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Nonlinear tuning curve vibration using a column of dry or wetted granular material vibrating over a clamped elastic plate

Emily Santos[1]
UMBC
1000 Hilltop Circle
Baltimore, MD 21250-0001

Murray Korman[2]
United States Naval Academy
Physics Department
572-C Holloway Road
Annapolis, MD 21402

ABSTRACT

A soil plate oscillator (SPO) apparatus consists of two circular metal flanges sandwiching and clamping a thin circular elastic plate. The apparatus can model the acoustic landmine detection problem, in particular the vibration interaction between a column of granular media and the elastic plate supporting the column. Uniform spherical soda-lime glass beads – representing a nonlinear mesoscopic elastic material – are supported at the bottom by the acrylic plate (4.5 inch diam, 1/8 inch thick) and cylindrical sidewalls (1/4 inch thick) of the upper flange. A 6 inch diam loud speaker placed 2 inches above the bead column is driven with a swept sinusoidal signal applied to a constant current amplifier to generate air-borne sound excitation from 50 – 1250 Hz. A small accelerometer fastened to the underside of the plate at the center measures the response using a spectrum analyzer. Nonlinear tuning curves of the plate vibration are measured using 350 g of dry beads for separate experiments with 2, 4, 6, and 8 mm diam beads. Experiments are repeated with beads wetted by mineral oil. Results show less frequency "softening" in the backbone curves (peak acceleration vs. corresponding resonant frequency) for wetted beads compared with dry beads. Nonlinear tuning curves are compared using (a) 6 mm diam beads, then (b) dry sifted masonry sand.

Keywords: Granular Mesoscopic Material, Vibro-acoustic, Nonlinear, Tuning Curve
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Plastic land mines are difficult to detect using conventional metal landmine detection

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[1] esantos1@umbc.edu
[2] korman@usna.edu

methods. Acoustic landmine detection has been used as a confirmation sensor in landmine detection scenarios, along with ground penetrating radar. Both technologies help detect landmines that are constructed from plastic or other non-metallic materials. While modelling acoustic landmine detection we use a model apparatus called a soil plate oscillator. See Figure 1 below.

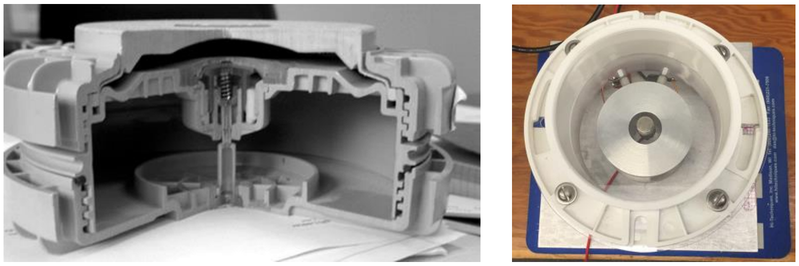

Figure 1(a) Cross section of an inert VS 1.6 anti-tank plastic land mine. The top-plate diam is 14.5 cm and the overall height is 9.3 cm. The VS 1.6, buried in a roadbed, can be detected using air-borne sound excitation and remote laser Doppler vibrometer measurements along the soil or gravel surface. (b) Soil – Plate – Oscillator SPO made with two white PVC flanges ID = 4.5 inches, wall thickness ¼ inch. The flanges clamp the circular acrylic plate which is 1/8 inch thick. (The AC coil located below the elastic plate and ½ inch diam magnet fastened to the plate shown in (b) were used in some of the experiments reported here.) Note: The density of the sand was 1.43 g/cc.

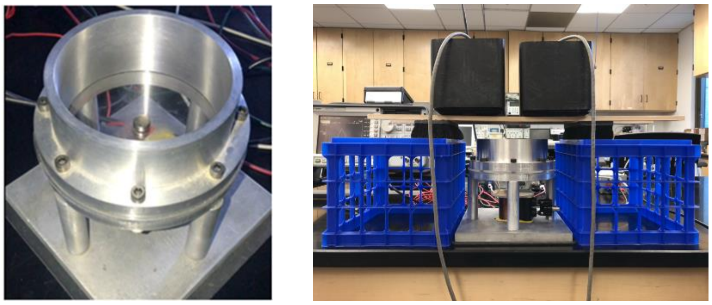

Figure 2 (a) Soil-Plate – Oscillator (SPO) made with aluminum flanges ID = 4.5 inches, wall thickness ¼ inch, acrylic plate is 1/8 inch thick. (b) Setup to use a Polytec 100 Laser Doppler vibrometer LDV to measure the soil surface particle velocity frequency response due to the air-borne sound from the pair of speakers (3 inch diam) driven by a single constant current amplifier. LDV is not show. (The AC coil located below the elastic plate and ½ inch diam magnet fastened to the plate shown in (b) were used in some of the experiments reported here.)

A soil plate oscillator (SPO) apparatus (Fig. 2) consists of two circular flanges sandwiching and clamping a thin circular elastic plate. The apparatus can model some aspects of the acoustic landmine detection problem. Here, uniform spherical glass beads – representing a nonlinear mesoscopic elastic material – are supported at the bottom by the acrylic or white PVC plate (4.5 inch diam, 1/8 inch thick) and stiff cylindrical sidewalls of the upper/lower flanges. We might call the SPO: a bead plate oscillator (BPO) when using beads. An accelerometer fastened to the underside of the plate is used to measure the frequency response. Here, an Endevco model number 2226C accelerometer signal connected to an op amp charge amplifier goes to an Agilent 356701A dynamic analyzer which measures the particle acceleration response vs. frequency.

2. EXPERIMENT 1: Tuning Curves

A ½ inch diam magnetic disk centred and fastened below the plate is driven by an AC coil placed below the magnet. Nonlinear tuning curves of the magnet's acceleration are measured by driving the coil with a swept sinusoidal signal applied to a constant current amplifier. Tuning curve experiments are performed using a fixed column of 350 grams of beads using 7 mm diameter beads in these experimental trials.

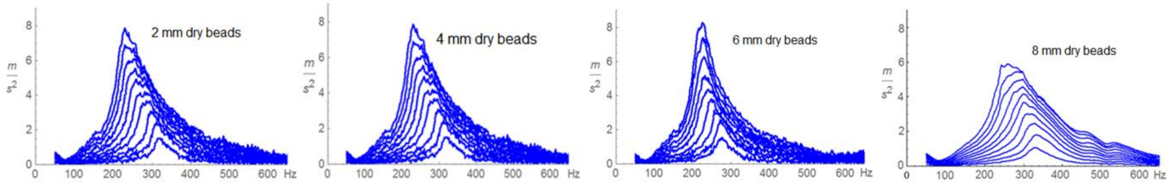

Fig 3. Tuning curves of dry (a) 2mm (b) 4mm (c) 6mm (d) 8 mm glass beads.

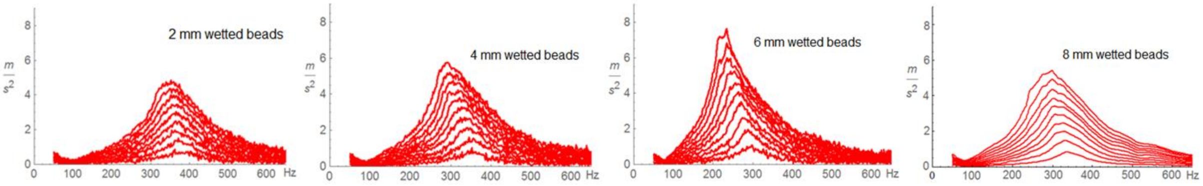

Fig 4. Tuning curves of wet (a) 2mm (b) 4mm (c) 6mm (d) 8 mm glass beads.

A comparison of the white PVC bead-plate-oscillator measuring the acceleration response vs. frequency (at the center of the underside of the plate) for incremented airborne drive levels. The mass of the beads was 350 g in each case. Wetted beads (using 1 tsp. mineral oil) show less nonlinear bending in the back-bone curves. For the 8 mm bead comparison, the nonlinear effects due to "wetting" are must less severe than for 2 mm wetted beads. See Figures 3 and 4 above.

3. EXPERIMENT 2: Two-Tone Tests

The interface between the flexural plate vibration and beads is a very nonlinear system. In two-tone tests, air-borne sound from two 3 inch diameter speakers drives the bead column surface at

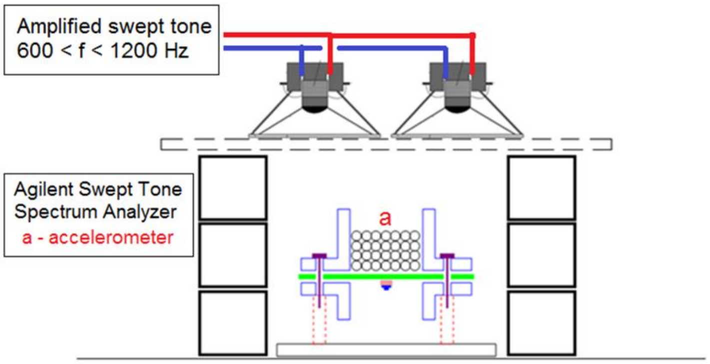

Fig 5. Two-Tone Test setup with white PVC and speakers. Accelerometer -placed on the surface of the glass beads which is connected to a charge amplifier and a spectrum analyser.

closely spaced frequencies near the fundamental resonance 910 Hz. (See Fig. 5.) Nonlinearly generated combination frequency tones are measured using 7 mm diameter beads in this demonstration experiment. The single tone tests and two-tone tests results are presented in Fig. 7.

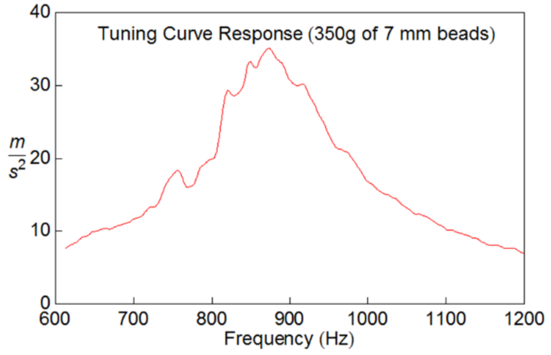

Fig 6. First find the tuning curve response which is near 900 Hz, then plan out the two-tone test.

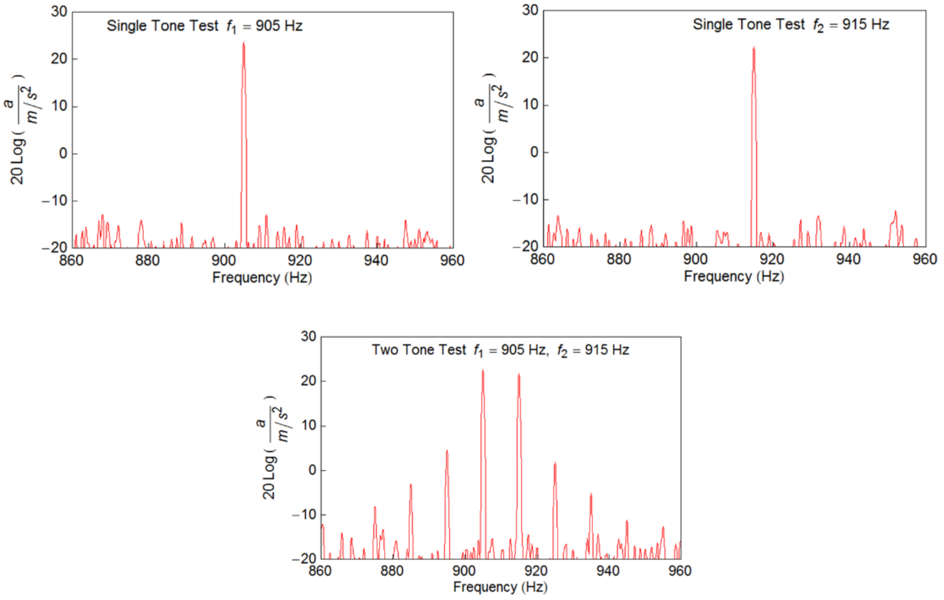

Fig 7. (a) Single Tone Test at 905 Hz (b) Single Tone Test at 915 Hz (c) Two-Tone Test at 905 and 915 Hz.

In Fig. 6 we use a resonant frequency near 900 Hz for the two-tone test. Single tone tests at 905 and 915 Hz are shown in Fig. 7(a) and (b). Some combination frequencies in Fig. 7(c) are:

$f_1 - (f_2 - f_1) = 895$ Hz, $f_2 + (f_2 - f_1) = 925$ Hz, $f_1 – 2 (f_2 - f_1) = 885$ Hz, $f_2 + 2 (f_2 - f_1) = 935$ Hz

4. EXPERIMENT 3: Tuning Curve Response vs. Drive Level

An AC coil drives a magnet on the plate underside or airborne sound from loud speakers above drives the system. In this experiment, an aluminium SPO is used to produce a tuning curve response from a magnet attached to the underside of the clamped elastic plate with no bead loading (Fig. 8(a)). Notice the slight increase in frequency versus the drive amplitude. This is due to plate nonlinearity, which can be seen in Fig. 9(a). This phenomena is called "frequency hardening." An aluminum SPO tuning curve response on the underside of the plate with 350 g of 7 mm beads (Fig. 8(b)) is shown in Fig. 9 (b).

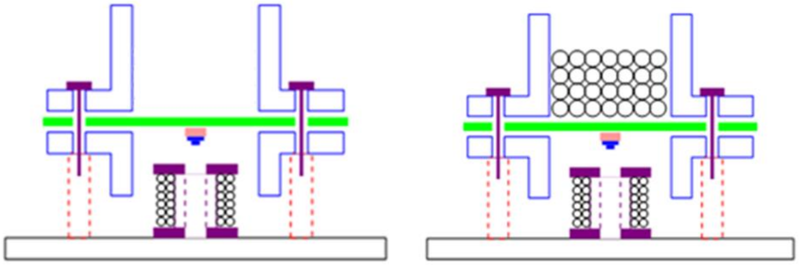

Fig 8. Soil plate oscillator (a) no bead loading (b) with bead loading. Along with the upper and lower flanges clamping the circular elastic plate, an AC coil is shown (below the plate) which drives the small ½ inch diam magnet that is fastened to the underside of the plate.

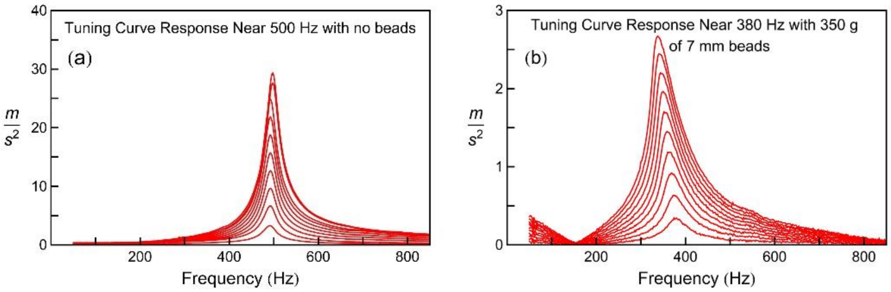

Fig 9. Aluminum SPO accelerometer response on the underside of the clamped elastic plate near the fundamental resonance of (a) the soil plate oscillator without bead loading and (b) with 7mm beads (not wetted).

The backbone curve is obtained by plotting the peak acceleration and corresponding resonant frequency from the tuning curve in Fig 9 (b). The back-bone curve (shown in Fig. 10) is obtained from the tuning curves (in Fig. 9(b)) and shows a linear slope that is characteristic of nonlinear

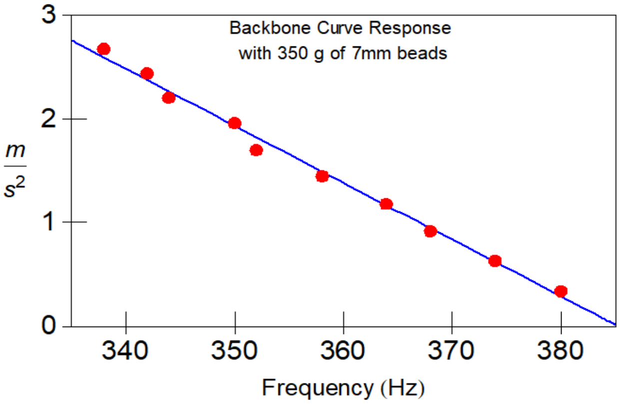

Fig 10. Backbone curve response with 350 g of 7mm glass beads.

mesoscopic elastic behaviour in geo-materials like sandstone such as Berea sandstone. When one observes a frequency decrease with increasing drive amplitude, we say the system exhibits an effective spring constant “softening”

5. EXPERIMENT 4: Sand vs. Beads

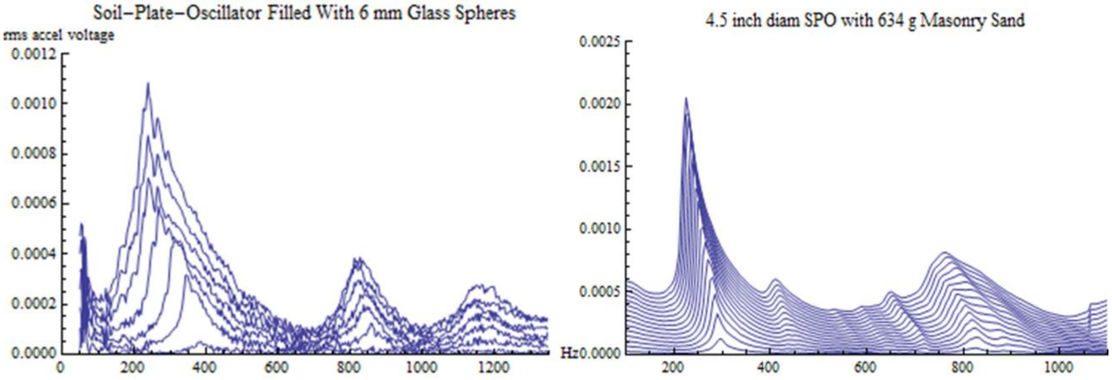

Fig 11. The SPO NL tuning curves are for (a) 6mm beads and (b) masonry sand. The SPO is now driven from below using the AC coil and ½ inch diam magnet fastened to the underside of the elastic plate at the center. The accelerometer with the charge amplifier has a sensitivity of 1.14 mVrms /(9.81 m/s^2). For a vertical rms voltage of 0.001 Vrms, the rms acceleration is 8.60 m/s^2.

6. DISCUSSION AND CONCLUSIONS

Developing an understanding of the air-borne excitation and vibro-acoustic detection of a complex structural elastic target buried in a soil or roadbed with natural weathered inhomogeneous layered granular media (including debris or shrapnel) is computationally challenging. However, a model apparatus called a soil (sand) plate oscillator SPO is a robust physical model of the nonlinear interaction of granular media (contained in an open cylindrical column). Here, sand is interacting with the vibration of a clamped circular elastic plate which supports the granular column. In acoustic landmine detection experiments a laser Doppler vibrometer LDV remotely measures the soil-surface vibration which could be over a target or measurements in the absence of a target.

False alarms could occur due to the natural inhomogeneous layering of weathered soil. However, tuning curve measurements on the surface over buried drum-like landmine simulants or an inert anti-tank plastic landmine (VS 1.6) exhibit nonlinear tuning curve behaviour that has a characteristic arched shape in the backbone curve. Tuning curve behaviour of the soil or gravel-like media (in the absence of a drum-like target) seem to exhibit somewhat less nonlinear tuning curve behaviour and the backbone curvature is significantly reduced.

The soil (sand or bead) plate oscillator SPO experiments involved measurements of the tuning curve vibration acceleration response vs. frequency near resonance with granular material loading. Here the accelerometer is placed on the underside of the elastic plate at the center. In nonlinear tuning curve experiments, with no granular medium loading, the tuning curves exhibited a slight “hardening” as the drive amplitude increased. Here, the nonlinearity is due to finite-amplitude atomic elasticity which introduces nonlinear terms in the elastic equations of motion for a thin clamped circular plate [1].

When a granular medium (glass beads or dry sifted masonry sand) is placed in the SPO, the vibration interaction between the flexural oscillations of the clamped plate and the granular medium above the plate is very nonlinear. (See Fig. 11.) For example, when the plate exhibits upward curvature (where the center of the plate is below the equilibrium position) one could imagine the granular particles crowding together). However, when the plate exhibits downward curvature (where the center of the plate is above the equilibrium position) one could imagine the granular particles loosing contact – to some degree. In a lumped element one dimensional (mass-nonlinear spring system) model developed by Caughey [2], the spring element is modelled as a bilinear hysteresis force. In driving the 1-dim system with a theoretical sinusoidal excitation, the frequency response of the system yields nonlinear tuning curves with "softening." Further, the tuning curves exhibit a backbone curve that has upward curvature. This curvature is in agreement with the experimental tuning curves measured in the SPO with glass bead or masonry sand loading. In acoustic landmine detection schemes this curvature (in the backbone curve) might be greatly diminished due to tuning curve resonances - just from the natural layering of the weathered soil.

A linear backbone curve can be described by mesoscopic nonlinear elastic behaviour - similar to the resonant tuning curve behaviour observed in geo-materials like sandstone [3-5]. With further increase in drive amplitude the SPO tuning curves exhibits a slightly arched or curvature behaviour. This behaviour, mentioned earlier can be predicted by using a bilinear hysteresis lumped element model [2] in a driven harmonic oscillator. Comparisons of the SPO tuning curves with a buried VS 1.6 inert plastic anti-tank landmine in a sand tank are reasonable and offer some insight on the future use of the SPO to model acoustic landmine detection using airborne sound.

Two-tone nonlinear tests are often used in mesoscopic nonlinear elastic systems to learn more about the nonlinearity of a system. For example an elastic material with a crack might generate a considerable nonlinear combination frequency component compared to a material that does not have a crack. The SPO generates a nonlinearly generated frequency component $f_1 - (f_2 - f_1) =$ 895 Hz that is just 18 dB down in level from the $f_1 = 905$ Hz primary frequency level.

Finally, in SPO tuning curve experiments we compare dry 2,4,6, or 8 mm glass beads with the results when the beads are wetted using just 1 teaspoon of mineral oil. Results show a drastic reduction in nonlinear tuning curve behaviour for the 2 or 4 mm beads, but much less of a reduction in the nonlinear behaviour for the 6 or 8 mm beads. In future work, we plan to study this effect more quantitatively using water as the wetting agent.

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8. REFERENCES

The following selected references (elastic plate nonlinearity [1], oscillator with bilinear hysteresis [2], nonlinear mesoscopic elasticity [3-5], acoustic landmine detection [6-13], and the soil plate oscillator model [14-17] should be helpful to the reader for further background on the research.

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