Proceedings Paper:

Hutchins, DA, Yang, J, Akanji, O et al. (6 more authors) (2015) The generation of impulses from narrow bandwidth signals using resonant spherical chains. In: 2015 IEEE International Ultrasonics Symposium (IUS). , 21-24 Oct 2015, Taipei, Taiwan. IEEE . ISBN 978-1-4799-8182-3

https://doi.org/10.1109/ULTSYM.2015.0050

The generation of impulses from narrow bandwidth signals using resonant spherical chains

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Abstract — An ultrasonic horn operating at 73 kHz has been used to excite one end of a chain of steel spheres. The signal transmitted along the chain was measured at the far end using a laser vibrometer. Various chain lengths, ranging from 2-10 spheres, have been studied. It was found that a set of solitary wave impulses were generated when a high input amplitude and a minimal pre-compression force was used. Both harmonics and sub-harmonics of the input frequency could be observed. Theoretical models were developed, based on the relevant equations of motion, which modelled the end conditions properly, and their predictions confirmed the experimental observations. Solitary wave impulses were generated only when certain numbers of spheres were used, corresponding to the establishment of resonances in the form of nonlinear normal modes (NNMs). It was found that longer chains led to wider impulse bandwidths. Increased pre-compression tended to damp out this phenomenon, but gave a weakly non-linear state where the time delay of propagation along the chain changed with applied static force. It was thus established that a gated sinusoidal input could be transformed into a set of impulses, of interest in biomedical applications.

Keywords—solitary wave impulses; harmonic generation; nonlinear waves

I. Introduction

A linear chain of spheres is known to exhibit strong nonlinearity, due to Hertzian contact between neighbouring spheres [1]. Under the correct conditions, solitary waves can then exist, and propagate along the chain if an impulsive force is used as the input signal. In a long chain, these waves have a characteristic form, with a periodicity that is predictable from the size of the spheres used. The nonlinear nature of the Hertzian contact between the spheres is dependent on the relative values of the oscillating applied force (f_m) and static pre-compression (f_0). Thus, if $f_m \ll f_0$, the chain acts like a continuous medium (a normal solid) supporting linear waves. If $f_m \approx f_0$, a weakly nonlinear wave is generated; but if $f_m \gg f_0$, propagation through the chain becomes highly nonlinear, and solitary waves can exist.

Such behaviour has been studied extensively for impulsive inputs [2]. However, as nonlinearity is greater when $f_m \gg f_0$, it seemed that interesting effects would occur if a very large input amplitude from an ultrasonic horn was used. It is this approach that is reported here. Preliminary studies have already been published by the authors [3]. In this paper, more details are given of the effect of changing input amplitudes (f_m), chain characteristics and static pre-compression forces (f_0).

II. Experimental Arrangement and Typical Outputs

A schematic diagram of the experimental arrangement is shown in Fig. 1(a). A chain of spheres was held within a cylindrical container, and a 73 kHz ultrasonic horn, used to excite one end of the chain. The waveform at the output was then recorded using a vibrometer. A photograph of the horn is shown in Fig. 1(b). This just touches the first sphere in the chain with the minimum pre-compression force.

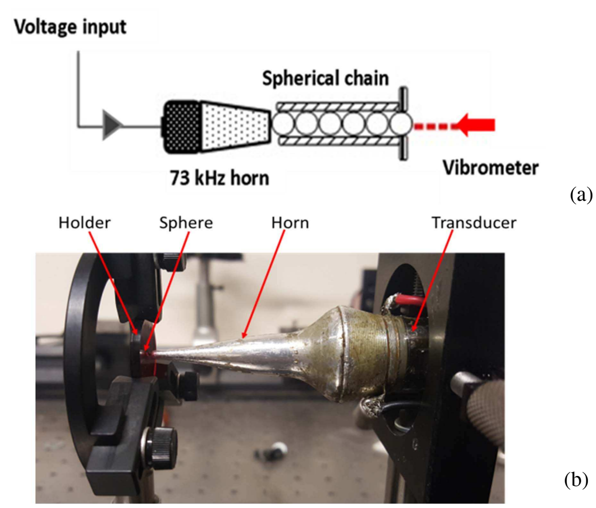

Fig. 1. (a) Schematic diagram of the experiment. (b) Photograph of the horn tip touching the first sphere of a chain, protruding from the cylindrical holder.

Examples of typical waveforms that resulted from a chain of 1 mm diameter chrome steel spheres are shown in Fig. 2. This shows both the input waveform from the horn, and the output from the far end of the chain, in terms of the particle velocity waveform. The pk-pk amplitude of both is shown for three different input amplitudes for a 6-sphere chain. At low input amplitudes (Fig. 2(a)), the output is an attenuated signal at 73 kHz. At intermediate inputs (Fig. 2(b)), the signal starts to change, with some evidence of impulsive behavior. Finally, once the input is of sufficiently high amplitude (Fig. 2(c)), a set of solitary wave impulses is present. This demonstrates that the apparatus has achieved its main aim of generating solitary wave impulses from a narrow bandwidth input.

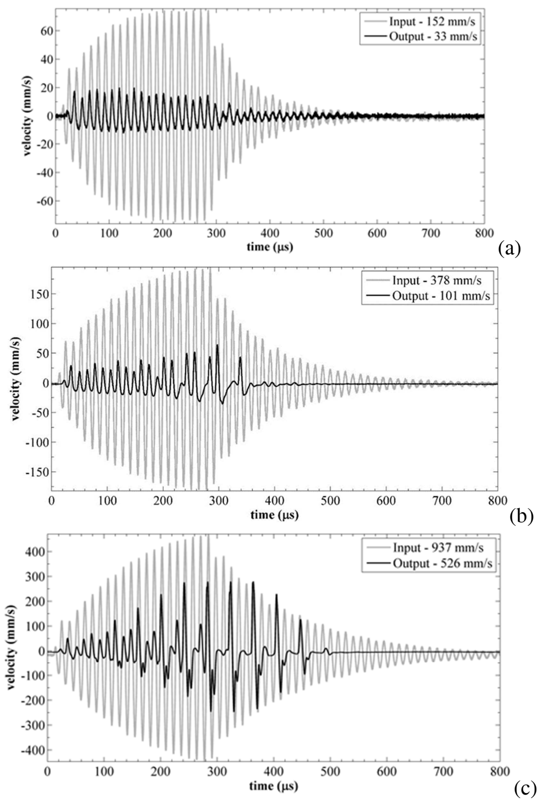

Fig. 2. Input (grey) and Output (black) signals for a chain of 6 steel spheres of 1 mm diameter as the input particle velocity amplitude was (a) 152 mm/s, (b) 378 mm/s and (c) 937 mm/s. The legends show the maximum peak to peak particle velocities of both the input and output signals.

It is possible to model the expected output from spherical chains, using the known input signal and the properties of the chain. Details of the analytical model used here are given in a previous publication [3]. The predictions for input amplitudes 378 m/s and 937 mm/s are shown in Fig. 3. While some minor differences exist, it is clear that the main features seen experimentally are predicted, with the higher input amplitude leading to a clearer set of solitary wave impulses.

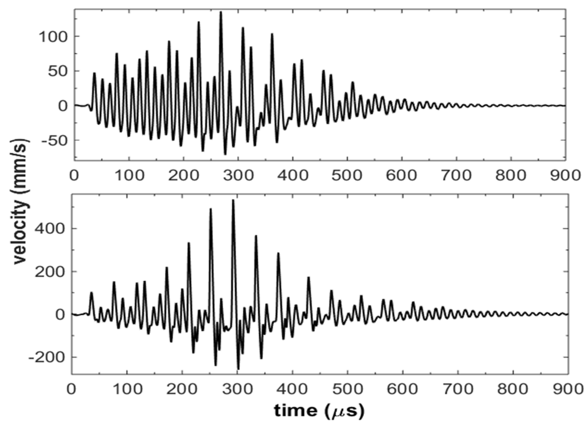

Fig.3. Theoretical predictions corresponding to the conditions used to produce the results in Fig. 2(b) and 2(c).

III. Results for different experimental conditions

A. Different lengths of chains

Experiments have been performed for a wide range of sphere materials, sphere sizes and chain lengths. To further explain the phenomena at work, consider the results obtained for a 73 kHz tone-burst input for different chain lengths for the 1mm diameter steel spheres. Using the same apparatus, the waveforms that result for selected chain lengths are presented in Fig. 4. Some general observations can be made. First, clear impulses were observed for chain lengths of 3, 6 and 10 spheres; in fact, other chain lengths in the range from 3-10 spheres did not result in clear solitary wave impulse generation. Further, the time duration between impulses increased with chain length, as individual impulses had a wider bandwidth (*i.e.* a shorter time duration). It should be noted that the duration of the tone-burst input was adjusted to get the best result; it was found that a longer excitation waveform was needed to get the best result from longer chain lengths.

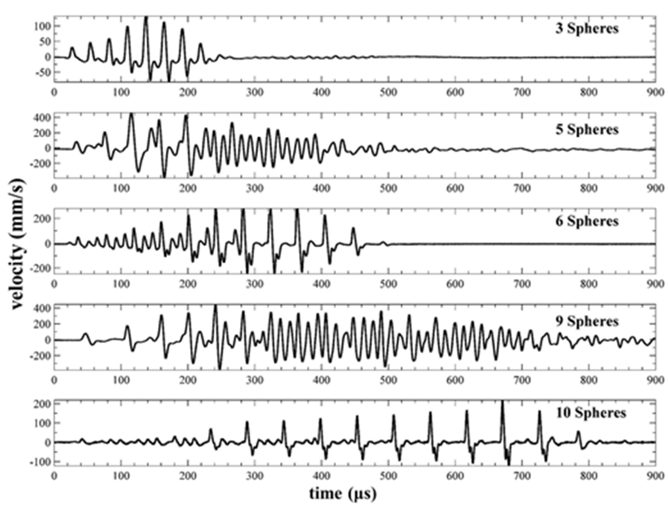

Fig. 4. A series of waveforms obtained from the experiments for various chain lengths and input duration at 73 kHz.

The spectra corresponding to the waveforms in Fig. 4 are shown in Fig. 5, and contain some interesting features. The vertical line represents the input signal at 73 kHz, and it can be seen that all spectra contain the expected peak at this frequency. However, consider the 3-sphere chain. This contains a large frequency peak at 1/2 this value (36.5 kHz), with a third peak higher than the input by the same amount. The 6-sphere case also contains a set of regularly-spaced frequency peaks, but these are now separated in frequency by 1/3 of the value of the input. Finally, the 10-sphere case has peaks separated by ¼ of this value.

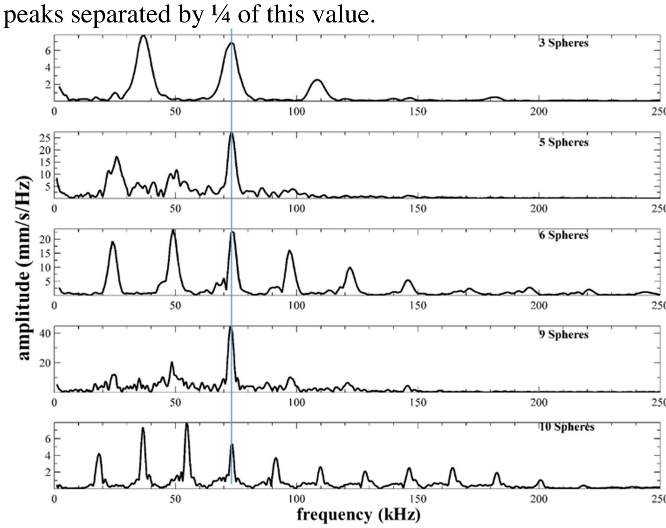

Fig. 5. Spectra of the particle velocity waveforms shown in Fig. 4.

It is clear from these results that the spherical chain naturally selects certain lengths at which a set of resonant peaks occur, each of which are separated by a sub-harmonic of the driving frequency. These resonances of the chain are examples of non-linear normal modes (NNMs) of the system, and the properties of NNMs have been described by other authors [4]. The interesting point is that such behaviour has not been observed previously – other studies were limited to larger spheres or limited drive amplitudes, and tended to be at low frequencies. Here, we have demonstrated that a high amplitude tone-burst at 73 kHz can create frequency peaks at frequencies in excess of 200 kHz, using the features that result in the presence of strongly non-linear systems. Inherent in this is the creation of NNMs by reflection from both ends of the chain.

The experimental creation of solitary wave impulses relies on the fact that $f_m \gg f_0$. In the experiment, care was taken to minimise the static pre-compression force f_0, but it was still finite due to contact with the ultrasonic horn. Theoretically, the models require that f_0 is finite to achieve an output such as that seen experimentally. It thus appears that some level of pre-compression is essential for the creation of the type of solitary wave impulses shown here.

B. Different sphere materials

Experiments have been performed on different sphere materials. Some examples are shown in Fig. 6 for a polymer (Delrin), chrome steel and tungsten carbide. These results and others indicate that the material from which the spheres are made has a secondary effect on the waveforms and spectra – the periodicity of the solitary wave impulses is the same, as seen in both waveforms and spectra. Thus, for a given excitation frequency, the overall length of the chain and the number of spheres it contains are the main criteria determining the periodicity of the impulses (and hence also the NNMs in the frequency spectrum). The overall bandwidth is, however, affected, with the higher modulus material (tungsten carbide) exhibiting the lowest bandwidth.

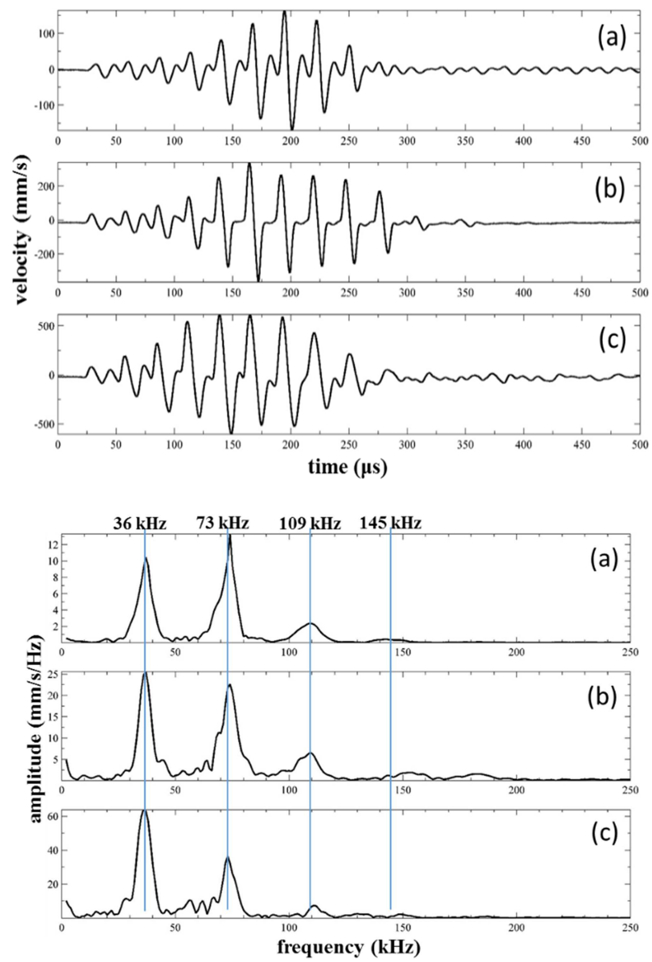

Fig. 6. Waveforms (top) and spectra (bottom) from experiments on a 3 x 1 mm chain of (a) polymer, (b) chrome steel and (c) tungsten carbide spheres.

C. Changes in pre-compression force

The apparatus used for this is shown in Fig. 7. A stylus profiler, usually used for measuring surface topographies, was

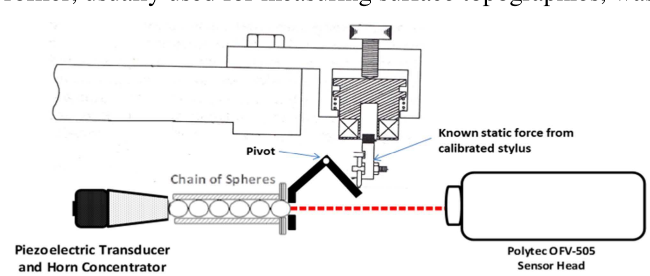

Fig. 7. Schematic diagram of the modified experimental arrangement, used to apply a known static pre-compression force (f_0) to a chain.

modified so as to apply controlled pre-compression forces f_0 to a chain. The probe contained an electromagnetic force actuator, a differential capacitive sensor and a leaf spring suspension system. Using a specially designed current drive, the force actuator provided a calibrated static contact force via a 1.5 mm diameter stylus. This apparatus was able to apply known static forces with a resolution of 1 mN. An overview of the pre-compression assembly is shown in Fig. 7. The stylus pushed vertically downward with a known force on the lever arm, which in turn transferred this force to the output end of the chain via an annulus through which the end sphere protruded. The profiler was mounted onto an aluminium platform with its stem clamped onto a Rank Taylor Hobson Talysurf 5 to support the magnet and coil placed directly above the stylus. It was noted that this changed the response of the chains slightly. In other work, it has been observed that small changes in these highly-resonant systems can cause observable effects – changing the holder material, for example. Here we have modified the end wall, changing the details of how the NNMs are extablished via reflection within the chain.

The response of a chain of three 1 mm diameter chrome steel spheres to increased levels of f_0 is shown in Figs. 8 and 9 for waveforms and spectra respectively. It will be seen that the periodic impulses created using the minimum f_0 (estimated at 10 mN) start to revert back to the periodicity of the input signal with increasing pre-compression, and that with an additional 80 mN, the impulses have been damped out by the increasing stiffness of the chain. The spectra indicate that this is associated with a supression of the subharmonics and harmonics. The system has thus become weakly non-linear.

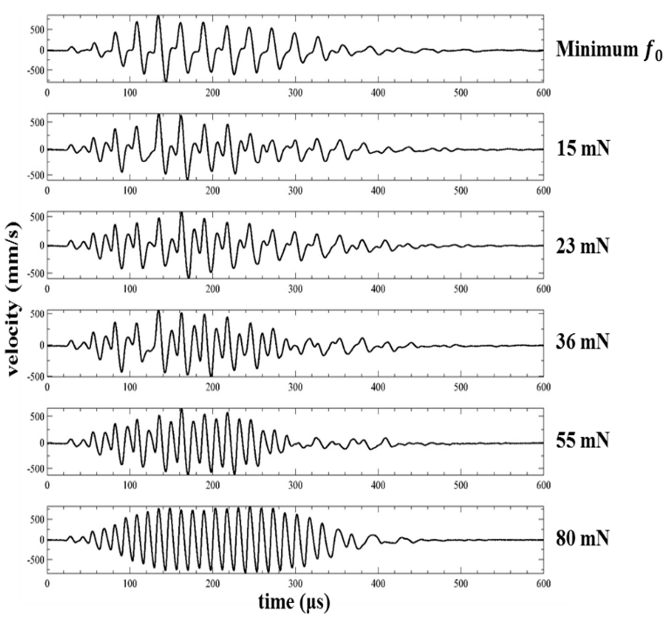

Fig. 9. Output waveforms for a chain of 3 spheres excited at 73 kHz and using the modified fulcrum to vary the pre-compression.

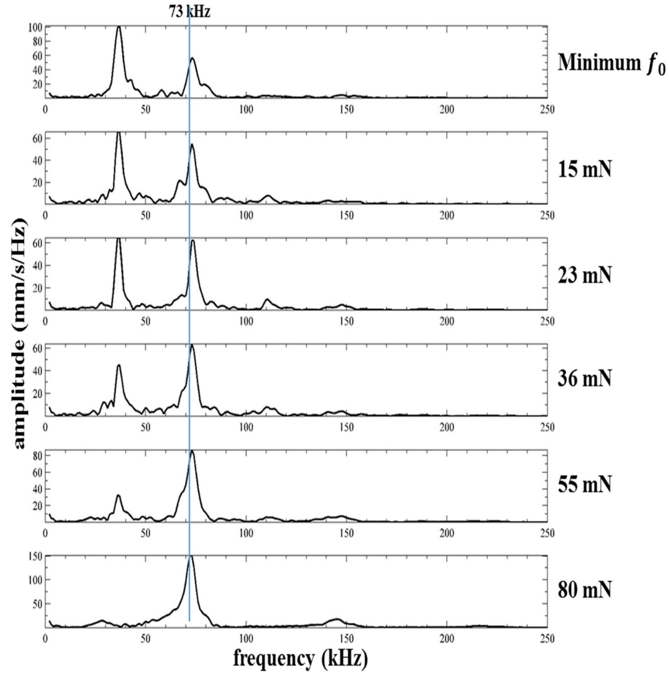

Fig. 9. Output waveforms for a chain of 3 spheres excited at 73 kHz and using the modified fulcrum to vary the pre-compression.

It is also interesting to observe that the propagation velocity of signals along the chain changes with f_0. This behaviour thus has features in common with observations of propagation in chains using impulsive inputs [2].

IV. Conclusions

It has been shown that a chain of spheres of finite length can exhibit resonant nonlinear normal modes (NNMs), when excited with a tone-burst of high amplitude from an ultrasonic horn. Solitary wave impulses can be created, whose characteristics can be changed for different chain configurations.

Acknowledgment

The authors gratefully acknowledge funding from the Engineering and Physical Sciences Research Council (UK) via grant number EP/K030159/1.

References

[1] V. F. Nesterenko, Dynamics of Heterogeneous Materials, Springer, 2001.

[2] C. M. Donahue, P. W. J. Anzel, L. Bonanomi, T. A. Keller, and C. Daraio, "Experimental realization of a nonlinear acoustic lens with a tunable focus," Appl. Phys. Lett., vol. 104, pp. 014103, 2014.

[3] D. A. Hutchins, J. Yang , O. Akanji, P. J. Thomas, L. A. J. Davies, S. Freear, S. Harput, N. Saffari and P. Gelat, "Evolution of ultrasonic impulses in chains of spheres using resonant excitation," Europhys. Lett., vol. 109, pp. 54002, 2015.

[4] J. Lydon, K. R. Jayaprakash, D. Ngo, Y. Starosvetsky, A. F. Vakakis and C. Daraio, "Frequency bands of strongly nonlinear homogeneous granular systems," Phys. Rev. E, vol. 88, 012206, 2013.