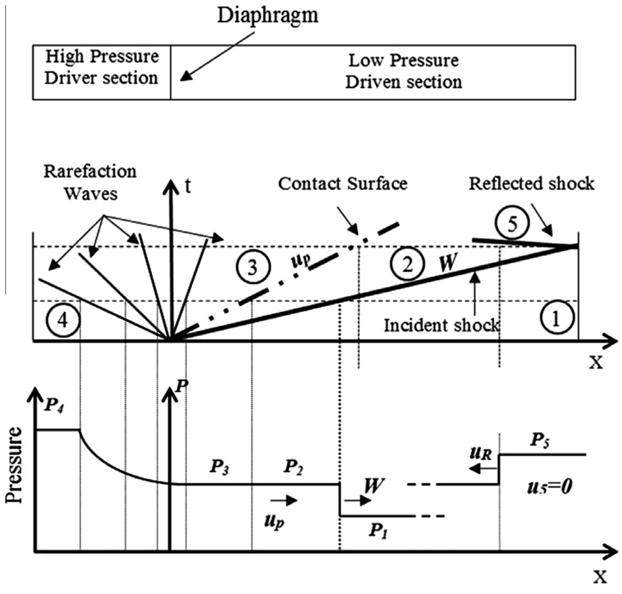

Fig. 1. Flow in a shock tube.