Some observations from a parametric study of the behaviour of benders in a polyurethane rubber

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Summary

This paper describes some observations taken from a series of tests in which a polyurethane rubber has been used as a soil substitute. The specification of the polyurethane is described as well as the techniques which were developed to mould it into a variety of shapes with consistent properties. The tip deflection of bender elements under excitation was characterised using a laser velocimeter both in air and also when protruding into a specimen. These results show that results taken from "self monitoring benders" are erroneous. Very thin synthetic samples allow us to establish the relationship between transmitter bender and receiver bender which are touching. Using the transfer function from this system it is possible to establish how to isolate the non-soil parts of subsequent transmissions. Significant crosstalk was experienced. This is characterised and the effect of artificially removing crosstalk on frequency domain measurements is discussed.

Introduction

Bender elements remain a popular tool for establishing the shear wave velocity and hence the low strain shear modulus, G_0, of soils. A wealth of experiments have been carried out on a variety of soil samples using different set-ups. Through-transmission tests using pulses – commonly step functions or a single cycle sine wave tuned to the resonance of the bender – remain the most common operating procedure in tests with bender elements. In practice such transmission tests are difficult to apply for determination of wave velocities, because no clear consensus exists on how to determine the true instant of arrival of the received wave. Lack of consensus is equivalent to uncertainty; attempts to quantify such uncertainty have produced discouraging results (100% for modulus in the case explored by Arroyo *et al.,* 2003a).

Efforts to establish dynamic bender-based tests on a firmer footing have a long history [notably Viggiani and Atkinson, 1995; Jovicic *et al.*, 1996]. It has recently become standard to discuss these matters using a dynamic linear systems approach [Lee and Santamarina, 2005; Arroyo *et al.*, 2006; Wang *et al.*, 2006] as shown in Figure 1. Of the subsystems concerned the interesting one is that of the material sample (system S2 in Fig. 1). This, however, is more or less obscured by other phenomena. Problems might appear there because measurements are located in the near field [Brignoli *et al.,* 1997] and / or because of sample-shape induced interference [Arroyo *et al.,* 2006]. Successfully avoiding the first problem is now possible either by a prescriptive approach [Arroyo *et al.,* 2003b] or by numerical simulation [Lee and Santamarina, 2005]. There is still no clear procedure available to avoid the second problem.

However, progress in the study of the sample subsystem does require a good knowledge of the peripheral subsystems, so that their contribution to the total system response can be successfully deconvolved. This paper investigates these peripheral subsystems: firstly the response of the transmitting bender element itself and subsequently the response of the receiving element when it is in direct physical contact with the transmitting element.

Attempts have been made by several authors to measure the response of a transmitter bender by making some portion of the piezo ceramic material electrically independent of the remainder of the material which is used to drive the element. The technique was first described by Schultheiss [1980] and has been used most recently by Wang *et al.* [2007]. The cut-away section is monitored to determine the actual movement of the bender. This is an alluring technique but results from these "self monitoring" bender elements – which indicate that the bender element faithfully follows the input signal – are not credible. Whilst themselves rather obscured by electrical noise, some previous results from a strain gauge mounted onto a bender element [Greening and Nash, 2004] as well as measurements taken of the velocity of a bender tip in air using a non-contact laser technique [Lings and Greenings, 2001] indicate that a bender element undergoing

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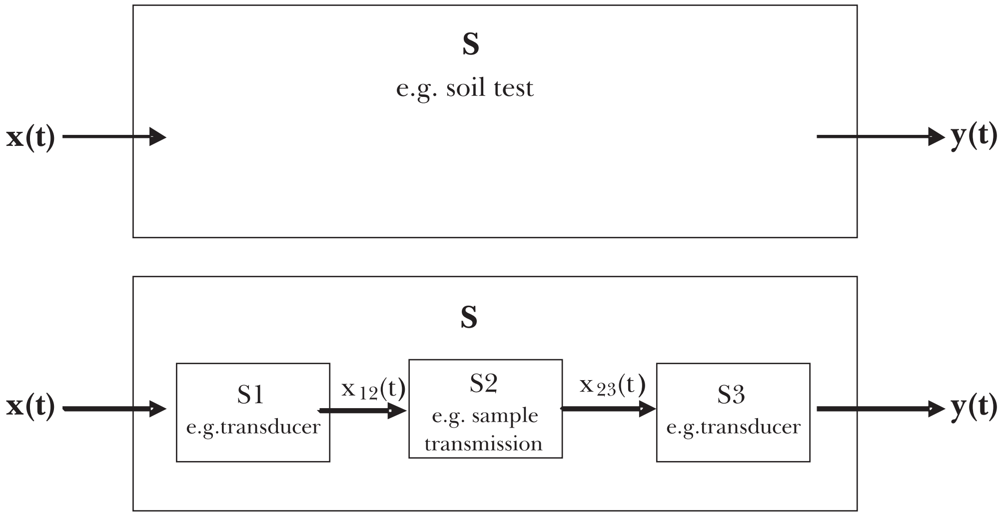

Fig. 1 – Dynamical system schemes for bender element testing.
Fig. 1 - Schemi dei sistemi dinamici per le prove con bender elements.

an impulsive excitation will tend to "ring" for some time after the excitation has finished.

This paper employs the laser monitoring technique in a more systematic fashion to establish the transfer functions between the electrical input and the mechanical response of bender elements embedded in a model soil. Another commonly employed technique of bender element monitoring (tip to tip measurements using another bender transducer) is also analysed.

Crosstalk is a phenomenon which is well known to anyone who has attempted bender element testing in practice. The term describes the situation where a signal finds its way electrically – and therefore virtually instantly – from the transmitting to the receiving electronics. While relatively benign in terms of pulse testing, the effect of crosstalk on frequency domain measurements such as those described by Blewett *et al.* [1999] and Greening and Nash [2004] is less well understood but is investigated herein.

Polyurethane rubber

A polyurethane rubber that goes by the commercial name of Poly RTV liquid rubber was chosen as the polymer to be used as a surrogate soil. This synthetic rubber is acquired in the form of two liquid components which, when mixed in the right proportions, vulcanize at room temperature; hence the abbreviation 'RTV'.

A family of cylindrical moulds was developed with the cylinder itself being composed of two symmetrical units split longitudinally and with circular endcaps which included "dummy" bender elements which created a void which into which bender elements would protrude. These endcaps could be placed at different positions within the mould allowing the height of the sample to be varied.

The densities of the two liquid components were known, and so the correct proportion of each part to use in the mixture was obtained by weight. After starting the mixture, a time window of 10 minutes was available during which the rubber parts could be mixed and poured into the moulds, after that either of these operations became impractical or even impossible since the mixture quickly becomes too viscous to handle. It was found more effective to fill the moulds with their longitudinal axis horizontal. More details of the sample forming procedures can be found in Rio, [2006].

The polyurethane rubber is a visco-elastic material which exhibits a great deal of damping. However, for the purposes of small strain at high frequency, the material is effectively linear. This type of material does have a track record in acting as a soil substitute (e.g. Stokoe *et al.*, 1990; Kim and Kweon, 2000).

A family of 24 samples was created. Three diameters – 38, 50 and 75mm – were used with samples of 8 different heights: 6, 10, 20, 30, 40, 50, 60 and 76mm. Thus a total of 24 different aspect ratios were investigated. Figure 2 shows all of the polyurethane samples which were tested during the project.

Given that the overall goal of the study was to investigate the effect of geometry on the signal transmitted by the bender element it was important to assess the influence of other factors such as the temperature of the laboratory and any manufacturing variability. Tests were carried out on the same sample (38mm diameter and 76mm tall) six times over an 81 day period which spanned all testing. Variations in properties of the samples were characterised through

Fig. 2 – Family of polyurethane samples tested.
Fig. 2 – Insieme dei provini in gomma poliuretanica.

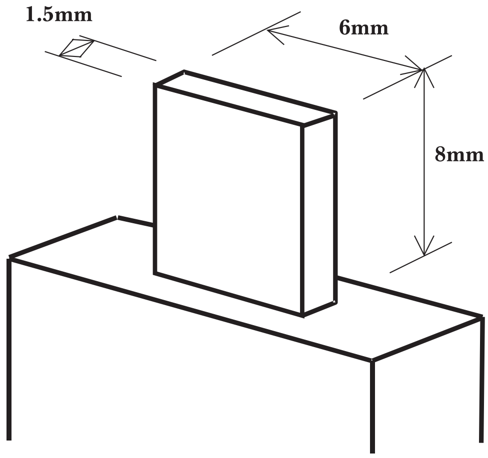

Fig. 4 – Dimensions of UCL bender.
Fig. 4 – Dimensioni dell'UCL bender element.

estimates of shear wave travel velocity using several popular techniques as shown in Figure 3. The results labelled *ps1* and *ps2* correspond to the best guess at first arrival from pulse signals with a characteristic frequency of 400Hz and 1200Hz respectively. The results shows as *sweep1* and *sweep2* result from the group velocity of waves determined from a phase delay plot the former being the average for waves with frequencies between 250Hz and 650Hz and the latter for the range 1kHz to 4kHz. *pip* denotes the pi-point technique in the frequency range 1.5kHz to 4kHz and *cs* is shorthand for continuous signal which describes a technique where relative phase of two continuous signals is used to establish travel time. Putting aside the very dramatic different results deriving from different techniques (particularly *sweep1* and *ps1* which both indicate an apparent slow transmission of shear waves at low frequencies), it is clear that there is some variation in the estimate of shear wave travel time but there is no trend across all of the techniques nor was the variation found to correlate with the age of the sample or the temperature of the room.

Bender element behaviour

Tests were carried out on bender elements manufactured at UCL with a 0.5mm thick bimorph encased in a two part epoxy leading to dimensions shown in Figure 4. A transmitter bender element was mounted in a 38mm wide platen such that the top 3mm of the element projected above the platen. A laser Doppler velocimeter (LDV) was used to mea-

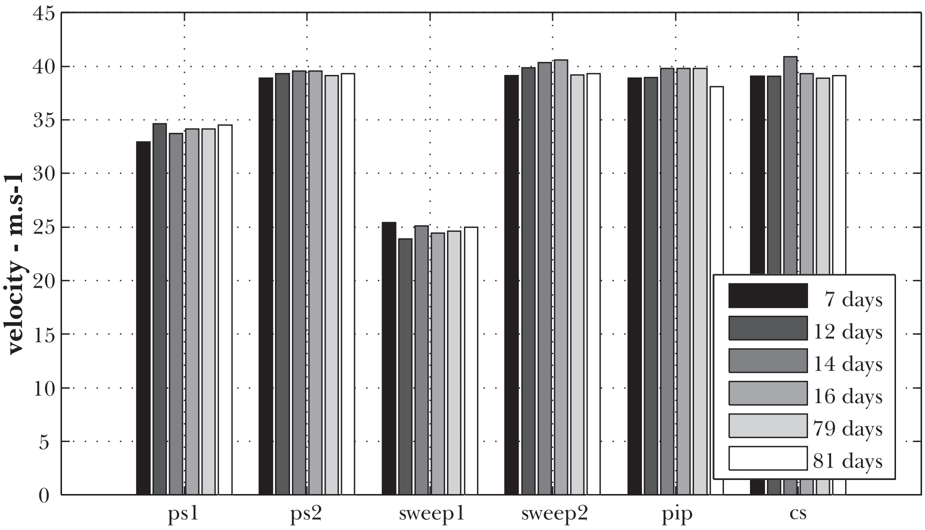

Fig. 3 – Repeatability test showing how estimate of shear wave velocity varies in a single sample in 6 different testing conditions.
Fig. 3 – Prova di ripetibilità che mostra come la stima della velocità delle onde di taglio vari nello stesso provino sotto 6 differenti condizioni di prova.

sure the lateral velocity of the tip of the bender element. A laser beam is directed towards a point on the tip of the bender. The reflection is compared with the transmitted signal yielding the instantaneous velocity of the bender tip.

Tests were carried out on the bender mounted in the platen but otherwise in air and unconstrained and also with the bender protruding by 3mm snuggly into the pre-formed voids in the polyurethane sample. It was necessary to cut a small channel in the base of the synthetic sample to allow the laser beam to reach the tip of the bender element (Fig. 5, left).

The transfer function between the drive signal and the signal from the LDV representing velocity was recorded in each case. Figure 7 shows the transfer function of the unrestrained bender element in air. It is not a surprise to discover that the bender acts as a rather lightly damped cantilever. The first – flexural – resonance is seen to occur at around 3.3kHz with a second mode appearing at 8.4kHz. The 180^o phase shift associated with each peak is consistent with the peaks being modes of the bender cantilever. When a transient time signal is applied to the element, it is seen to "ring" significantly (Fig. 8). That is, the bender continues to resonate for long after the excitation signal has reached zero. The frequency of vibration after the forced period is dominated by the resonant frequency of the element itself. While intuitively correct, this observation contradicts the evidence from self-monitoring benders (see, for example, WANG *et al.*, 2007). The implication is that the self monitoring benders are responding to electrical activity far more significantly than to mechanical movement of the unit.

When the element is mounted within the polyurethane, a distinct change in behaviour is noted as Figure 9 shows. The first resonant frequency has increased to 4.9kHz and the damping has also increased. This new dynamic behaviour characterises the combined bender / polyurethane system. The stiffness of the system, the mobilised mass as well and especially the damping of the system have all changed.

The transient tip movement of the bender is shown in Figure 10. It gives a clear picture of the characteristics of the pattern of waves set up in the sample.

The damping of the bender in free air is found to be around 2.5% of critical. The bender inserted in the polyurethane sample finds itself in an environment in which energy is lost very effectively through hysteresis so it is not surprising to discover that the damping is significantly higher at around 25% of critical. Using the published calibration data for the LDV, tip displacements of around 2.5μm are estimated for excitation with a signal of 20V peak to peak for the bender mounted in a polyurethane sample.

Tip to tip measurements

One of the doubts relating to interpretation of bender element signals is the part played by the dynamics of the bender elements and the electronics associated with their amplifications and data acquisition. This is of particular concern when employing frequency domain techniques for determining shear wave travel time [BLEWETT *et al.,* 1999; GREEN-

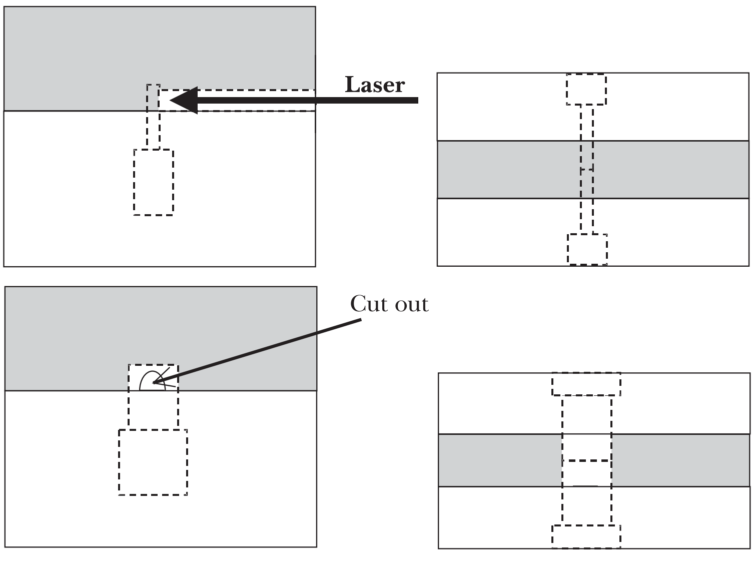

Fig. 5 – Polyurethane samples: cutout for laser (left) and tip to tip configuration (right).
Fig. 5 – Provini in poliuretano: incisione per il laser (sinistra) e configurazione punta-punta (destra).

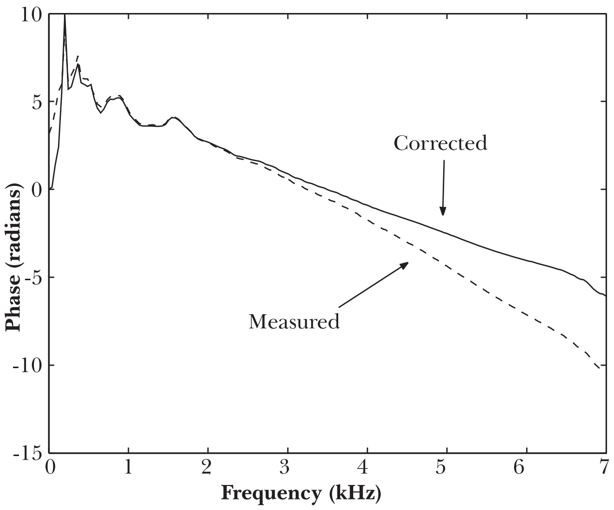

Fig. 6 – Phase delay plot corrected for instrumentation phase delay – short transmission distance.
Fig. 6 –Andamento del ritardo di fase corretto per tenere in conto il ritardo di fase dello strumento - piccola distanza di trasmissione.

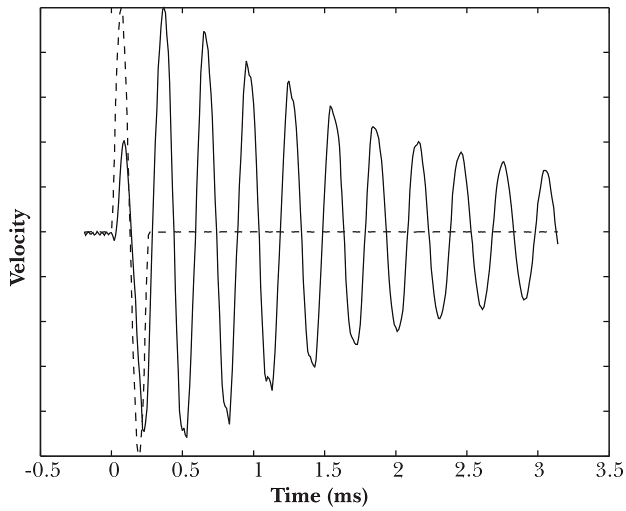

Fig. 8 – Response of bender in air subjected to 4kHz single cycle excitation.
Fig. 8 – Risposta di un bender element in aria soggetto a un'eccitazione a singolo ciclo di 4 kHz.

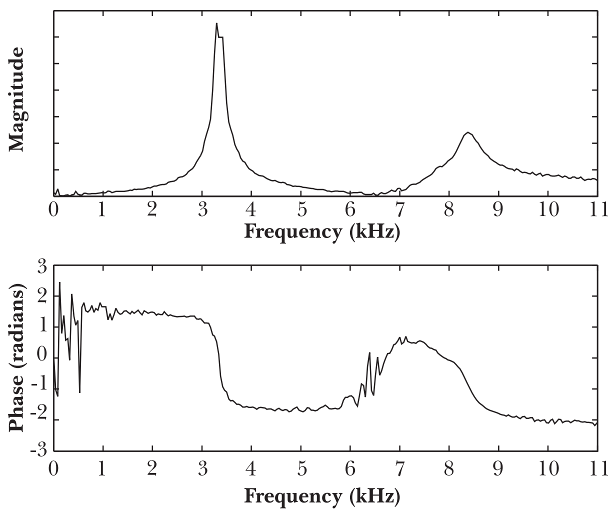

Fig. 7 – Magnitude and phase of transfer function estimate of lateral response of free bender element.
Fig. 7 – Ampiezza e fase della stima della funzione di trasferimento per la risposta laterale di un bender element libero.

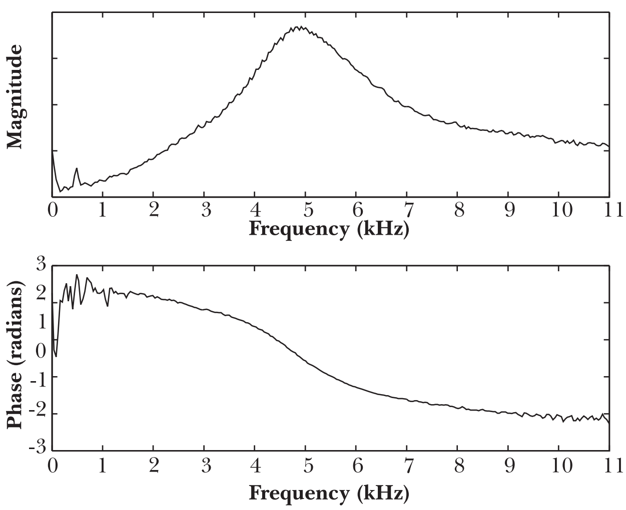

Fig. 9 – Magnitude and phase of transfer function estimate of lateral response of free bender element mounted in polyurethane sample.
Fig. 9 – Ampiezza e fase della stima della funzione di trasferimento per la risposta laterale di un bender element inserito nel provino di poliuretano.

ING and NASH, 2001] since, as Figure 1 shows, the phase delay of the system will include unwanted contributions from the systems shown as S1 and S3.

A 6 mm thick synthetic soil sample with a continuous slot allowed a transmitter and receiver bender mounted in facing sample platens to touch each other tip to tip as the right hand side of Figure 5 shows. The transfer function of this system (shown in Fig. 11) indicates that most information is transferred at and around the 5kHz frequency which we have already shown is the resonant frequency of the bender element mounted in polyurethane.

The phase shift of the transfer function shows a gradual phase lag of around 2π radians developing over a wide frequency range – from 0-9 kHz in this case.

By subtracting this transfer function from the transfer function measured with bender elements some distance away from each other, it is possible to isolate the part of the transfer function for which the soil is responsible. The phase lag is spread nonlinearly along the range from DC to around 8kHz. The greatest rate of change of phase lag corresponds to the resonance of the system. As a guide to the effect that this phase lag has on estimates of travel time, if the phase lag were linearly distributed in the 0-8kHz range, this would imply that waves of all fre-

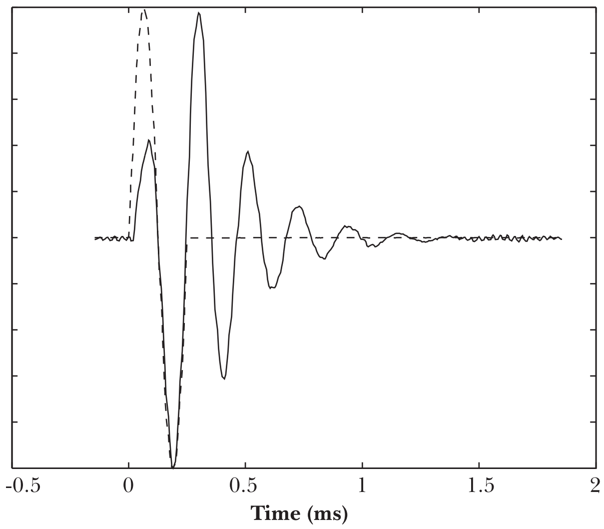

Fig. 10 – Response of bender in polyurethane sample subjected to 4kHz single cycle excitation.
Fig. 10 – Risposta di un bender element nel poliuretano soggetto a un'eccitazione a singolo ciclo di 4 kHz.

quencies are delayed by 0.125ms. This *apparent* delay could cause significant errors in the calculation of shear wave travel time, especially over short transmission lengths. Figure 6 shows the result of removing the instrumentation phase delay for a signal being propagated over only 14mm.

Crosstalk

Another perennial difficulty with bender element testing is dealing with crosstalk, where an attenuated facsimile of the transmitted signal is registered in the received signal. This occurs as a result of insufficient electrical shielding between the signal experienced by the receiving bender and the much larger transmitted signal. LEE and SANTAMARINA [2005] offer some good advice on how best to construct bender elements to avoid the effects of crosstalk.

In this study it was found impossible to completely eradicate crosstalk. Figure 12 shows a typical manifestation of the phenomenon. The amplitude of the crosstalk component is of a similar magnitude in this case to the received signal. At around 0.3mV, the cross talk is several orders of magnitude lower than the input signal (10V). Estimates of the extent of crosstalk were made using pulse signals with varying characteristic frequencies. The results - shown in Figure 13 - indicate that the level of crosstalk is reasonably constant with frequency.

For pulse signals the cross talk does not pose any difficulties. For frequency domain type measurements, the cross talk can overwhelm weak signals reducing the useful range over which phase delay techniques can be applied.

Figure 14, for example, shows the result of re-estimating the phase of a transfer function having removed crosstalk assuming the 0.3mV per 10V rate just described. The dashed line shows the estimated phase delay line before crosstalk is artificially removed. It is clear that a significant amount of extra information has become available.

Being, by definition, a perfect match of the input signal, the crosstalk also tends to give a misleadingly positive picture of coherence when taking the transfer function between transmitted and received signals. The dashed line in Figure 15, for example, shows values of coherence which gives the impression that the transfer function has little noise cor-

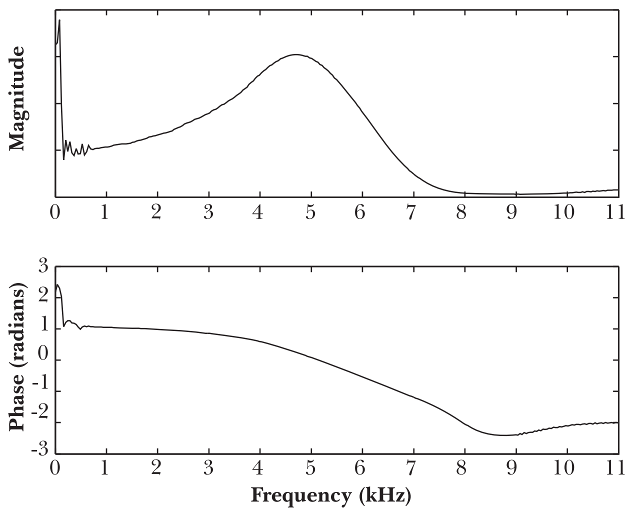

Fig. 11 – Magnitude and phase of transfer function estimate of bender transmitter and receiver touching tip to tip and surrounded by polyurethane.
Fig. 11 – Ampiezza e fase della stima della funzione di trasferimento per un sistema trasmettitore-ricevitore in contatto punta-punta all'interno del poliuretano.

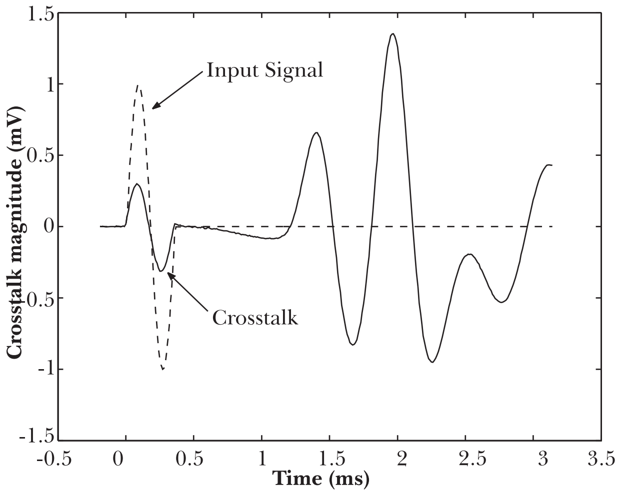

Fig. 12 – Typical crosstalk.
Fig. 12 – Tipico esempio di crosstalk.

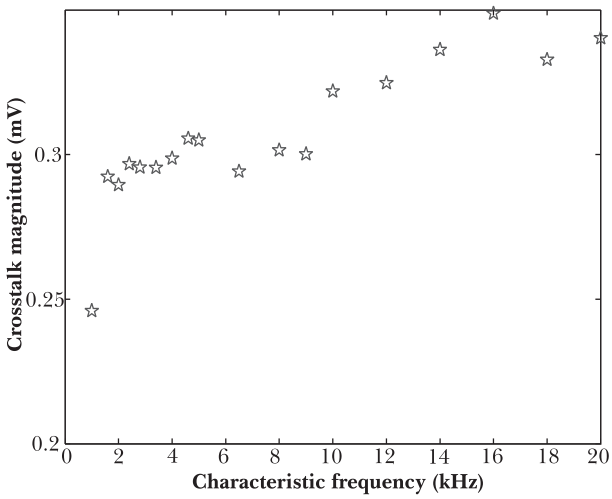

Fig. 13 – Variation in crosstalk with characteristic frequency of pulse transmitted signal.
Fig. 13 – Variazioni nel crosstalk in funzione della frequenza caratteristica del segnale impulsivo trasmesso.

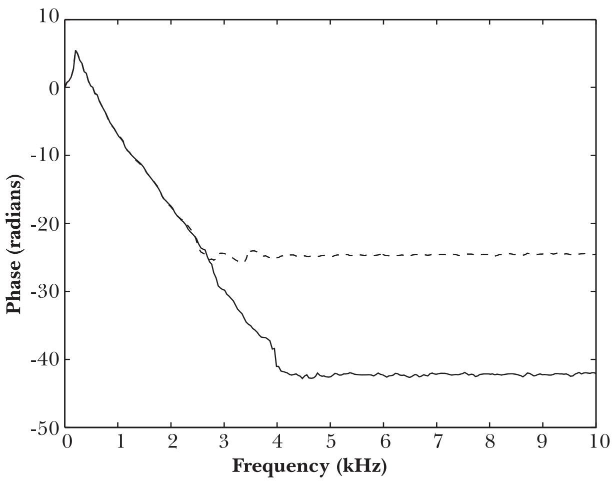

Fig. 14 – Phase delay estimation with crosstalk (dashed line) and with crosstalk removed (solid line) (76mm tall, 75mm wide sample).
Fig. 14 – Stima del ritardo di fase con rimozione del crosstalk (altezza campione 76 mm, larghezza 75 mm).

ruption. The solid line shows a truer picture of the coherence once the crosstalk component of the received signal has been removed.

Concluding remarks

The behaviour of a typical transmitting bender in both air and in a soil-like material has been characterised. A typical tip response in a material whose properties resemble those of certain soils is shown to act as a heavily damped oscillator with a peak amplitude in the region of microns. The results from self monitoring bender elements are shown to be very significantly misleading.

The transfer function of "non soil" components of a bender element test has been established by means of a tip to tip test. The results reveal a phase lag of 2π developing over around 8kHz. While not affecting waves of different frequencies equally the average added delay is around 0.125ms. The extent to which this phenomenon affects the results will depend on the technique being used to interpret the results.

The effect of crosstalk frequency domain measurements has been discussed and a technique for its artificial removal has been suggested. The effect of crosstalk is benign in terms of time of flight / pulse testing but will have the effect of distorting the phase delay relationship at frequencies where the response of the bender drops to a similar order of magnitude to the crosstalk. Crosstalk can also make the coherence of a series of transfer function estimates appear misleadingly positive.

This paper does not solve the central mystery of bender element testing: the most accurate means of interpreting bender element results. It does however, through use of a surrogate soil, shed light on several aspects of bender element testing which were hitherto only in the realms of speculation and debate.

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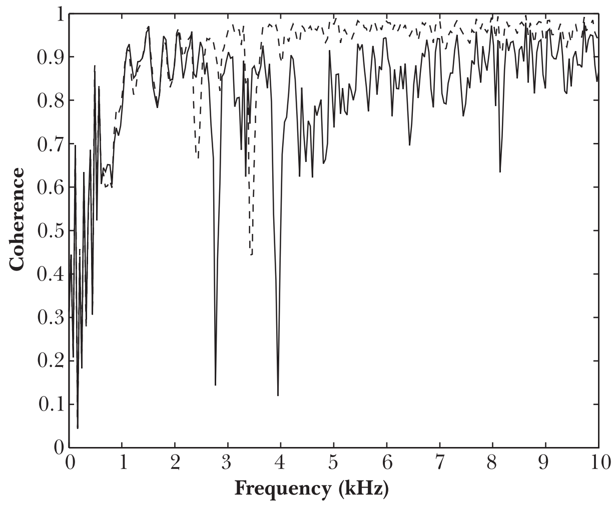

Fig. 15 – Coherence of transfer function for 76mm long, 75mm diameter sample with and without crosstalk removed.
Fig. 15 – Coerenza della funzione di trasferimento per il provino con diametro 75 mm, lungo 76 mm, con e senza rimozione del crosstalk.

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Osservazioni da uno studio parametrico del comportamento di bender elements in gomma poliuretanica

Sommario

L'articolo descrive alcune osservazioni sperimentali tratte da una serie di prove in cui una gomma poliuretanica è stata impiegata in sostituzione del terreno. Vengono descritte le specifiche del poliuretano, le tecniche sviluppate per modellarlo nelle differenti forme e le conseguenti proprietà dell'oggetto. L'inflessione dei bender elements durante l'eccitazione è stata caratterizzata mediante l'utilizzo di un velocimetro laser, sia in aria, sia all'interno del campione. Queste osservazioni mostrano che i risultati ottenuti mediante "auto monitoraggio" dei bender elements non sono affidabili. L'utilizzo di campioni sintetici molto sottili consente di determinare la relazione tra elemento trasmittente e ricevente in contatto tra loro. Usando la funzione di trasferimento e questa modalità, è possibile stabilire come isolare lo strumento dalle onde che si propagano successivamente nel mezzo. Si è osservato e caratterizzato un notevole crosstalk (interferenze elettromagnetiche), e sono discussi gli effetti della rimozione artificiale di tale crosstalk sul dominio della frequenza.