Voice-Coils As Reciprocal Transducers in Structural Health Monitoring Applications

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VOICE-COILS AS RECIPROCAL TRANSDUCERS IN STRUCTURAL HEALTH MONITORING APPLICATIONS

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ABSTRACT

The feasibility of using voice-coils as reciprocal transducers of mechanical waves is investigated. It is speculated that these transducers could be used in a seismic network for structural health monitoring purposes, transmitting relatively undamped low frequency waveforms such as surface waves. This would permit long distances between transducers. The force generation capacity and vibration sensitivity of five types of voice-coil transducers are compared in the lower sonic spectrum. As a verification of the concept, the transducer type evaluated to be the most practical is used to measure the natural bending mode frequencies of a small concrete beam.

KEYWORDS : *SHM, voice-coil, reciprocal transducer, surface waves.*

1 INTRODUCTION

The purpose of structural health monitoring (SHM) is to continuously examine the physical integrity of a structure. Contrary to discrete non-destructive testing surveys, the continuity of SHM makes it possible to detect *events* and take action on them. It is also possible to assemble statistics and annual trends, improving with time. SHM is a multidisciplinary field with many different technologies and applications. One type of structure whose health is of interest to monitor consists of those made from concrete. The monitoring methods most commonly used for structural health monitoring of such structures are probably modal analysis of bending modes and Acoustic Emission (AE), but many others exist. Modal analysis is assumed to be insensitive to the micro-cracks that develop in the early stages of concrete degradation and thus not suitable if very early warnings are desired. AE instruments record the ultrasonic emissions generated when such micro-cracks open. These high frequency waves attenuate quickly and therefore a relatively dense network of sensors is required for structural coverage. An alternative, if the desire is to cover large concrete structures with a minimum number of sensors, is to use surface waves. They are known to propagate long distances with little attenuation compared to AE signals. The depth sensitivity of surface waves increases with decreasing frequency. Surface waves in the ultrasonic frequency range are thus only sensitive to micro-cracks near the surface of the structure. A network of transducers which can transmit and receive surface waves in the sonic spectrum would therefore be of additional interest. Each node in that network would be occupied by a transducer that can work either as a transmitter of surface waves or as a receiver. Modern accelerometers often have built-in electronics that make them unsuitable for transmission, but there are examples of networks of reciprocal piezoceramic elements [1], [2]. Similar applications have used piezoelectric wafers (PZT) embedded in the concrete structure as reciprocal transducers [3]–[5].

In this paper we investigate and propose the use of voice-coil transducers as surface mounted reciprocal transducers in SHM networks. One common such transducer is the geophone used in seismic measurements. It is normally used only as a receiver and then only below a couple of hundred Hz. Five different types of voice-coil transducers were studied in the frequency range 10 Hz to 5 kHz.

2 BACKGROUND

Voice-coil transducers are based on the principle of a spring-mounted coil which moves within a magnetic field. Due to its own inertia, the coil remains stationary while the case moves with ambient vibrations. The coils' relative motion through the magnetic field generates a voltage proportional to the velocity. If, instead, an electric signal is applied over the poles, the moving coil will move within the magnetic field with a velocity proportional to the current. Conservation of energy implies that the responsivity of the coil-magnet system as a force transducer, in Newtons per Ampere, and its sensitivity as a velocity transducer, in Volt per meter per second, are identical [6]. Thus voice-coil transducers can be used reciprocally as both receivers and transmitters of mechanical waves.

The spring-mass system in a voice-coil works as a harmonic oscillator with a given resonant frequency in its working axis, which is commonly referred to as the natural frequency. This is the lower bound of the bandwidth of the transducer [7]. To allow the coil freedom to move in its intended axis, voice-coils are constructed in such a way that some movement perpendicular to this axis is possible. Resonant frequencies in this direction, as well as rotational motions, are known as "spurious" frequencies. When used to receive seismic data, the lowest spurious frequency of geophones is commonly regarded as the upper bound of the bandwidth of the sensor [8]. This frequency is typically a few hundred Hz.

Inertial force actuators are often characterized by the frequency range in which they effectively output force. We want to extend the knowledge of how these transducers operate outside their anticipated range of working frequencies and how they work as receivers.

3 TRANSDUCER CHARACTERIZATION

3.1 Experimental setup

Five types of voice-coil transducers are evaluated in this paper: two omni-directional geophones, with different impedances, one inertial force actuator, and two electro dynamical exciters. A pair of transducers of each type was used. Information about the transducers is presented in Table 1.

Table 1: List of the five evaluated voice-coil transducers.

Name	Description	Manufacturer	Weight	Nominal impedance
SM-6 375 Ω	Geophone	ION	81g	375Ω
SM-6 3500 Ω	Geophone	ION	81g	3500 Ω
IFX30-100	Inertial force actuator	Motran	940g	1.6 Ω
EX60S	Electro dynamical exciter	Visaton	120g	8 Ω
EX45S	Electro dynamical exciter	Visaton	60g	8 Ω

Each transducer was evaluated in three steps: force responsivity, receiving sensitivity, and efficiency in transmission directly between reciprocal transducers through concrete.

3.1.1 Force responsivity

The actuating abilities of the transducers were evaluated by measuring the force exerted by the transducers as a function of frequency. Our interest in possible generation of harmonics by the transducers necessitated external programming of the Hewlett Packard 36665A Dynamic Signal Analyzer (DSA), used in the experiments, in order to create plots of the response spectra, $A(f_r)$, as a function of the source frequency, f_s, i.e. $A(f_r,f_s)$.

The DSA was used to step through a range of source frequencies, f_s, and to calculate a frequency response spectrum, $A(f_r)$, of the signal from the force transducer measured for each source frequency. A Brüel & Kjaer (B&K) power amplifier type 2734 was used to amplify the driver signal from the DSA Source before it was fed to the voice-coil. The power amplifier monitor signal was fed into the DSA Ch 1 as a reference. The force exerted by the transducer was measured by a B&K force transducer type 8200, the output of which was amplified by a B&K charge amplifier type 2635 and then fed to the DSA Ch 2. A 150 kg concrete cube acted as a firm fundament. A sketch of the experimental setup is presented in Figure 1a.

The frequency of the input sinusoidal signal was stepped from 10 to 5000 Hz. The frequency sweep was performed at different voltage levels in order to check the linearity range of the transducers. Only measurements from one voltage level are presented here due to lack of space. The voltage range of the input was different for the different types of transducers, based on input impedance and on manufacturer recommendations.

3.1.2 Receiving sensitivity

The DSA was used to step through a range of source frequencies and to calculate a frequency response spectrum of the signal from the voice-coil transducer, measured at each source frequency. The DSA Source was amplified by the 2743 power amplifier connected to a B&K vibration exciter type 4808 equipped with a B&K type 8001 impedance head. The voice-coil transducer was mounted on top of the impedance head. The accelerometer output of the impedance head was integrated by the 2635 charge amplifier and fed, as a velocity measurement, to the DSA Ch 1 for reference. The force output of the impedance head was not used. The output from the voice-coil transducer was fed to the DSA Ch 2. The frequency sweep was performed at different voltage levels and thus for different velocities. A sketch of the experimental setup is presented in Figure 1b.

3.1.3 Reciprocal concrete transmission efficiency

To verify that it is indeed possible to transmit mechanical waves through concrete using these voice-coil transducers, measurements were made on the previously mentioned concrete block. The block was cubic with a 0.4 m side. Two identical transducers were used for this experiment– one for transmission and one for reception. Small metal plates were adhered to the centre of two opposing sides of the block. These plates had threaded holes which enabled the transducers to be exchanged and firmly fixed in place. The transducers were thus located horizontally, facing each other with 0.4 m solid concrete between them.

The DSA Source was used, via the power amplifier, to apply a sinusoidal signal with swept frequency to the transducer that acted as transmitter. The monitor output of the power amplifier was fed into Ch 1 of the DSA for reference. The output from the receiving transducer was fed into the DSA Ch2. A sketch of the experimental setup is presented in Figure 1c.

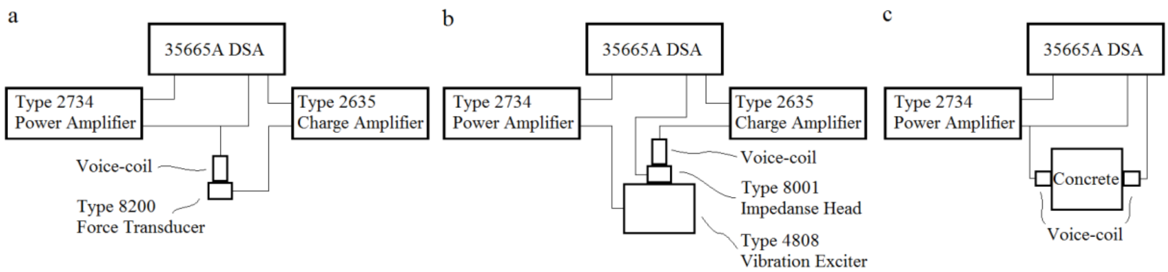

Figure 1: a) Experimental setup for force responsivity measurements (N/A), b) vibration input sensitivity (V/[m/s]) and c) reciprocal concrete transmission efficiency measurements (V/A).

3.2 Results

In order to conserve space, graphical results are only presented for the 3500Ω geophone, but similar diagrams were generated for all transducers. The general characteristics were similar for all transducers but the most important differences are presented.

3.2.1 Force responsivity

From the DSA the FFT spectra of the output signals from the force transducer were recorded. The force amplitude was divided by the current applied to the transducer in order to get a unit that facilitated comparison of the different transducer responsivities. Plotting the FFT spectrum for each frequency step generated a diagram like that in Figure 2, where the response from the SM-6 3500Ω geophone is presented. In the figure the frequency of the driving sinusoidal signal is assigned to the x-axis and the resulting force spectrum is assigned to the y-axis. The colour indicates the amplitude of the spectrum in an N/A (Newton/Ampere is conventional in actuator specifications) decibel scale.

Much information can be read from these diagrams; the dominating diagonal line corresponds to the linear response of the transducer to the frequency of the applied driver signal. The amplitude along this line is the conventional frequency response of the transducer. Also visible in the figure are the undesired harmonics, corresponding to the diagonal lines with slopes equal to multiples of that of the fundamental line. At a driving signal frequency of 268 Hz, relatively high amplitudes can be seen along the whole spectrum. This driving frequency corresponds to the spurious frequency of the geophone and here the moving mass was displaced to the extent that it hit the end points of the case. This phenomenon gives rise to non-linear effects. Also visible in the figure are some horizontal lines, for instance at ~3.2 kHz on the y-axis. These are electrical disturbances, picked up by the DSA. They are present regardless of the frequency of the driving signal. The close proximity of the 3.2 kHz disturbance to the amplitude peak along the main diagonal line is purely coincidental, which was confirmed by performing a DSA measurement with no transducer connected to the circuit.

Figures such as this were created for each transducer type and for several values of input signal voltage. Figure 3a shows the transducer responsivity for the SM-6 3500Ω geophone in Newton per Ampere, at the fundamental frequency, as a function of driver signal frequency. The graph shown in Figure 3a corresponds to the amplitude along the dominating diagonal line in Figure 2. The main peak in Figure 3a, at ~3.1 kHz, corresponds to the frequency at which the transducer exhibits resonance. This peak is naturally located at different frequencies for the different transducers, based on their weight and structure. The spurious frequencies can be seen in the interval 220-300 Hz. Between these and the resonance peak at ~3.1 kHz, the frequency response is rather flat which indicates a useful range of operation. At frequencies above the resonance peak, the response decays with frequency but a useful force level is measured up to at least 5 kHz.

Table 2 presents the force responsivity in the flat region of the frequency response for the different evaluated voice-coil transducers, measured at 1 kHz.

3.2.2 Receiving sensitivity

In Figure 3b the sensitivity, in V/(m/s), of the SM-6 3500Ω geophone is plotted as a function of vibration frequency. At ~3.1 kHz the resonance of the transducer can be seen, and at 220-300 Hz the spurious frequencies can be seen. As mentioned above, geophones are normally only used below these spurious frequencies. As can be seen from Figure 3b the transducer has a relatively flat region up to the resonance peak at 3.1 kHz. The similarity between Figure 3a and Figure 3b suggests reciprocity between transmission and receiving, as suggested by [6]. Table 2 shows the sensitivity in the flat region of the frequency response, measured at 1 kHz, for the different evaluated voice-coil transducers.

3.2.3 Reciprocal concrete transmission efficiency

During the first measurements between two identical transducers through concrete the results were not intuitive – the amplitude suspiciously increased greatly with increasing frequency. Figure 4a shows such a frequency response. Further measurements in a wider frequency range demonstrated that the amplitude increased steadily up to ~25 kHz before starting to decline. This was confirmed to be caused by electrical coupling between the two transducers through the concrete. This phenomenon was averted by connecting the case of the transducers to system signal ground.

Figure 4b shows a transfer function between two identical transducers, both of which have electrically grounded cases. The y-axis in this figure shows the receiver output voltage as a function of the current driving the transmitter. As can be expected from the results in the previous sections, the figure shows a peak at 3.1 kHz. There are some peaks between 4 and 5 kHz that numerical modelling suggests are natural frequencies of the concrete block.

Table 2 shows the ratio between receiver voltage and transmitter current at 1 kHz for the different voice-coil transducers.

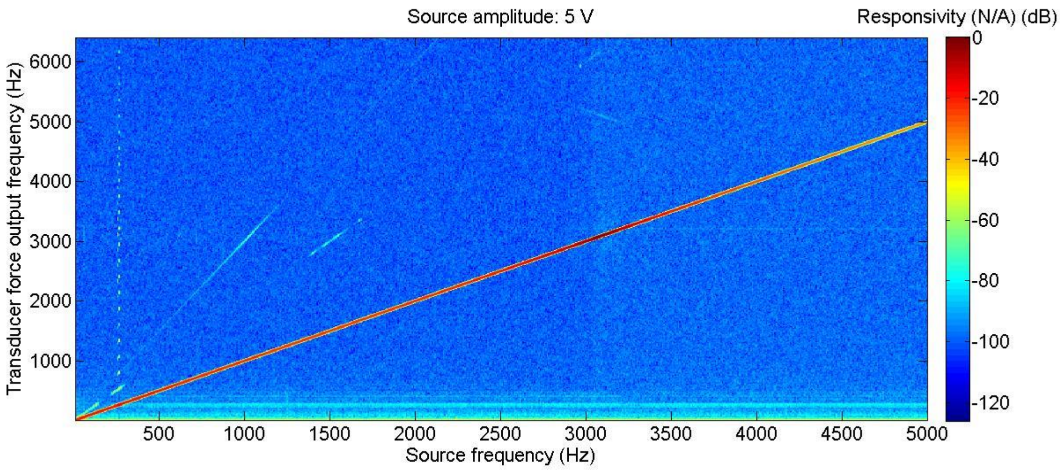

Figure 2: Spectra (y-axis) of the transducer responsivity as a function of the driver signal frequency (x-axis) for an SM-6 3500Ω geophone. The amplitude of the responsivity is displayed as colour in a normalized decibel scale. The driver signal has an amplitude of 5V.

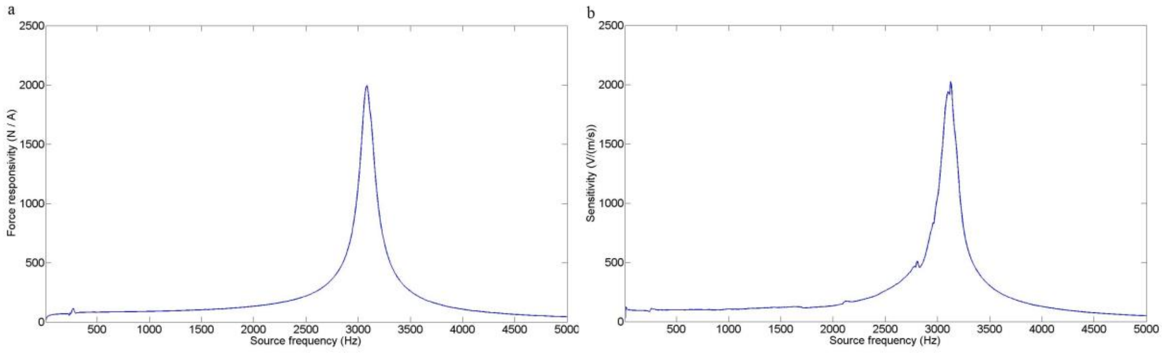

Figure 3: a) The responsivity, in N/A, of the force output, at the same frequency as the driving sinusoidal signal, as a function of frequency, for an SM-6 3500Ω geophone. The driver signal has an amplitude of 5 V.

b) The sensitivity, in V/(m/s), at the same frequency as the vibrator input signal, of an SM-6 3500Ω geophone as a function of vibration frequency.

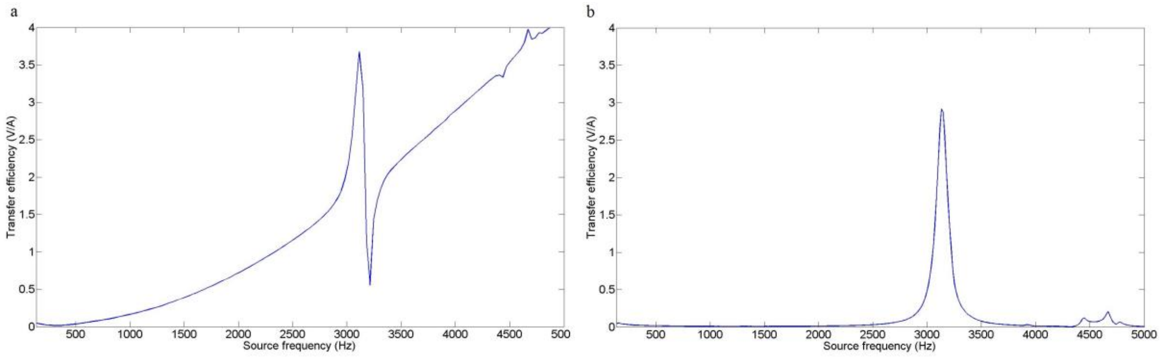

Figure 4: Transfer ratio between output voltage from a receiving SM-6 3500Ω geophone and input current to a transmitting SM-6 3500Ω geophone, as a function of frequency. a) The cases of the transducers were *not* electrically grounded, b) the geophone cases were electrically grounded.

Table 2: Results from the evaluation of the five voice-coil transducers.

Transducer	Sensitivity [V/(m/s)] at 1 kHz	Force responsivity [N/A] at 1 kHz	Transfer efficiency through concrete block [µV/A] at 1 kHz	Peak resonance frequency [Hz]
SM-6 375 Ω	31	33	1270	3100
SM-6 3500 Ω	92	89	9630	3100
IFX30-100	9	9	93	2000
EX60S	7	5	31	4000
EX45S	4	3	20	4200

4 VERIFICATION OF CONCEPT

The above results indicate that voice-coil transducers can be used for structural health monitoring. The SM-6 3500Ω geophone in particular appears practical. As a verification of the concept, two geophones of this type were used to investigate the natural frequencies of a small reinforced concrete beam.

4.1 Experimental setup

The dimensions of the beam were 0.81x0.15x0.10 m. The beam was placed on two Styrofoam supports 17 cm from the ends. Two custom-made, ~1 cm thick, aluminium plates were fastened to the edges of the beam using adhesive. The plates had threaded holes which enabled the transducers to be attached in various locations and directions. For the sake of verification, different configurations were set up, directing the transducers to excite different modes of the beam. The configuration presented here is where the transducers were placed orthogonal to the beam in the weak direction. In this configuration the transducers could excite, and measure, the bending modes of the beam in one plane. Figure 5 shows the placement of the transducers.

The DSA Source was programmed to generate a frequency sweep in the frequency response mode. The DSA Source signal was amplified by a small TTI WA301 voltage amplifier. The driver signal from the amplifier was fed into the DSA Ch 1 for reference and the output of the receiving transducer was fed into the DSA Ch 2 unamplified.

A finite element model of the beam was made in COMSOL Multiphysics using assumed physical properties of the concrete. Eigen-frequency analysis was used to find the natural frequencies and mode shapes of the beam. Frequency analysis, with an approximation of the load from the transmitter, was used to calculate a theoretical frequency response graph.

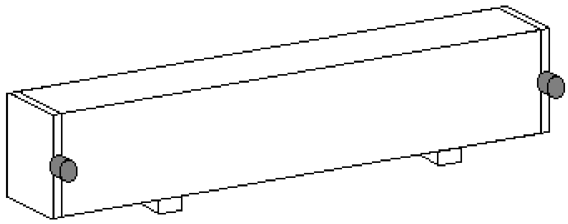

Figure 5: The placement of the transducers on the concrete beam.

4.2 Results

Figure 6 shows the frequency response measured by the receiving geophone as well as corresponding measurements made in the finite element model. The amplitude of the data from the model is normalized to the experimental data. The location of the peaks in the response function for the measured experimental data matches those of the modelled data well. The mode shape analysis in the finite element model confirms that the detected natural frequencies indeed correspond to the bending modes of the beam.

In the experimental data the resonance peak of the transducers is present at ~3.1 kHz. Since this does not correspond to a natural frequency of the beam, it is not present in the model data.

A hammer hit to the same location of the beam would have generated the same result, but the analysis requires a strong signal. The extreme narrow band excitation with the geophone enables detection at an *enormously* much lower signal level, which transforms into larger measurement ranges.

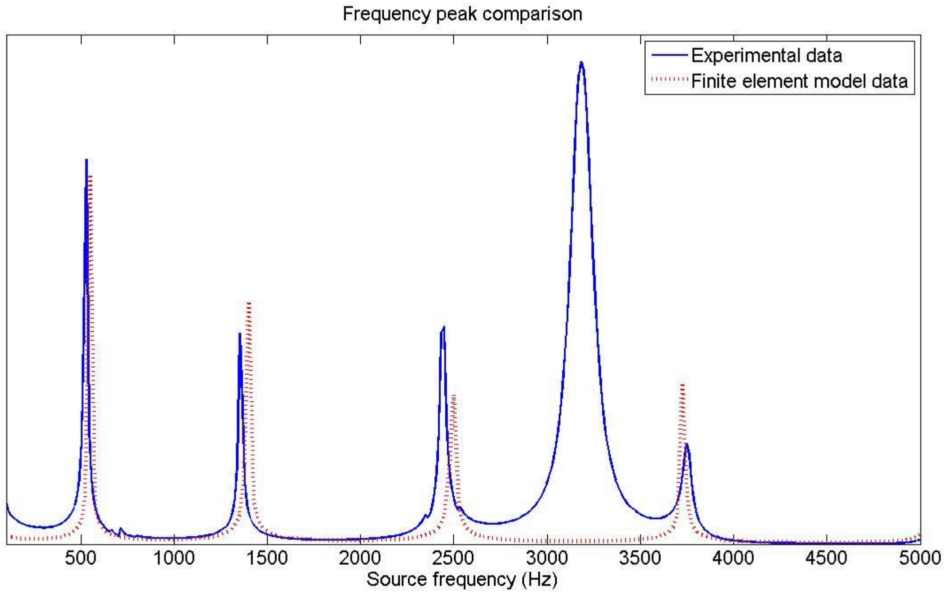

Figure 6: The frequency response function of the concrete beam. The blue line (solid) shows the experimental frequency response measured using the voice-coil transducers and the red line (dotted) shows velocity data from the finite element model. The amplitudes are normalized.

5 CONCLUSION

The data presented in this paper indicates that voice-coil transducers can indeed be used as reciprocal transducers for mechanical waves in the frequency range ~300-5000 Hz. This, combined with their robustness, makes them suitable for applications in structural health monitoring, where they can be surface mounted. The mass and structure of the transducers give rise to a resonance peak for the transducers themselves. This peak must be accounted for, so that it is not mistaken for a natural frequency of the monitored structure. On the other hand, it is obviously a frequency where the detection distance can be very large.

Different types of voice-coil transducers were evaluated. The inertial force actuator and electro-dynamical exciters were, as expected, the most potent exciters, as they could exert the most force on the structure. They were, however, relatively insensitive as receivers. The electro-dynamical exciters also generated relatively strong harmonics which are not desired, as power is wasted on unintentional frequencies. Also: in material characterization applications harmonics can be used as a measure of the non-linearity of the material, known to be the best indicator of micro-cracks. Then it would be a disadvantage to have harmonics generated by the measurement equipment itself.

The geophones proved to be the voice-coil transducers best suited for reciprocal operation, due to their high sensitivity. This was confirmed in the experiment where a signal was transmitted through a concrete block – the geophones displayed the highest output per input power. Of the two geophones the higher impedance version, SM-6 3500Ω, proved to be the most efficient. These geophones are also small, lightweight, robust and relatively inexpensive.

It proved necessary to electrically ground the case of the geophone to prevent electric coupling between transmitter and receiver through the concrete. This must also be considered when using piezoelectric transducers, especially patches embedded in the concrete. Discovering an undesired electric contact in experiments such as these can be difficult since the measured signal is in the expected frequency range and the amplitude is also affected by degradation of the concrete – through an increased electrical resistivity when degradation proceeds [9].

6 REFERENCES

[1] M. Sun, W. J. Staszewski, R. N. Swamy, and Z. Li, "Application of low-profile piezoceramic transducers for health monitoring of concrete structures," *NDT E Int.*, vol. 41, no. 8, pp. 589–595, Dec. 2008.

[2] Vallen Systeme, "AMSY-6 System Description," no. July, p. 51, 2013.

[3] G. Song, H. Gu, Y. L. Mo, T. T. C. Hsu, and H. Dhonde, "Concrete structural health monitoring using embedded piezoceramic transducers," *Smart Mater. Struct.*, vol. 16, no. 4, pp. 959–968, Aug. 2007.

[4] W.-I. Liao, J. X. Wang, G. Song, H. Gu, C. Olmi, Y. L. Mo, K. C. Chang, and C. H. Loh, "Structural health monitoring of concrete columns subjected to seismic excitations using piezoceramic-based sensors," *Smart Mater. Struct.*, vol. 20, no. 12, p. 125015, Dec. 2011.

[5] S. Yan, J. Wu, W. Sun, H. Ma, and H. Yan, "Development and application of structural health monitoring system based on piezoelectric sensors," *Int. J. Distrib. Sens. Networks*, vol. 2013, pp. 1–12, 2013.

[6] E. Wielandt, "Seismic sensors and their calibration," in *New Manual of Seismological Observatory Practice 2*, 2012, pp. 1–49.

[7] R. Brincker, T. L. Lagö, P. Andersen, and C. Ventura, "Improving the classical geophone sensor element by digital correction," in *Proc. of the International Modal Analysis Conference, Orlando, FL, USA, Jan. 31-Feb. 3, 2055*.

[8] K. Faber and P. W. Maxwell, "Geophone spurious frequency: What is it and how does it affect seismic data quality?," *Can. J. Exploiration Geophys.*, vol. 33, pp. 46–54, 1997.

[9] J. F. Lataste, C. Sirieix, D. Breysse, and M. Frappa, "Electrical resistivity measurement applied to cracking assessment on reinforced concrete structures in civil engineering," *NDT E Int.*, vol. 36, no. 6, pp. 383–394, Sep. 2003.