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# Nonlinear tuning curve and two-tone tests using glass beads vibrating over clamped elastic plate

--Manuscript Draft--

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| **Manuscript Number:** | |
| **Full Title:** | Nonlinear tuning curve and two-tone tests using glass beads vibrating over clamped elastic plate |
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| **Abstract:** | A soil plate oscillator (SPO) apparatus consists of two circular flanges sandwiching and clamping a thin circular elastic plate. The apparatus can model the acoustic landmine detection problem. Uniform spherical 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 stiff cylindrical sidewalls of the upper flange. A magnetic disk centered 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. In two-tone tests, air-borne sound from 3 inch diameter speakers drive the bead column surface at closely spaced frequencies near the fundamental resonance. Nonlinearly generated combination frequency tones are compared for each of the bead diameter experiments. |
| **Section/Category:** | Physical Acoustics |

# 1. INTRODUCTION

## A. FROM NONLINEAR ACOUSTIC LANDMINE DETECTION EXPERIMENTS TO SOIL PLATE OSCILLATOR EXPERIMENTS

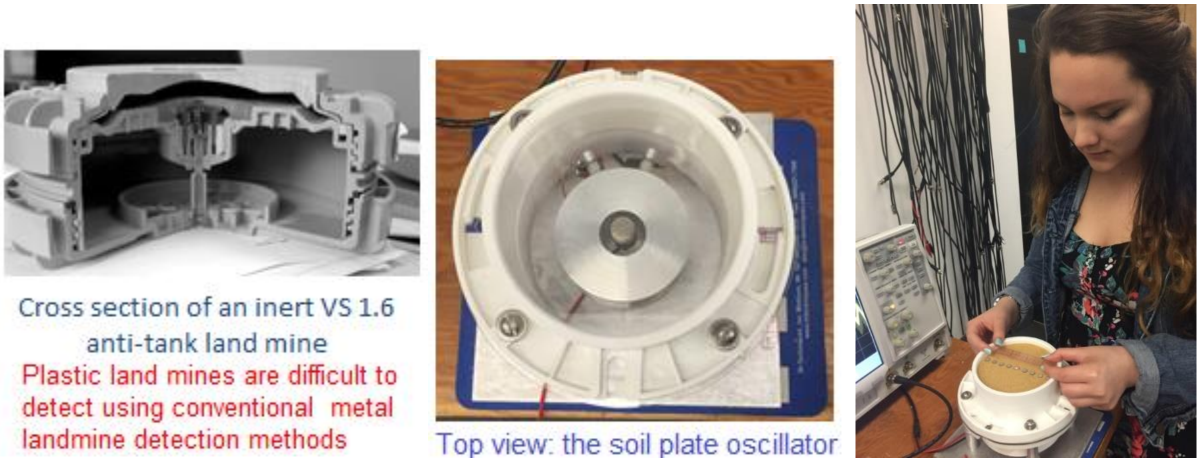


***Figure 1. Left to right: VS 1.6 land mine, top view of soil plate oscillator, and co-author EVS .***

In Fig. 1 above, the complexities of the top plate vibration structure of a buried inert VS 1.6 plastic anti-tank land mine are modeled by the clamped circular elastic plate which supports a cylindrical column of dry sifted soil or masonry sand. This model apparatus is called the soil-plate oscillator SPO.

## B. THE SOIL PLATE OSCILLATOR

A soil plate oscillator (SPO) apparatus consists of two circular flanges sandwiching and clamping a thin circular elastic plate. The apparatus can model the acoustic landmine detection problem. Here, uniform spherical 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 stiff cylindrical sidewalls of the upper/lower flanges. We might call the SPO: a bead plate oscillator (BPO) when using beads.

A magnetic disk centered 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. The Soil Plate Oscillator (SPO) models the nonlinear vibration between the granular media (glass spheres or sand) and the clamped elastic circular plate. In acoustic landmine detection “on the mine” backbone curves of peak acceleration versus the corresponding frequency have a upward curvature, whereas “off the mine” tuning curve resonances due to soil layering have backbone curves that exhibit linear behavior. See Ref 1 for more details. SPO backbone curves also exhibit some upward curvature.

## C. OVERVIEW OF SPO EXPERIMENTS

Nonlinear tuning curve experiments and separate two-tone tests were performed using a fixed column of 350 grams of 7 mm diameter glass soda lime beads in a 4.5 inch diameter SPO made with ½ inch thick aluminum flanges. Here tuning curves are measured near the fundamental frequency that is around 425 Hz at low drive amplitude. In order to prepare for the two-tone test, tuning curves were then measured near 910 Hz. Airborne-sound was generated from separate loudspeakers that where driven by 905 and 915 Hz tones, respectively. Combination tones were measured by placing an accelerometer on the surface of the beads. Then, using a similar 4.5 inch diam SPO with ½ inch thick white colored polyvinyl chloride PVC flanges, tuning curves were compared using a fixed column of 350 g of 6 mm diam dry soda lime beads (of density 2.6 g/cm$^3$) and in a second experiment using a fixed column of 634 g of dry sifted masonry sand (of density 1.3 g/cm$^3$). See Ref(s) 1-10 for more details about acoustic landmine detection and SPO’s.

## 2. EXPERIMENTAL SETUP AND RESULTS

Figure 2. shows the experimental setup of the soil plate oscillator with and without bead loading. Here the swept sinusoidal electronic tone slowing sweeping from 50 to 850 Hz (input to a constant current amplifier) drives the AC coil which generates a sinusoidal force on the magnet that is fastened to the underside of the circular acrylic elastic clamped plate. The Agilent dynamic spectrum analyzer (model 35670A) in swept model operation records the accelerometer (Endevco 2226C) signal (connected to an op amp charge amplifier) into channel 1 of the spectrum analyzer to generate a calibrated rms acceleration vs. frequency response curve. Next, the swept sinusoidal signal is incrementally increased and swept, so that a collection of tuning curves can be recorded and saved into the digital memory of the analyzer. See Fig. 3.

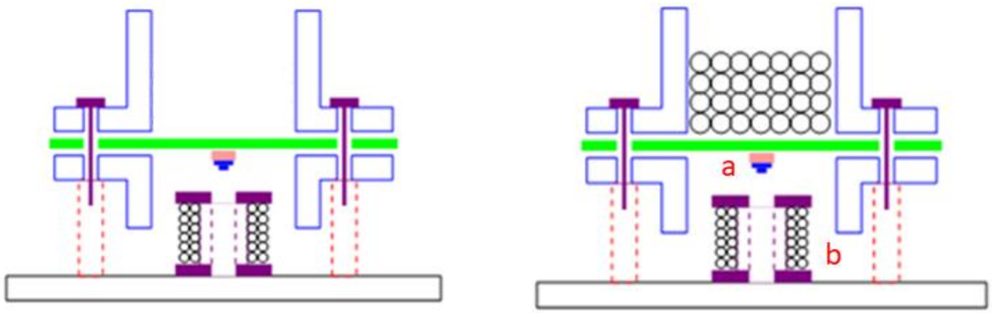


***Figure 2. Left to right: Soil plate oscillator – no bead loading. Soil plate oscillator with bead loading. (a) Magnet and accelerometer, (b) AC enamel wire coil. In cross-sectional view are the upper and lower flanges clamping the circular elastic acrylic plate of 1/8 inch thickness. (Clamped diam is 4.5 inches.)***

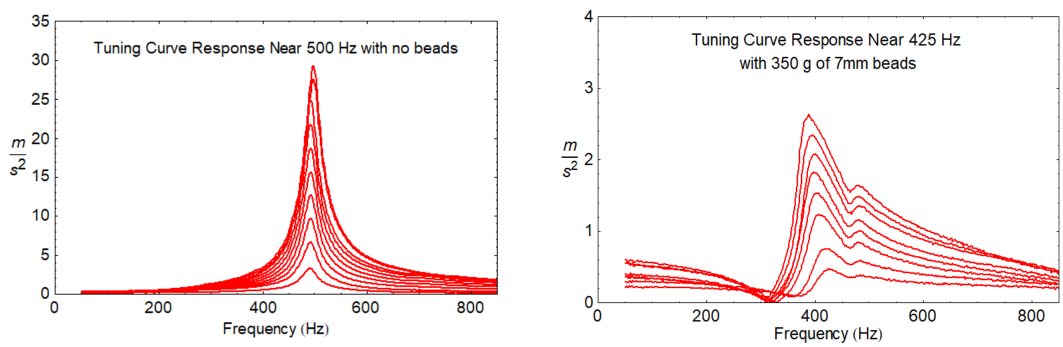


***Figure 3. Aluminum SPO accelerometer response on the underside of the clamped elastic plate near the fundamental resonance of (a ) the soil plate oscillator without bead loading and (b) with 7mm beads***

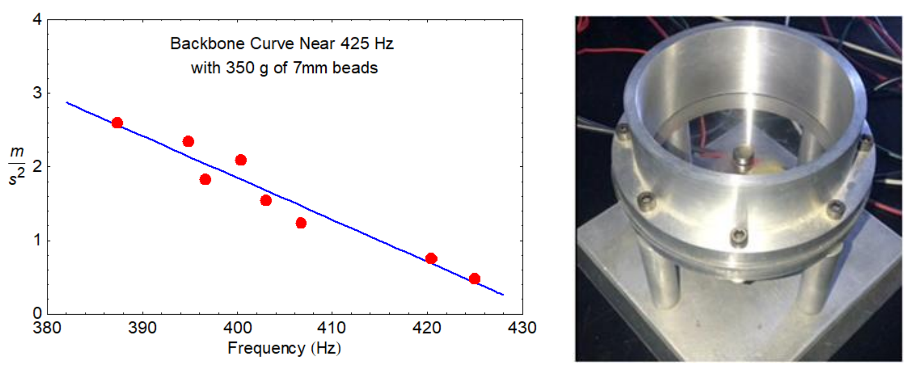


***Figure 4. (a) Aluminum SPO backbone curve response on the underside of the clamped elastic plate with 7 mm diam bead loading is obtained by plotting the peak acceleration and corresponding resonant frequency from the tuning curves in Fig. 3. (b) Image of soil plate oscillator using aluminum flanges that are ½ inch thick with a circular column of 4.5 inch inside diameter and ¼ inch wall thickness***

When one observes a frequency decrease with increasing drive amplitude, we say that the system exhibits an effective spring constant “softening.” The back-bone curve from the tuning curves shows a linear slope that is characteristic of nonlinear mesoscopic elastic behavior in geomaterials like sandstone. See Fig 5 below for a comparison of the tuning curve response for a white PVC SPO with 6mm glass beads and dry sifted masonry sand.

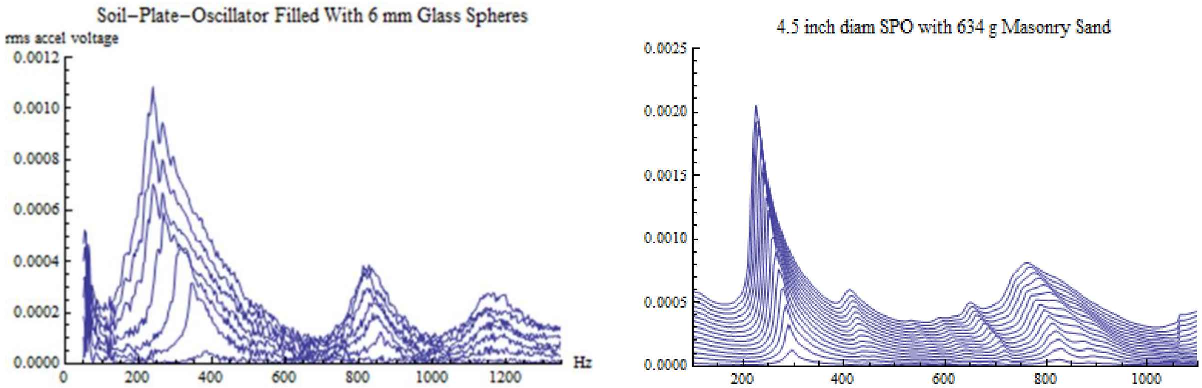


***Figure 5. Comparing the tuning curve response on the underside of the clamped elastic plate (a) with 350 grams of 6 mm diam beads (b) with 634 grams of dry sifted masonry sand.***

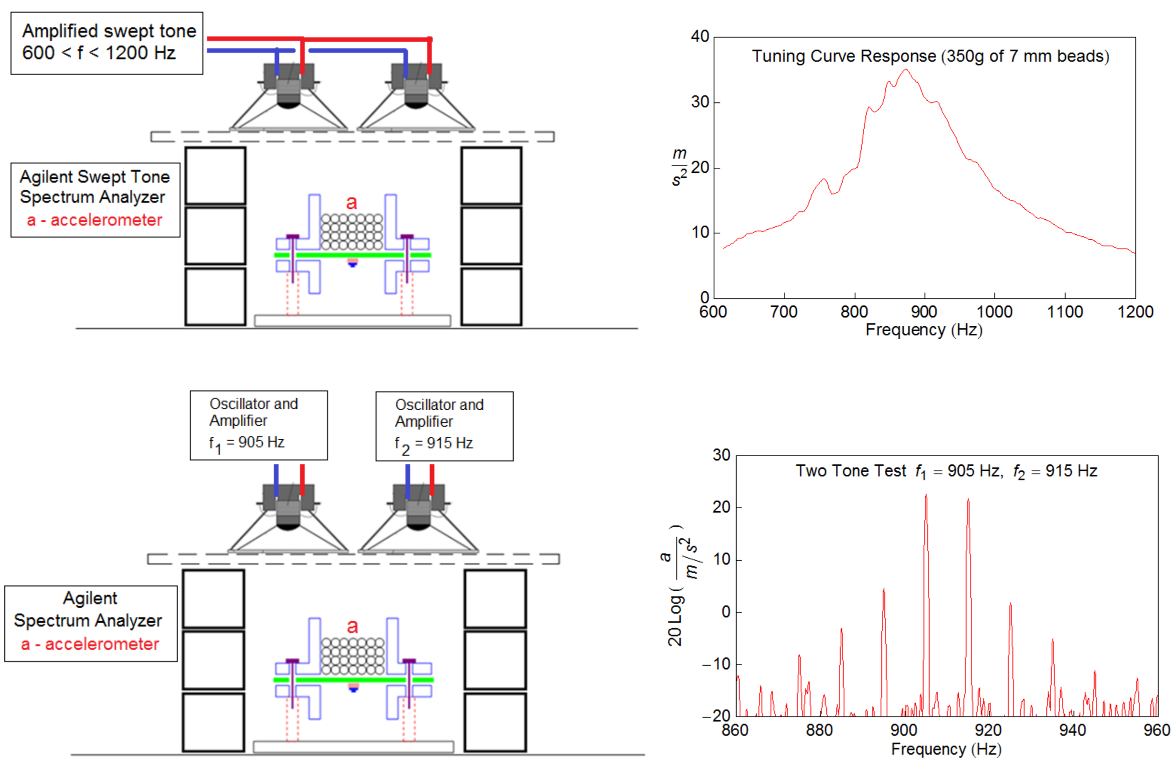


***Figure 7. (a) Aluminum soil plate oscillator with 350 grams of 7mm glass beads. Airborne sound generation from two loud speakers (with a diam of 3 inches) drives the column of glass beads from above. (b) An accelerometer located on the surface of the beads measures the acceleration tuning curve response vs. frequency from $600 < f < 1200$ Hz. (c)Two Tone Test using the aluminum soil plate oscillator with 350 grams of 7mm glass beads. Airborne sound generation from two loud speakers (each with a diam of 3 inches) drives the column of glass beads from above with tones of $f_1 = 905$ Hz and $f_2 = 915$ Hz, respectively. (b) An accelerometer located on the surface of the beads measures the average Fast Fourier Transform, FFT, rms acceleration vs. frequency in the band from $860 < f < 960$ Hz.***

Before we can do a two tone test, we need to do a swept sine tuning curve measurement near a resonance. See Fig 7(b). Here we choose an SPO resonance near 910 Hz. In order to obtain a FFT response of the two tone test excitation that is created when both loudspeakers are used, we will drive one speaker at 905 Hz and the other at 915 Hz. See Fig. 7(c). As you can see from Figure 7(d), there are two main peaks at 905 Hz and 915 Hz. On the left side of peak 905 there are peaks 10 Hz apart that are increasing. On the right hand side of peak 915 there are peaks 10 Hz apart that are decreasing. This shows the nonlinearity of the system attributed to the combination frequencies.

## 3. CONCLUSION

The soil-plate oscillator (SPO) has been studied with soil (masonry sand) and with several different sizes of soda lime glass beads. The nonlinear SPO experiments involving tuning curves and two tone tests are thought to be an idealized experimental model of the field experiments involving highly complex buried plastic landmines. In our experiments the granular material is dry and homogeneous. The two tone test experiments and tuning curve experiments are in some ways similar to the studies that involve measuring nonlinear mesoscopic elasticity found in geomaterials such as bera sandstone. Our experiments reveal a similar mesoscopic elastic behavior to bera sandstone as well as an actual buried VS-1.6 plastic landmine buried in an open concrete wall soil tank filled with dry sifted masonry sand or loess soil. See Ref(s) 5,6,10. The results shown in Fig 4(a) reveal a backbone curve that exhibits linear behavior. This linear behavior cannot be explained by classical (atomic) elasticity in the bead particles, but rather by the interaction between grain contacts (bead contacts) characteristic of mesoscopic nonlinear behavior in sandstones.

## ACKNOWLEDGMENTS

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