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Time-delay estimation and correlation analysis of acoustic signals in granular media using wavelet decomposition

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Abstract—**The transmission of pulsed ultrasonic signals along a chain of spheres has been studied experimentally, with a view to determine the exact nature of propagation along such chains at ultrasonic frequencies. The transmitted signals were measured using a laser vibrometer, and the resultant waves were analyzed using wavelet decomposition. This allowed the frequency components and the first arrival time to be examined. The propagation velocity along the chain was found to be much smaller than the bulk sound speed of the sphere material. Increased non-linearity also led to higher frequencies being present at higher input levels.**

Keywords—Granular media; Wavelet decomposition; Time-delay; Nonlinear contact law

I. INTRODUCTION

Acoustic wave propagation through granular media was investigated by Nesterenko in 1983 [1]. This work showed that a granular system inherently exhibits rich dynamic behavior, due to interactions between the grains. This has potential for a variety of engineering applications, e.g., in biomedical ultrasound and non-destructive evaluation (NDE).

The dynamic response of these materials was initially solved in the discrete model of a single chain on the basis of the nonlinear contact, i.e. Hertz law between neighboring particles [1]. The wave transmission is tunable, as it depends on the pre-compression in the chain, which determines the propagation regime that exists in a particular granular medium. In Nesterenko's analytical solution, the strongly nonlinear solitary waves are the main mode of transmission in chains where no pre-compression is applied, or where the amplitude of the impacting force is much larger than that of the initial compression. The result is solitary waves, the properties of which were validated experimentally using impulsive signals, generated by the mechanical impact of a striker [2, 3]. Further work has examined harmonic excitation of such chains, in which numerical calculations predicted the existence of nonlinear periodic waves in a pre-compressed chain of spheres [4].

In such a situation, Jayaprakash et al. [5] predicted the presence of frequency bands which are denoted as propagation and attenuation bands (PBs and ABs)), effectively stating that there are likely to be certain allowed modes in which non-linearity would be expected. Furthermore Lydon et al. [6] considered an experimental system of two beads and harmonically excited the first bead by an actuator at near zero pre-compression to study the resultant frequency bands. They concluded that PB bands exhibit strongly nonlinear and non-smooth dynamics at lower frequencies and AB bands present weakly nonlinear and smooth behavior at higher frequencies. The frequency range of their studies was 10 Hz-5 kHz.

In order to extend the study of the granular media to the field of biomedical ultrasound, we have constructed an experimental system to observe the dynamic behavior of a single chain of spheres at higher excitation frequencies (73 kHz and above). Smaller spheres of 1 mm diameter were also used. The results are reported elsewhere in these Proceedings [7]. Both traveling solitary wave impulses and the weakly nonlinear behavior were observed in our experiments. Due to the complexity of the nonlinear dynamics that occurred in these chains, it is thus important to identify the first arrival time and the maximum intensity of the resultant waves, and also to exhibit the intrinsic change in signal transmission. In addition, the measurement of the propagation time along the chain is important for the development of new ultrasonic devices based on chain-like structures. For example, sound bullets can be generated and controlled by ordered arrays of granular chains, achieving a focusing effect via a nonlinear acoustic lens [8]. In developing such a technique, it is essential to determine the time delay of each array accurately, since the flight time of each array will be different by varying the static pre-compression of the chains. Also, it is important to be able to identify different features, even when they are in the presence of noise.

Here, the wavelet decomposition technique was used for estimation of the time delay of acoustic signals transmitted along granular chains. This is because wavelet transformation can decompose the measured signals into scales with different time and frequency resolutions, and can give improvements over the more traditional Fast-Fourier Transformation (FFT) [9]. In our experiments, the velocity signals of both the tip of the resonant transducer used to drive the first sphere, and the last sphere of the chain, were measured using laser vibrometry. Both signals were then decomposed into a sub-set of time-domain signals, each of which covered a definite frequency band. The behavior of particular frequency bands (e.g. those with the maximum amplitude or which are strongly non-linear) could then be studied in terms of their time delay. This was designed to provide a greater understanding of the properties of such chains under different excitation conditions.

II. EXPERIMENTAL PROCEDURE

A single chain of spheres has been investigated experimentally, as shown schematically in Fig.1. The spheres were Grade 10 Chrome Steel of diameter 1 mm. Cylindrical holders for various lengths of chain were fabricated from photopolymer resin using Micro-stereolithography (MSL). The spheres were positioned so as to be just in contact under negligible pre-compression. The first sphere was excited harmonically by a longitudinal ultrasonic horn, which was driven by Agilent 33120A function/Arbitrary waveform generator and a power amplifier. This produced a resonant response at 73 kHz. Coupling gel was used between the first sphere and the transducer for good acoustic transmission as well as to decrease the possible pre-compression force. The last sphere was positioned against an aperture, so that the particle velocity waveform could be measured using a Polytec laser vibrometry system. The velocity signal of both the tip of ultrasonic horn and that of the last sphere in the chain were both recorded in this way, to allow a comparison between the two.

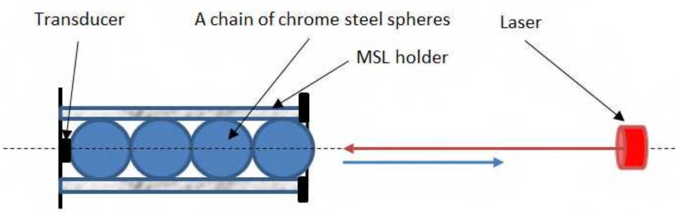

Fig.1. Experimental arrangement for studying spherical chains.

A. *Experimental parameters*

In order to observe both weakly and strongly nonlinear waves generated by the granular chain, the amplitude of output signals of the transducer was gradually increased by controlling the input drive voltage to the ultrasonic horn over the range 41-153 V. As a result, the gradual evolution of solitary wave impulses could be studied. The voltage drive waveform was in the form of a tone-burst of 20 cycles duration, although the output from the horn elongated this because of its resonant response.

B. *Experimental results*

Fig. 2 shows the results obtained when both input (horn tip) and output (last sphere in chain) signals are plotted for different input voltages from the power amplifier.

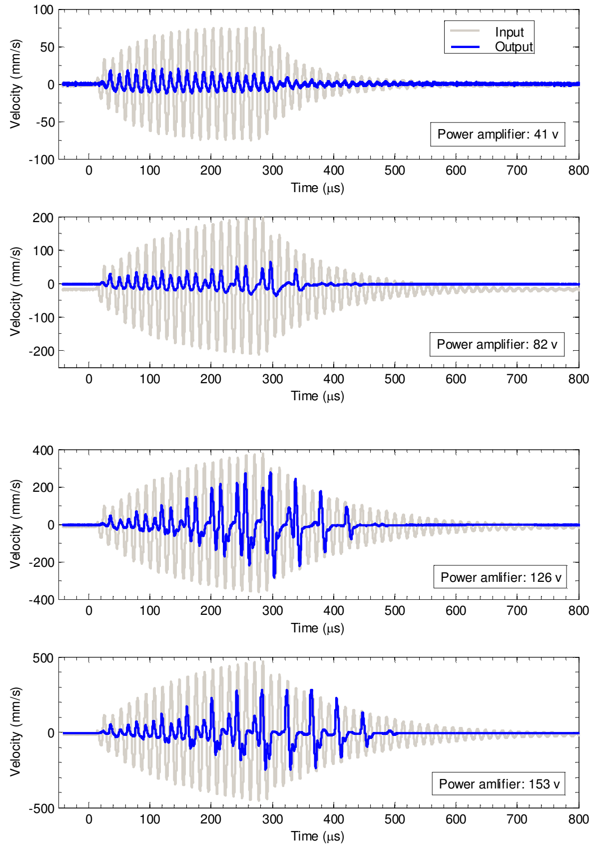

Fig.2. Velocity profiles of the tip of the transducer and the last sphere of the chain, which are referred as the input and output signals, respectively.

As seen in Fig.2, resonance appears in both the transducer and the chain. When driven by a low voltage (41 V), the resultant wave was weakly non-linear and smooth. Little energy was transferred along the chain, and the wave gradually attenuated. However, as the input voltage was increased, the acoustic signals recorded within the chain changed completely - solitary wave pulses were created at high drive voltages, due to strongly non-linear contacts between spheres and subsequent multiple reflections within the chain. Therefore, the experimental output signals consisted of waves with different modes, dependent upon the input voltage level. Noise was also present, especially at low input voltages. As mentioned above, wavelet decomposition provides precise information in both time and frequency domain [9], and it was thus used here to estimate the time delay of acoustic waves in the chain. It was chosen as it can be used on many different types of signals, and is useful even if dispersion or attenuation is present (as in the present case).

III. RESULTS AND ANALYSIS

A. *Wavelet Decomposition*

The discrete wavelet transform is given as [10]:

$$DWT_{\psi}f(m,n) = \int_{-\infty}^{\infty} f(t)\psi_{m,n}^{*}(t)dt, \quad (1)$$

where m and n are positive integers, and where

$$\psi_{m,n}(t) = 2^{-m}\psi(2^{m}t - n)\ . \quad (2)$$

$\psi_{m,n}$ is the dilated and translated style of the mother wavelet $\psi(t)$. The asterisk denotes a complex conjugate. A signal can be composed into scales with different time and frequency resolution due to the multi-resolution analysis (MRA) algorithm. Multi-levels of approximated and detailed coefficients are generated in the wavelet decomposition. The algorithm of wavelet decomposition in the first two levels is illustrated in Fig. 3. The symbols h and g represent low-pass and high-pass decomposition filters respectively. At the first decomposition level, the original signal is passed though both filters, followed by sub-sampling by a factor of 2. cA1 and cA2 are the approximated coefficients of the original signal at levels 1 and 2. cD1 and cD2 are the detailed coefficients at levels 1 and 2. Therefore the details of output signals in different frequency bands can be exhibited in time domain by the MRA analysis.

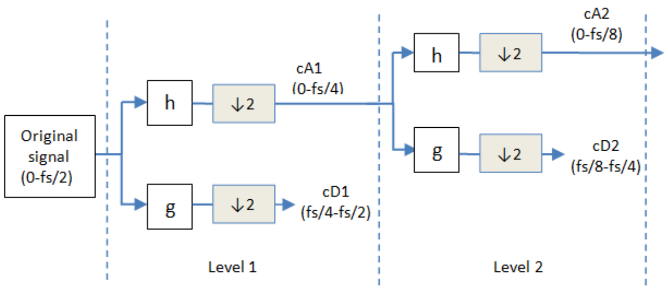

Fig.3. Two levels wavelet decomposition.

The sampling rate of signals in our experiments is 100 MHz, and considering the low input frequency of the resonant horn, as well as the time resolution, a six level wavelet decomposition of the output signal was used. The wavelet transformation was performed for velocity signals of both the input and output of the chain. As described above, the velocity signals were measured at gradually increasing input voltages. Fig.4 illustrates several selective waveforms in wavelet decomposition of the output signal for the highest input voltage of 153 V. In Fig. 4, A6 represents an approximated component of the signal in level-6; D4-D6 then give the detailed components in levels 4-6 respectively. Each level corresponds to a different frequency band. These are D4: 3.125-6.25 MHz; D5: 1.563 – 3.125 MHz; D6: 781 kHz – 1.563 MHz; A6: 0-781 kHz.

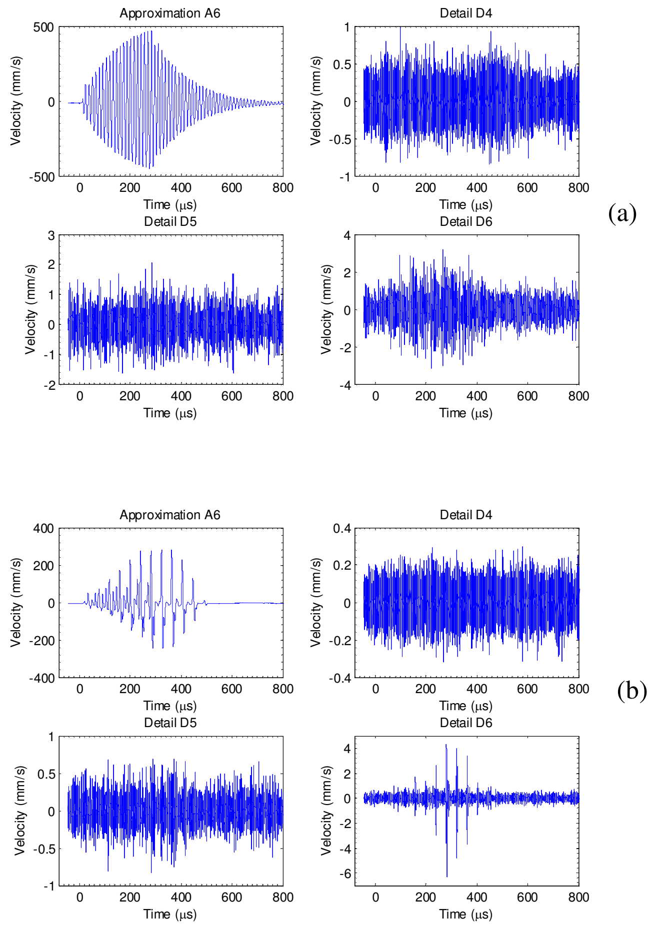

Fig.4. Decomposed waveforms under 153 v input voltage. (a) Decomposition from the horn tip (input signal); (b) decomposition from the output signal (last sphere of the chain).

Consider first Fig. 4(a), where a lot of noise was evident in D4, D5, and D6 at the maximum input voltage level. This means that the input did not contain appreciable energy at frequencies above 780 kHz, as expected from a resonant horn source. However, for the signal at the last sphere, Fig. 4(b), there was evidence that the impulses created due to non-linearity and dispersion had appreciable amplitudes in D6, *i.e.* in the 781 kHz – 1.563 MHz range.

An additional feature of wavelet processing is that it allows the approximation A6 to be used for travel time estimation, as it now has a much improved signal to noise ratio (SNR). For example, it is possible to examine the first arrival of the waveform at the far end of the chain more precisely, relative to the start time of the input waveform, and hence derive an approximate propagation delay along the chain. Fig. 5 shows an expanded waveform of both (a) the input and (b) the output from A6 in Figs.4 (a) and (b) respectively. The time-delay can be identified as 8.74 μs, and for a 6 mm chain, the propagation velocity along the chain was thus 686 m/s.

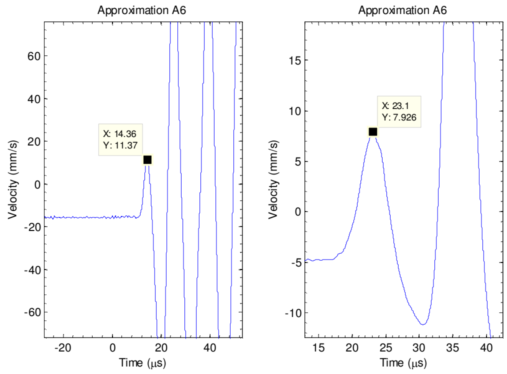

Fig.5. Expanded time waveforms from A6 in Fig.4 for (a) the input and (b) the output.

Fig.6 shows the same decomposed waveforms of the output signal of the chain for the lowest input voltage (41 V). It can be seen that, in this case, the signal contains noise in D4-D6. This means that, as expected, the low input level has not led to any appreciable non-linearity, and hence the lack of signals at these higher frequencies. It is interesting to note that the measured acoustic propagation velocity value, as estimated from A6, changes with the input amplitude; in fact, it increases to 731 m/s for this lower amplitude.

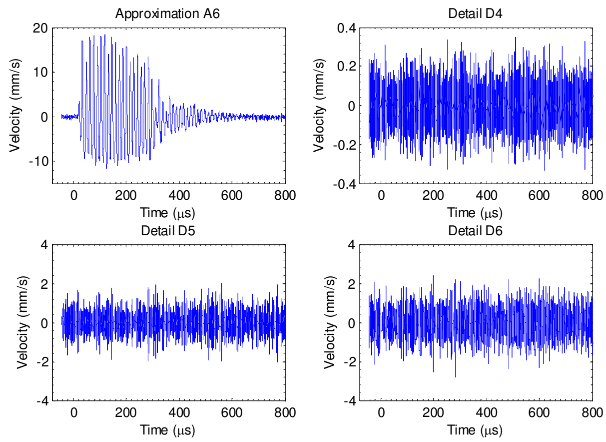

Fig. 6. Decomposed waveforms of the output signal of the chain for a 41 V input voltage.

B. Correlation analysis

Correlation coefficients for input and output signals of the chain in the following four different input voltages (41V, 82V, 126V, 153V) are calculated and presented in Table 1. A0 represents the two original signals; A6 denotes two approximated signals which were obtained in level-6 wavelet decomposition. With an increase in input voltage, both correlation coefficients gradually decrease, so that the output is less linearly dependent with respect to the input. Hence, the results verify that for the low amplitude input, the output signal exhibits weakly non-linear behavior; conversely, under high amplitude inputs, non-linear effects are enhanced and the signals evolve to form the impulses which were observed in Fig.2.

TABLE I. CORRELATION COEFFICIENTS.

Drive Voltage (V)		**41**	**82**	**126**	**153**
Correlation coefficient	**A0**	0.7573	0.6428	0.5560	0.4686
	A6	0.7668	0.6431	0.5561	0.4687

IV. CONCLUSIONS

A single chain containing six 1mm diameter steel spheres has been studied under high frequency excitation. At low amplitudes, the output signals are weakly non-linear, but with an increased input amplitude, solitary wave pulses evolve. The wavelet analysis has shown that the higher amplitudes lead to impulses with components at frequencies an order of magnitude higher than the input at 73 kHz. In addition, the time delay of the wave along the chain was estimated based on wavelet decomposition. The propagation velocity is much smaller than the bulk sound speed of the sphere material due to strongly non-linear Hertzian contact between spheres, and varies with input amplitude.

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