Influence of Transducer Coupling in Ultrasonic Testing

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Abstract
Couplants are necessary in most cases of ultrasonic testing, due to large acoustic mismatch between air and solid material. Signal amplitude as well as wave type are greatly affected by couplant properties. This paper is discussed influence of various coupling methods on received signal in frequency domain. Coupling of both transmitter-specimen and receiver-specimen in a pitch-catch setup are investigated on common building material.

Keywords: Coupling, Transfer function, Pulse compression, Maximum Length Sequence (MLS), Impact-Echo (IE), Young modulus, Impulse response, Linear time-invariant system, time of flight (TOF), Nondestructive testing (NDT)

1. Introduction

Ultrasonic waves introduced into the specimen are changed and reflected as they interact with inhomogeneities. Received signal contains information, which can be interpreted as defects or material properties. The classical defectoscopic approach is to look at reflected echoes or to measure time of flight. However, more sophisticated methods focus on information contained in the frequency spectra, to estimate dynamic modulus of elasticity or to assess severity of micro-cracking. Pure examples of such are Nonlinear Elastic Wave Spectroscopy (NEWS) [1] or Impact-Echo. Regardless of ultrasonic method applied transducer coupling is always problematic. Due to high acoustic mismatch between air and solids, the most convenient air coupling is often out of the question [2]. Immersion testing, on the other hand is more useful, but not in Civil engineering. Cementitious or clay products significantly change their material properties when soaked.

Most defectoscopic method applied for Civil engineering purposes use gel coupling. Unfortunately, the inconvenient soaking effect prevents long-term continuous testing and maintaining the correct gel layer is tricky [3]. If the gap is to wide gel couplant is acting as a separate material and waves are reflected on the boundaries. Also constant force should be applied during measurement.

The answer to those problems might me fixed-coupling, for instance with bee’s wax. Significantly higher energy levels are transferred in and out of the specimen, transducers are firmly attached which is useful for long-term measurements and improvement of SNR. These advantages come with a price. The transducer and specimen are bonded together and the resonance frequencies of the sample are altered. Added mass and extended therefore affects resulting longitudinal vibrations [4]. According to the analytical Eq. 1, for dynamic modulus of elasticity of longitudinally vibrating 1D element, it is quite clear, that any fixed coupling will result in lowering of fundamental frequency [5,6].

\[ E_{\text{dyn}} = 4\rho(fl)^2 \]  

It should also be noted that fixed coupling allows propagation of horizontally oriented sheer waves. The effects various coupling has on resonance frequency of the sample are investigated in this article.
2. Experimental setup

Tension/compression properties of all materials as such, can be quantified using Young's modulus. Furthermore Young's modulus can be calculated when the device under test (DUT) fundamental frequency is known. Linear time-invariant systems (LTI) can be completely described by a system impulse response (IR). If the stimulus signal fulfills criterions described in [7], IR can be simply calculated using cross-correlation with response signal. Initial delay of calculated IR is principally the same as Time of Flight (TOF) measured directly by classical Ultrasonic pulse testing. Of course, omitting dispersive waves and group velocities resulting in the process.

The great advantage rests in the frequency domain. Spotted peaks correspond to fundamental frequency and higher harmonics. Severity of harmonic distortion can be used to quantify damage of tested sample.

2.1 Specimen

In order to make results mutually comparable, all experiments were conducted on the same cement-mortar specimen with dimensions 40 x 40 x 160 mm, w/c = 0.46. The mortar preparation mixture contained CEM I 42.5R cement and quartz sand in a ratio of 1 to 3. In compliance with Czech standard ČSN 721200, 3 sand grades (0-1, 1-3, 3-4 mm) were used to be blended in weight ratio 1:1:1. Specimen was aged at temperature of 22°C and a relative humidity of 55 % for 24 hours. Afterwards placed in a water bath for 27 days and then dried at a temperature of 60°C for two days.

2.2 Measurement procedure

Influence of bee’s wax coupling and gel coupling is in this article compared with results from classical Impact-Echo (IE). According to results from article [4], frequency measured by IE method, by procedure described below, is in the range of ±1 % from air coupled measurement. Therefore peaks obtained from IE method are a suitable reference. Influence of transmitter (TX) and receiver (RX) coupling was tested by Pseudorandom Binary Sequence (PRBS) of Maximum length sequence (MLS). In order to make both methods comparable the same data acquisition device (DAQ) and the same MII receiver was used. Sampling parameters were set close to the highest available limits of NI PCI 6251 card, which is 1 MS/s with 16-bit resolution. NI Labview programming language was used for both signal acquisition and conditioning.

2.2.1 Impact-Echo

Impact-Echo is a well described a commonly used non-destructive testing (NDT) method in civil engineering [6,8]. The variation of IE is sometimes called Hammer resonance method, since it better describes the procedure. Physical principle behind this method is generation of a Dirac delta function and direct recording of a system impulse response (IR). A hammer is used to excite the system. Since no signal processing is required the method is very simple and extremely accurate. However, energy delivered into the system is limited by short contact time. Furthermore, increasing of impact energy leads to undesirable nonlinear effects. As a result, massive elements, soft or fragile substances cannot be tested by this method.
2.2.2 Maximum length sequence
Mathematical properties such as well defined frequency spectrum, repeatability and perfect auto-correlation make MLS a wise choice for excitation signal [9]. There are infinitely many Maximum length sequences, defined by their order and primitive polynomials [10]. For the test is used only one sequence, which is continually repeated [11]. In this way, the signal does not have to be record at the beginning of the sequence, but anywhere as long as the record length is the same as the length of the sequence. This being said, one can deduce the same timing source must be used for both generation and recording. The signal is absolutely repeatable and since it must be synchronized a time averaging (25 times) is applied to improve the Signal to noise ratio (SNR). As long as the sampling rate is an integer multiple of the generation rate, the MLS sequence behaves in a manner that more energy is shifted towards lower frequency bands. Selected divider of the sampling frequency leads to 200 kHz generation frequency.

Previously mentioned PCI card was utilized as D/A convertor of to generate the sequence and A/D convertor to record the signal. Generated electrical sequence of 0 V and 1 V was then amplified to 0 V and 10 V and send to the transmitting transducer [11,12]. Prior to acquisition the signal was amplified and filtered analog bandpass filter (0.3-300 kHz). Analog filtering is crucial to prevent frequency aliasing given by continuous sinc² frequency spectra of MLS [13].

2.2.3 Sensors and transducer
Different combinations of wax and gel coupling between DUT and piezoelectric transmitter/receiver were tested. A small (6,5 mm) piezoelectric receiver DAKEL MIDI was used for both IE and MLS testing. Originally three bolt-clamped Langevin transducers were intended as transmitters. However, results from transducer designated as BK03 we inconclusive because of a single dominant resonance at 32 kHz. Other two transducers, designated according to their shape (CONE, CYLINDER) had more convenient frequency characteristics. All Langevin transducers are designed to operate at their resonance frequency in order to create maximum displacement to observe nonlinear behavior. Their use for generation of broadband signals, such as in this article is not common.

![Figure 1. Transducers](image)
3. Results

On Fig. 1 to 4, respectively 5 to 7 are displayed frequency spectra obtained with CONE and CYLINDER transducers. Individual plots indicate the coupling between transmitter (TX) and specimen and also between specimen and receiver (RX). Measured spectra are compared to hammer impact resonance measurement (IE) (black plot. Figures clearly show that position of frequency peaks is influenced by coupling. As it was said in the introduction, lower fundamental frequency is to be expected with fixed coupling. Unfortunately all harmonic frequencies seem to be completely erratic, comparing them to both IE and between each TX. The arising of second peak for CONE transducer at first harmonic is clearly a result of fixed coupling between TX and specimen. Although the transfer characteristic of the CONE TX shows no anomaly in the region, TX and specimen fixed together can create such unexpected peaks. This finding makes fixed coupling of TX doubtful at best. On the other hand fixed coupling of small MIDI receiver seems to have no such side effect (green plot).

Best representation of frequency spectra offers Gel-Gel coupling, because the specimen is not influenced by transducers. In fact, measured fundamental frequency was always higher than of fixed-coupled IE, which is perfectly in accordance with the additional mass phenomenon.

![Figure 2. Frequency spectra measured with CONE transducer on mortar sample](image)

![Figure 3. Fundamental frequency CONE transducer](image)

![Figure 4. Second harmonic frequency CONE transducer](image)
Figure 5. Frequency spectra measured with CYLINDER transducer on mortar sample

Figure 6. Fundamental frequency
CYLINDER transducer

Figure 7. Second harmonic frequency
CYLINDER transducer

Table 1. Peak positions

<table>
<thead>
<tr>
<th>TX name, coupling</th>
<th>1\textsuperscript{st} [Hz]</th>
<th>diff. [%]</th>
<th>2\textsuperscript{nd} [Hz]</th>
<th>diff. [%]</th>
<th>3\textsuperscript{rd} [Hz]</th>
<th>diff. [%]</th>
<th>SNR [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IE_RX WAX</td>
<td>13936</td>
<td>0.0</td>
<td>27577</td>
<td>0.0</td>
<td>40644</td>
<td>0.0</td>
<td>66</td>
</tr>
<tr>
<td>Cone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX Wax_RX WAX</td>
<td>13580</td>
<td>-2.6</td>
<td>Double</td>
<td>NA</td>
<td>41537</td>
<td>2.2</td>
<td>67</td>
</tr>
<tr>
<td>TX Gel_RX WAX</td>
<td>14198</td>
<td>1.9</td>
<td>27647</td>
<td>0.3</td>
<td>40635</td>
<td>0.0</td>
<td>42</td>
</tr>
<tr>
<td>TX Gel_RX Gel</td>
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<td>0.4</td>
<td>27662</td>
<td>0.3</td>
<td>40875</td>
<td>0.6</td>
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<tr>
<td>TX Wax_RX Gel</td>
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<td>-2.8</td>
<td>Double</td>
<td>NA</td>
<td>41533</td>
<td>2.2</td>
<td>55</td>
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<tr>
<td>Cylinder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TX Wax_RX WAX</td>
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<td>3.1</td>
<td>40943</td>
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<td>45</td>
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<tr>
<td>TX Gel_RX WAX</td>
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<td>1.9</td>
<td>27647</td>
<td>0.3</td>
<td>40635</td>
<td>0.0</td>
<td>42</td>
</tr>
<tr>
<td>TX Gel_RX Gel</td>
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<td>27669</td>
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<td>40904</td>
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<td>28502</td>
<td>3.4</td>
<td>41179</td>
<td>1.3</td>
<td>54</td>
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</tbody>
</table>
4. Conclusions

Fixed coupling by bee’s wax is very useful when it comes to transferring large energy or for long-term measurement. However, one must keep in mind that new vibration modes can arise from fixed coupling with a transmitter. Fixed coupling of receiver will only slightly shift the frequencies to lower values, which due to the added mass of sensor.

Gel coupling of both transmitter and receiver is certainly the best approach, but it is not suitable for long-term measurement (soaking effect). Also higher amplification is needed.

This experiment, frequencies above 50 kHz needed to be filtered out because of noise problems.

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