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In situ calibration of acoustic emission transducers by time reversal method

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ABSTRACT

Conventional methods of calibration of acoustic emission transducers require an already calibrated reference transducer and/or special test specimen. Moreover the calibration results are not directly transferrable to practice, since they are dependent on bonding conditions and mechanical properties of the medium. In this paper a reference-free in situ calibration method is proposed. It is based on a combination of time reversed acoustics and reciprocal calibration and allows accurate determination of transducers' frequency responses. The method was developed and successfully experimentally verified assuming that frequency response of used transducers is the same for transmission and reception. Subsequently the analysis was extended considering irreversible transducers and applied to experimental data. Of five tested transducers, three were found reversible and two demonstrated resonance frequency shift in lower frequency region between reception and transmission.

1. Introduction

The primary quality required from acoustic emission (AE) transducers is their sensitivity to dynamic surface displacement. Therefore the majority of transducers is designed as undampened piezoelectric transducers working in relative narrow bands around their dominant resonances. As a consequence, AE transducers exhibit complicated impulse responses which significantly affect their output signal. This is not a problem of AE testing only, since it concerns all applications where either AE transducers, other piezo-transducers or piezo patches are used (e.g., guided waves SHM, nonlinear ultrasonic methods, etc.). Many applications utilize raw signals expressed in arbitrary units without impact to their performance. However, in cases when actual surface displacement needs to be measured, or when results of separate experiments need to be comparable, a transducer calibration is necessary. Furthermore, it is advantageous when physical interpretation of AE events is attempted; also it can improve AE events localization.

Transducer calibration in broader sense can be classified into different levels. The basic calibration consists in determining the frequency response of a transducer; next step is including the evaluation of frequency phase shift (being equivalent to measuring transducer's impulse response); and the ultimate level is the absolute calibration, where electrical output signal is matched to an exact mechanical quantity (displacement, velocity or acceleration). There are different methods of transducer calibration with varying requirements on experimental configuration and instrumentation, which usually follow the demanded level of calibration.

The most straightforward methods of absolute calibration use a calibrated reference transducer, e.g., a capacitive transducer (ASTM E1106) or laser vibrometer [1]. The calibration is then performed by comparing outputs of the tested and the reference transducer. Alternatively, a reference signal can be obtained by numerical simulations [2]. These methods utilize standardized broadband sources like capillary or pencil-lead break, ball impact, electric spark, etc. Another method requiring a reference transducer is surface-to-surface calibration where the transducer under test is mounted directly against the face of the source transducer [3]. Reference-free methods are based on the reciprocity calibration [4]. The reciprocity calibration uses three transducers with approximately same frequency bandwidths which are reversible, i.e., capable of acting as a transmitters and receivers with the same impulse responses.

None of the aforementioned methods is directly applicable in situ. The transducers are calibrated on special test specimens, e.g., steel or glass blocks, and the calibration is performed for longitudinal and surface waves separately. It has been shown that

Abbreviations: AE, acoustic emission; TR(A/C), time reversal (acoustics/calibration).

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transducers respond not only to out-of-plane displacement but to in-plane displacement as well leading to phase cancelation phenomena in case of surface waves [5]. Another obstacle is the dependence on material, coupling conditions and time. The result is that even though it is possible to perform an accurate absolute calibration, transferring the results into practice might be difficult. There were attempts to develop in-situ calibration methods, but for sensitivity calibration only, and they require a specifically designed conical transducer as a source [6].

In this paper, a reference-free in-situ method of frequency response calibration is proposed. The method is based on reciprocal calibration and time reversed acoustics (TRA). Rationale behind employment of time reversal method is provided in Section 2 along with the theoretical development of time reversal calibration (TRC) for reversible transducers. The practical implementation is described in Section 3. Signal processing and calibration results are presented in Section 4. The applicability of TRC with irreversible transducers is discussed in Section 5.

2. Time reversal for transducer calibration

The introduction of TRA in transducer calibration was motivated by the elimination of the need for special test specimens. Some calibration methods use large steel blocks as wave buffers—with the purpose to prevent reflections and wave conversions affecting the results of a calibration. Indeed, wave propagation described by Green's function is a significant part of the signal chain from a source to a measured transducer output (1). However; TRA provides an effective way how to remove the influence of Green's function from the measurement. TRA is currently used in many research fields for its ability to focus elastic wave energy and reconstruct the source function with high precision even in inhomogeneous and anisotropic scattering media. Initial experiments were performed with transducer arrays [7] but later it was discovered that in reverberating media, reflections can be regarded as virtual transducers and TR experiment can be performed using a single transducer only [8,9]. Furthermore it has been shown that complex sources acting in multiple dimensions can be reconstructed using a scalar 1D transmitter [10]. In conclusion, by using TRA it is possible to reconstruct an arbitrary wave field created by a transmitter in its location with a single transducer regardless of medium complexity. Nevertheless, it will be shown that the result of TR experiment will be still affected by impulse responses of employed transducers.

A TR experiment is accomplished in two steps: forward and backpropagation. In the first step, transducer i transmits an arbitrary signal $s(t)$ into the medium and the response is recorded by receiver j. The resulting signal can be expressed by the convolution

$$u_{ij}(t) = h_j(t) \times g_{ij}(t) \times \tilde{h}_i(t) \times s(t) \tag{1}$$

where $g_{ij}(t)$is Green's function between transducers i and j, $h_i(t)$ is the impulse response of ith transducer for reception and $\tilde{h}_i(t)$ for transmission. In the second step, forward propagation signal $u_{ij}(t)$ is time reversed and transmitted back from jth transducer. Near the focal time the following approximation is valid [11]

$$\begin{aligned} w_{ji}(t) = \;& h_i(t) \times g_{ji}(t) \times \tilde{h}_j(t) \times u_{ij}(-t) \approx \\ &\approx h_i(t) \times \tilde{h}_i(-t) \times h_j(-t) \times \tilde{h}_j(t) \times s(-t) \end{aligned}$$

(2)

It is evident from Eq. (2) that the result of TR experiment is symmetrical with respect to transmitter-receiver configuration, i.e., $w_{ji}(t) = w_{ij}(t)$. Examples of both steps of TR experiment are shown in Fig. 1 (details of experimental configuration are in Section 3). Note that the efficiency of TR focusing is dependent on particular experimental configuration, i.e., the focal amplitude is a function of not only impulse responses but of the record length of $u_{ij}(t)$and transducer locations as well [12]. However these effects are frequency independent and therefore do not affect the calibration result.

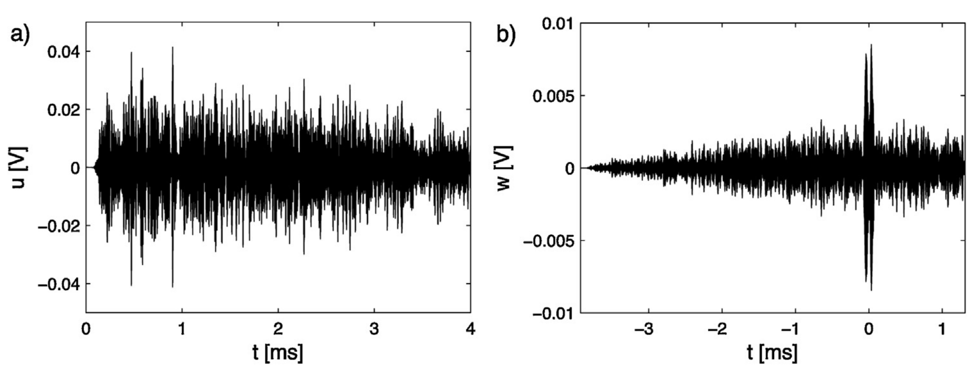

Fig. 1. Two steps of time reversal experiment. The result of forward (a) and backpropagation (b) is shown (for the detail of source reconstruction see Fig. 5a).

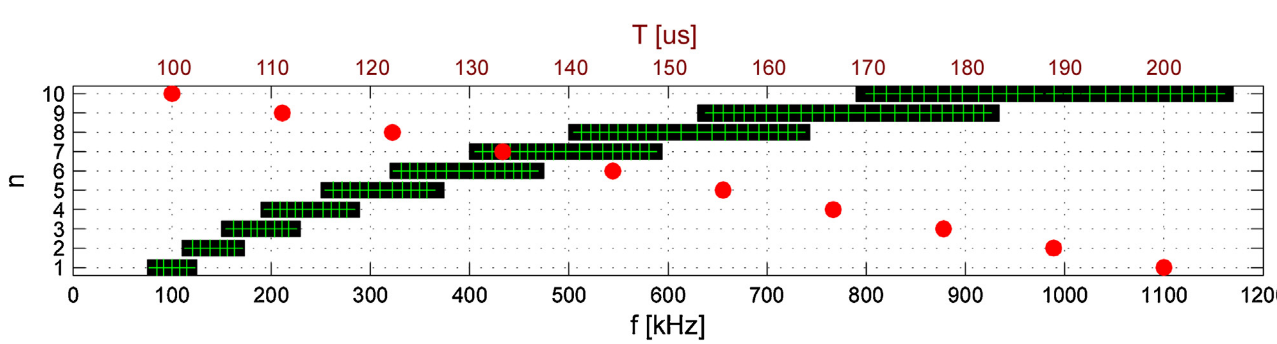

Fig. 2. Schematic of frequency bands of 10 applied source functions. Crosses mark output frequencies after "deconvolution" (see Section 5.1). Dots mark corresponding signal duration.