

METAL, CERAMIC & FOAM COMPOSITE CONES

BY STEVE MOWRY

Metal cones and/or diaphragms have been utilized in transducers for many years. The typical diaphragm is a solid homogeneous material of aluminum, magnesium, titanium or an alloy of the same. The metal cones and diaphragms perform quite well within their respective piston bandwidth; however, at the onset of the modes of vibration there is a characteristic of high Q energy storage and release, breakup. It is not uncommon to measure a 10 dB or more peak in the frequency response at the first mode, f_1 with subsequent peaks and dips related to $f_2, f_3 \dots f_n$, for transducers utilizing metal or ceramic diaphragm assemblies. This characteristic along with the higher densities of metal and ceramic verses paper has resulted in paper becoming the cone material of choice for the last several decades.

Having visited paper cone manufacturing facilities within the USA, Europe, Mexico and Asia, it has been observed that the manufacturing processes are extensive and difficult to control. Paper cones start out as a soup-like mixture of pulp, fibers and chemicals in water called the slurry. Subsequently there are forming processes, on screens, and there are drying and treating processes. The resultant paper cone can change properties very quickly if a supplier of the paper pulp is changed. I am quite certain that most transducer professionals have had to deal with this problem at some time. Furthermore, both during production and in the field, the properties of a paper cone can change with the environment and particularly relative humidity. The paper cone is not a stable material and it is difficult to control the inherent variability, whereas metals and polymers are typically very stable leaving only the manufacturing processes to control.

When companies began to add carbon and/or aramid fibers to the paper pulp/slurry, the term composite also began to appear. These processes resulted in increased stiffness and improved damping. A search of the US Patent Office website indicated that most of the patents have expired and the process of adding carbon and/or Kevlar® fibers to paper cones has become commonplace within the industry for paper cone manufacturers. Paper cone manufacturing techniques have improved the performance of paper cones but variability issues simply cannot be overcome. The speed of sound in the paper-based material is much lower than in most metals. The speed of sound in a solid material is related to ratio of stiffness to mass of the material,

specifically $c_m = \sqrt{\frac{E_m}{\rho_m}}$ (ms^{-1}). Where E_m is the Modulus of Elasticity and ρ_m is

the mass density. However, paper has the characteristic of inner loss that is much higher than metals. This loss property relates to the Q of the modes of vibration or more commonly referred to as resonances. The higher the inner loss of the cone, the lower the Q of the modes or resonances. While the typical paper cone has an inner loss ratio of 0.02 to 0.06, most metals have inner loss ratios of 0.005 to 0.007. The low inner loss property of metals can be increased by applying a high inner loss coating, typically a liquid polymer,

to the cone; however, this comes at the cost of reducing the speed of sound in the structure, the cone, and will inherently increase the mass of the structure.

A composite cone to be investigated is the true 'Sandwich Composite' (SC). This is quite common in applications for boats, airplanes, aerospace, bicycles, automotive and even tennis rackets. The typical configuration is a molded sandwich of carbon fiber / polymer foam / carbon fiber; however, for transducer diaphragm applications, the sandwich can also be metal / polymer foam / metal. It shall be shown that although this composite is the most costly, it has the potential for a very high performance cone.

There are at least two famous loudspeaker manufacturers that has implemented the sandwich class of composite cone, W Sandwich®. The first makes the following claims. "W membranes, the latest development in the sandwich concept uses a glass-glass structure based around a structural foam core, (Patent No 2,615,345) and the Poly-K sandwich structure comprising two sheets of Kevlar® on both sides of a core comprised of tiny hollow beads is a unique solution in the production of membranes, featuring an optimal weight – rigidity – dampening balance, (Patent No 2,731,579)." Unfortunately, after extensive searching within the US and World Patent and Trademark Office databases, these patents could not be found. The patent numbers correspond to unrelated inventions dating back to the mid 1950's. The trademark 'W Sandwich' was also searched for; however, no records could be found in the USPTO database. These claims can be found at <http://www.focal-fr.com/gb/societe/tek.htm>. The second manufacturer describes the sandwich composite cone in detail; however, this company makes no claim as to propriety of this topology. A white paper on the topic of the development of their new 'Flagship Loudspeaker' is available for download at

In all the following simulations, cone angle, cone inside diameter, cone outside diameter and boundary conditions shall remain constant. Only the materials shall be changed to represent each class of metal composite cones. I will begin with a plated/anodized solid magnesium cone that can be used as a reference for subsequent simulations.

It should be noted that other metals and materials such as aluminum, carbon fiber, aramid fiber or fiberglass are potential substitutes for the magnesium material used within the following models. However, I am of the opinion that magnesium has the most desirable properties and is the most effective material for the applications that are discussed.

Geometric Properties:

CONE #1: 5 μm thick Ceramic / 100 μm thick Mg / 5 μm thick Ceramic

Material Properties:

Magnesium:

Modulus of Elasticity, $E_M = 4.40 \times 10^{10}$ Pa

Mass Density, $\rho_M = 1.84 \text{ g cm}^{-3}$

Poisson's Number = 0.3 Unit-less

Inner Loss, $\tan\delta = 0.005$ Unit-less

Ceramic:

Modulus of Elasticity, $E_C = 2.75 \times 10^{11}$ Pa

Mass Density, $\rho_C = 3.58 \text{ g cm}^{-3}$

Poisson's Number = 0.3 Unit-less

Inner Loss, $\tan\delta = 0.007$ Unit-less

Figures 1 through 5 illustrate the axis-symmetric mode shapes of a simple anodized magnesium cone within the Finite Element Model.

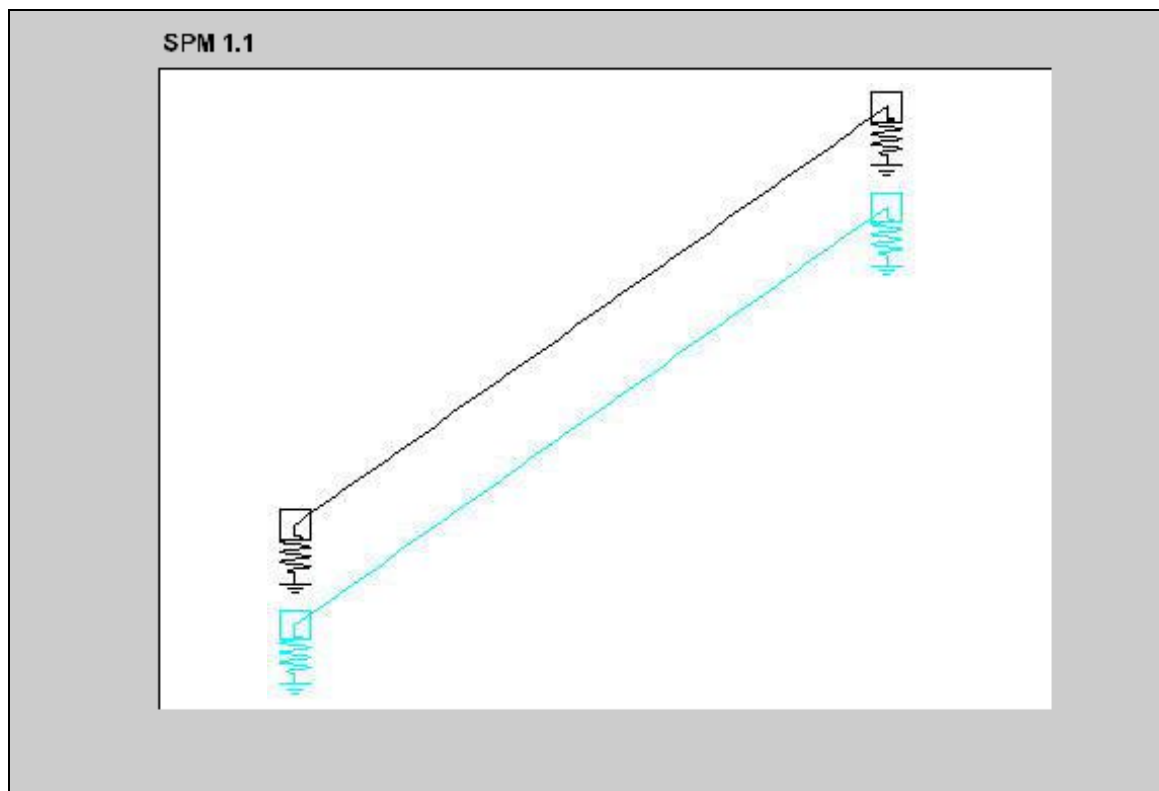


FIGURE 1. MODE SHAPE @ $f_0 = 146$ Hz

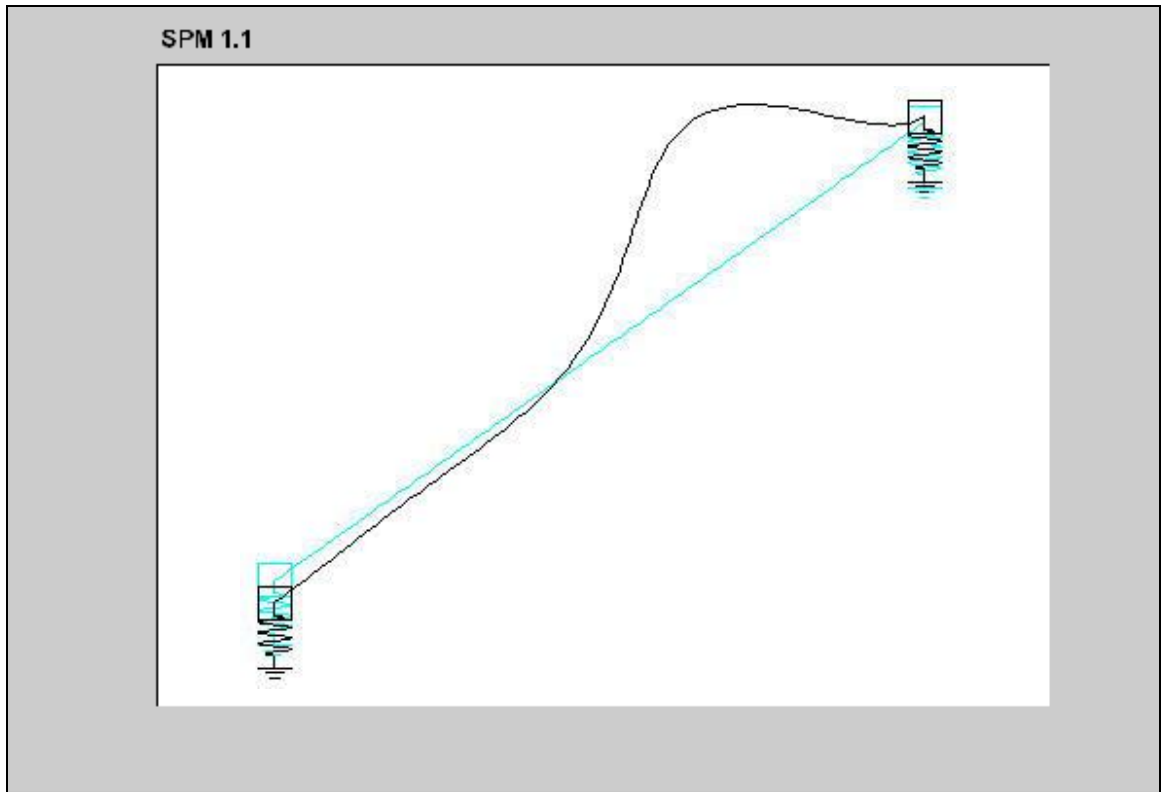


FIGURE 2. MODE SHAPE @ $f_1 = 4.6$ kHz, DAMPING = 0.005

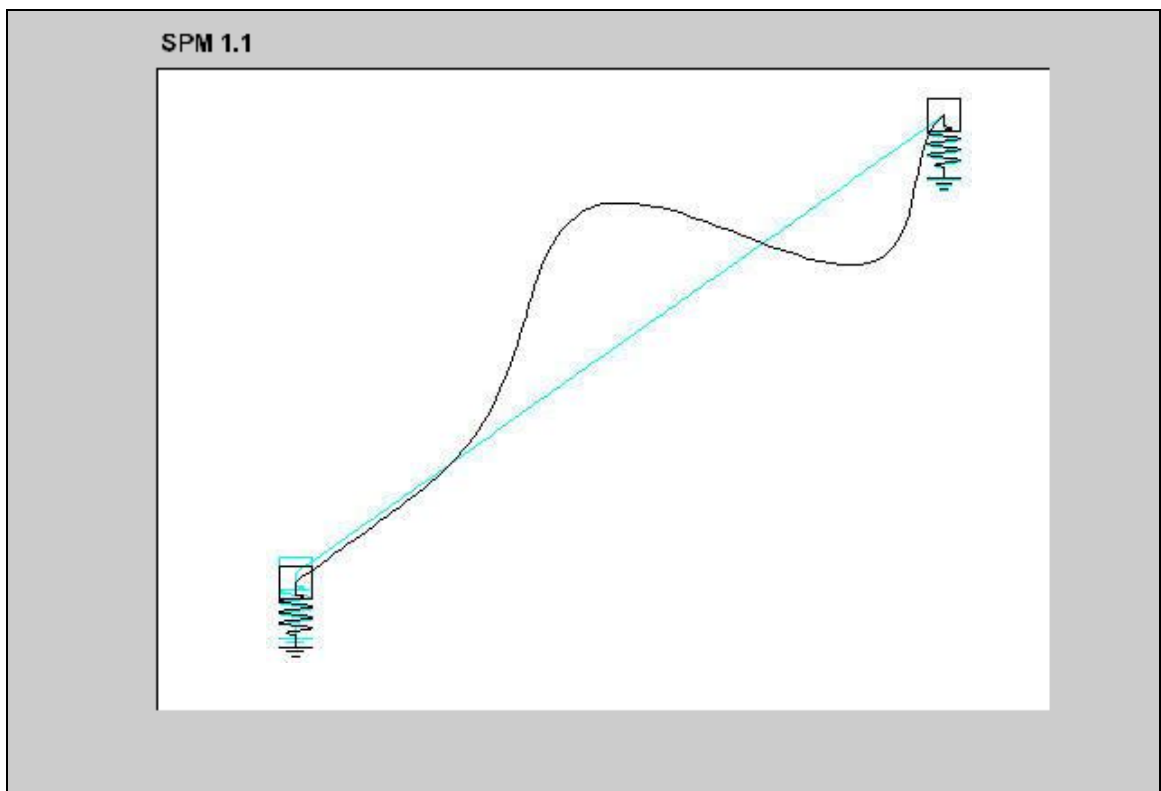


FIGURE 3. MODE SHAPE @ $f_2 = 5.3$ kHz, DAMPING = 0.005

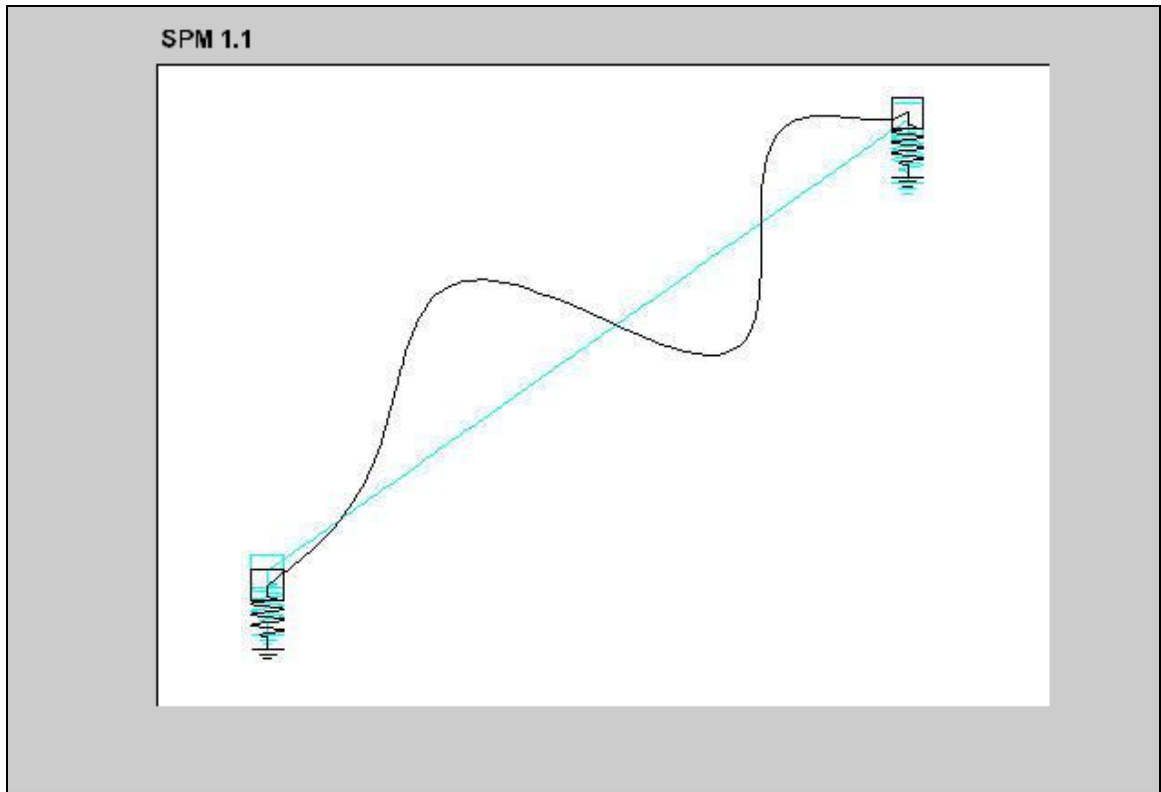


FIGURE 4. MODE SHAPE @ $f_3 = 5.9$ kHz, DAMPING = 0.005

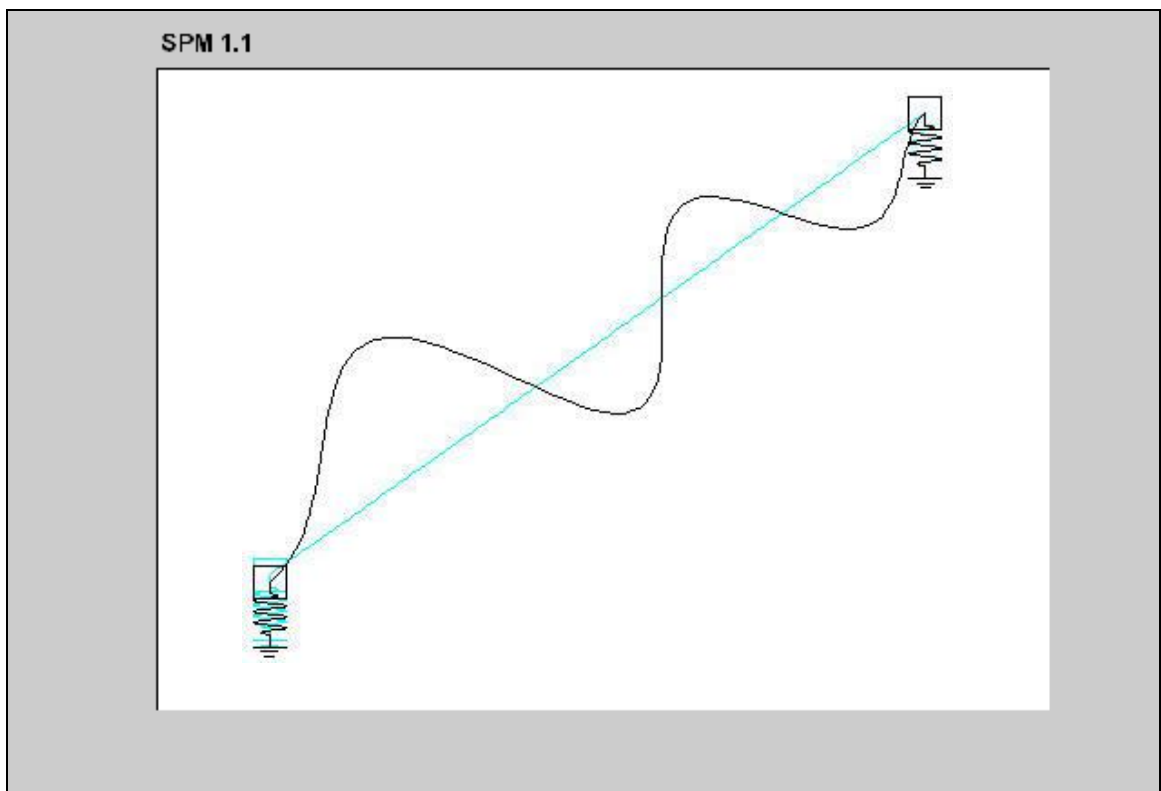


FIGURE 5. MODE SHAPE @ $f_4 = 6.8$ kHz, DAMPING = 0.005

The magnesium cone performs quite well. It is suitable for use up to approximately 4 kHz; however, at about 4.6 kHz expect a high Q peak in the response followed by non-uniform response that is rolling off with increasing frequency. This cone is suitable for a mid bass or midrange application. The typical manufacturing process is stamping or casting, depending on complexity of geometry, then plated. This cone has the lowest cost of the five simulations; however, it also has the lowest performance.

Figures 6 through 10 illustrate the axis-symmetric mode shapes of a Deep Anodized magnesium cone. Due to the very high modulus of elasticity of the Ceramic, the net shape can be thinned to 75 μm .

Geometric Properties:

CONE #2: 25 μm Ceramic / 25 μm Mg / 25 μm Ceramic

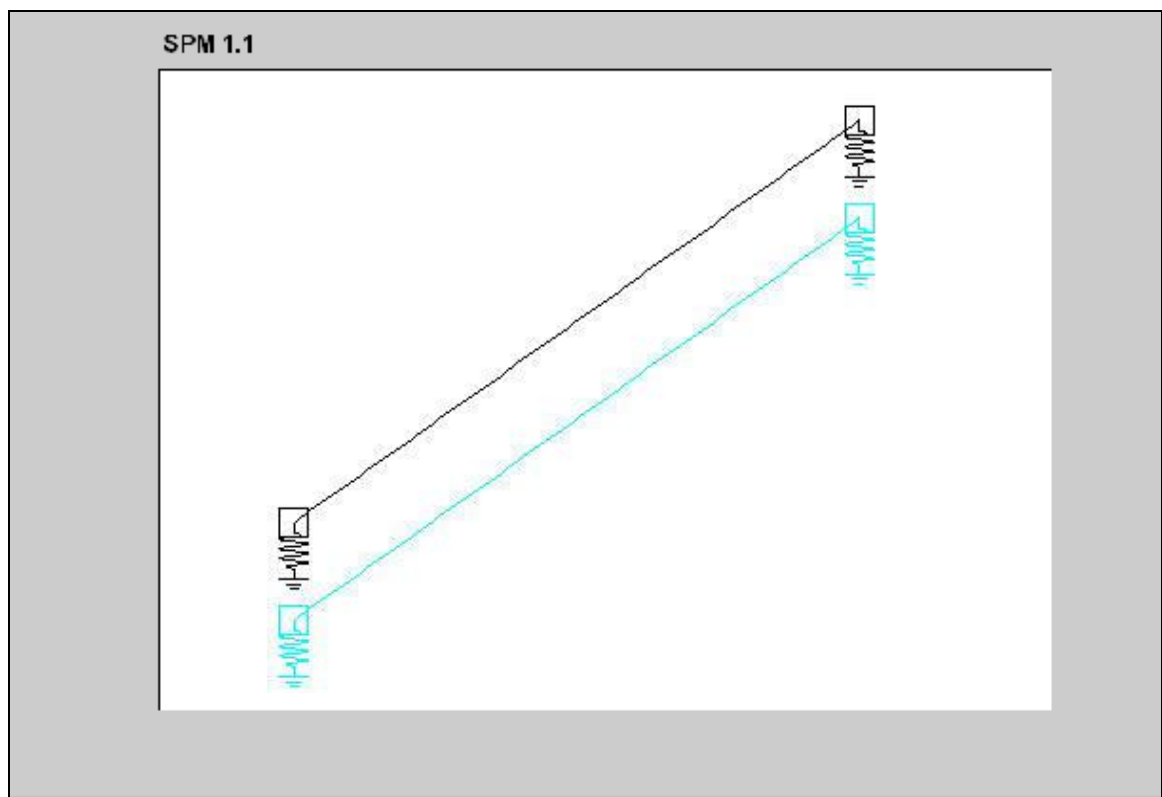


FIGURE 6. MODE SHAPE @ $f_0 = 146$ Hz

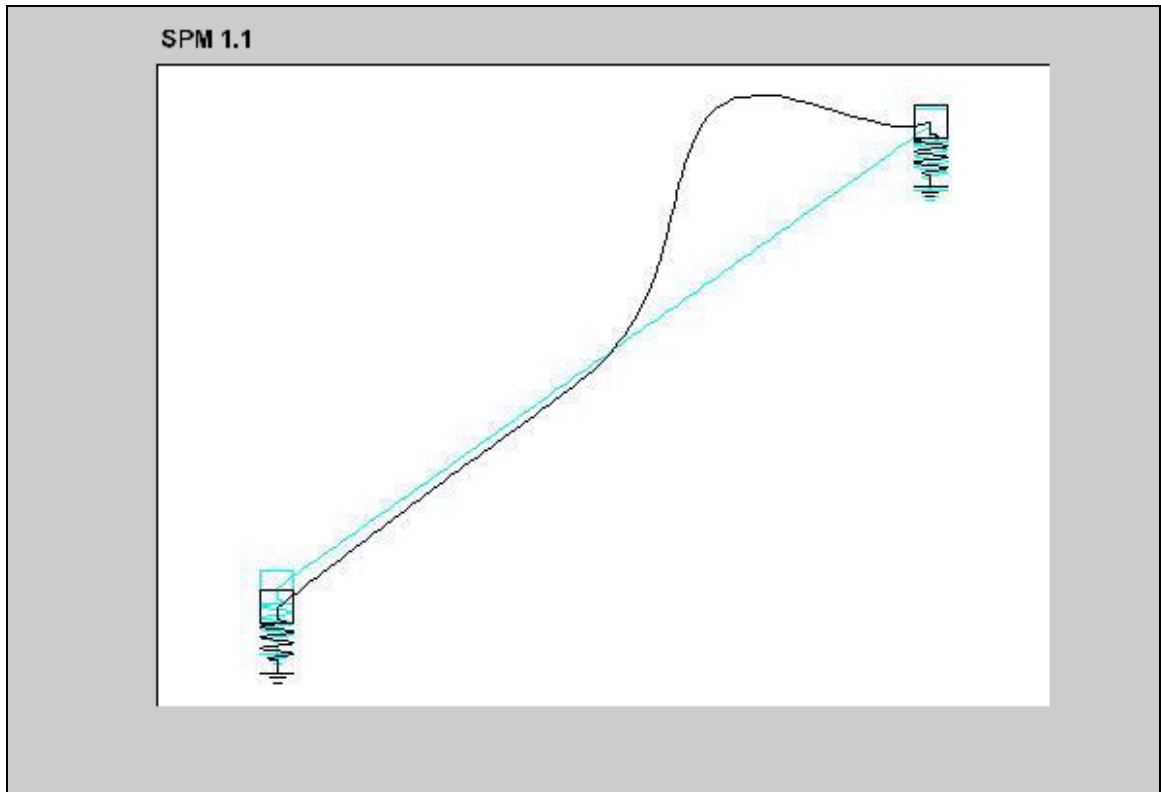


FIGURE 7. MODE SHAPE @ $f_1 = 6.4$ kHz, DAMPING = 0.006

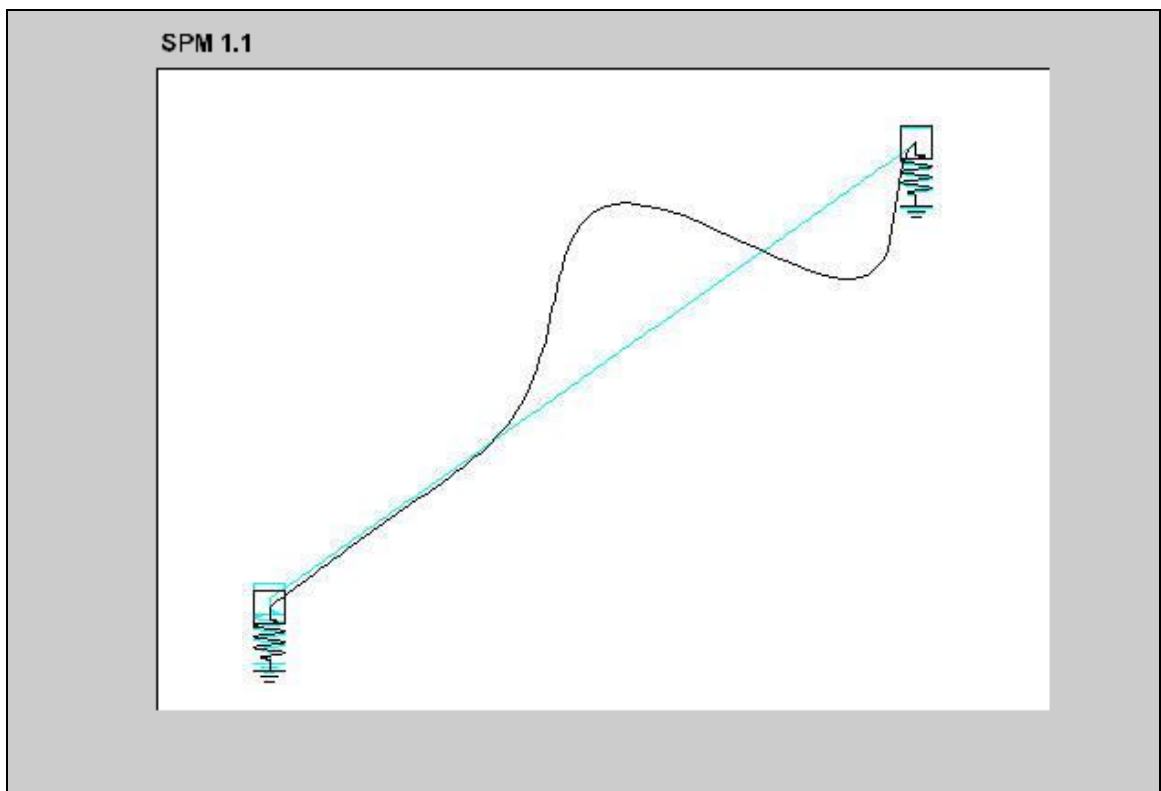


FIGURE 8. MODE SHAPE @ $f_2 = 7.2$ kHz, DAMPING = 0.006

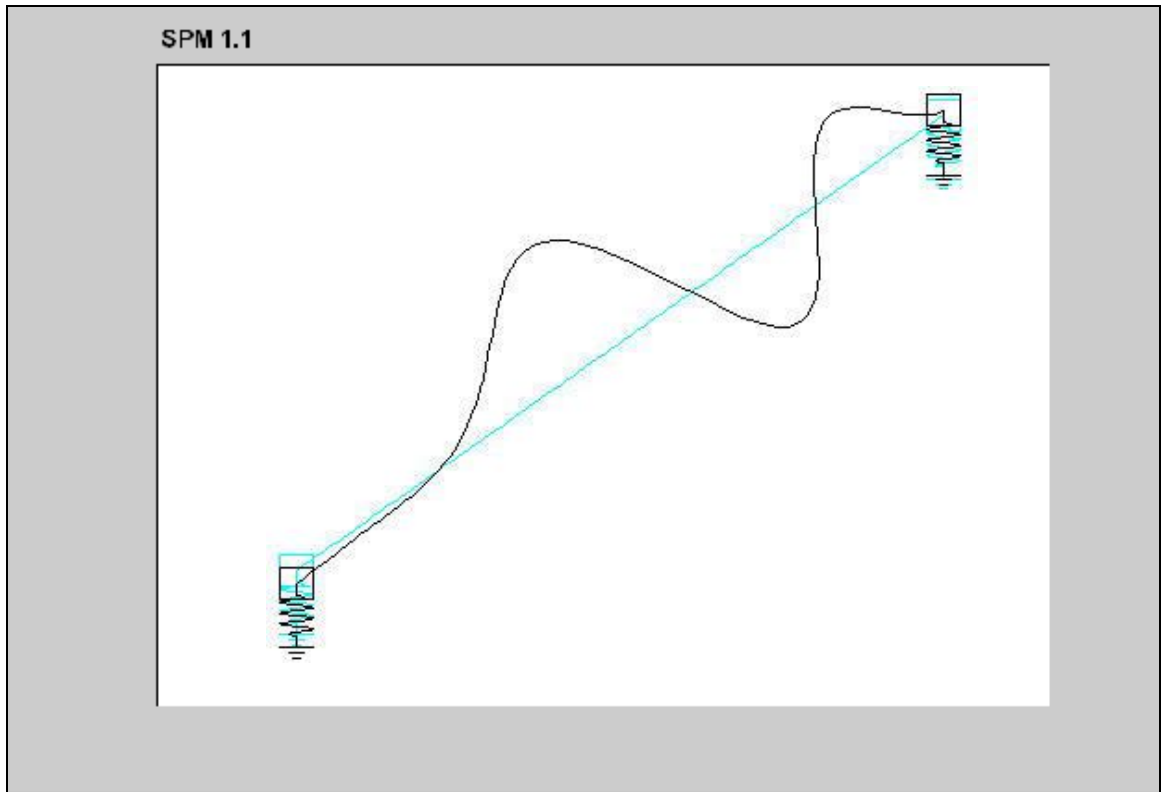


FIGURE 9. MODE SHAPE @ $f_3 = 7.9$ kHz, DAMPING = 0.006

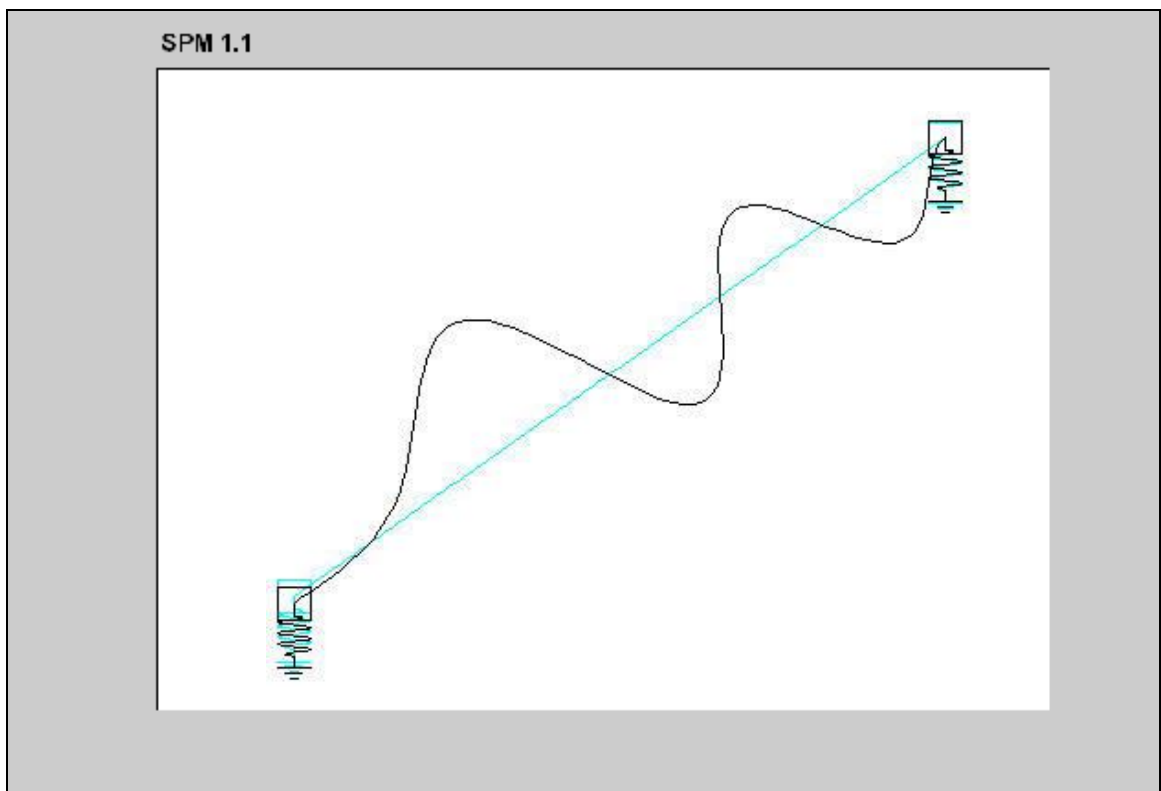


FIGURE 10. MODE SHAPE @ $f_4 = 8.8$ kHz, DAMPING = 0.006

The Deep Anodized magnesium cone is an impressive invention. The performance of the cone is very good and the manufacturing process is

simple and stable, stamp and deep anodize. An example of this process is Keronite coating, <http://www.keronite.com/>.

This cone is suitable for use up to approximately 6 kHz, an improvement of ½ octave above the plated magnesium cone. However, at about 6.4 kHz expect a high Q peak in the response followed by non-uniform response that is rolling off with increasing frequency. The damping has been improved by about 20% over the magnesium cone but is still quite low at 0.006. This cone is well suited for mid bass or midrange applications. This material/process is also a good cost effective solution for small high frequency diaphragms. The patent holder has implemented 6½ inch to 1inch transducers utilizing either Deep Anodized aluminum or magnesium.

Figures 11 through 15 illustrate the axis-symmetric mode shapes of a Metal Matrix Composite with a woven ceramic core material infiltrated with magnesium and plated.

Geometric Properties:

CONE # 3: 5 μm Ceramic / 25 μm Mg / 30 μm Ceramic / 25 μm Mg / 5 μm Ceramic

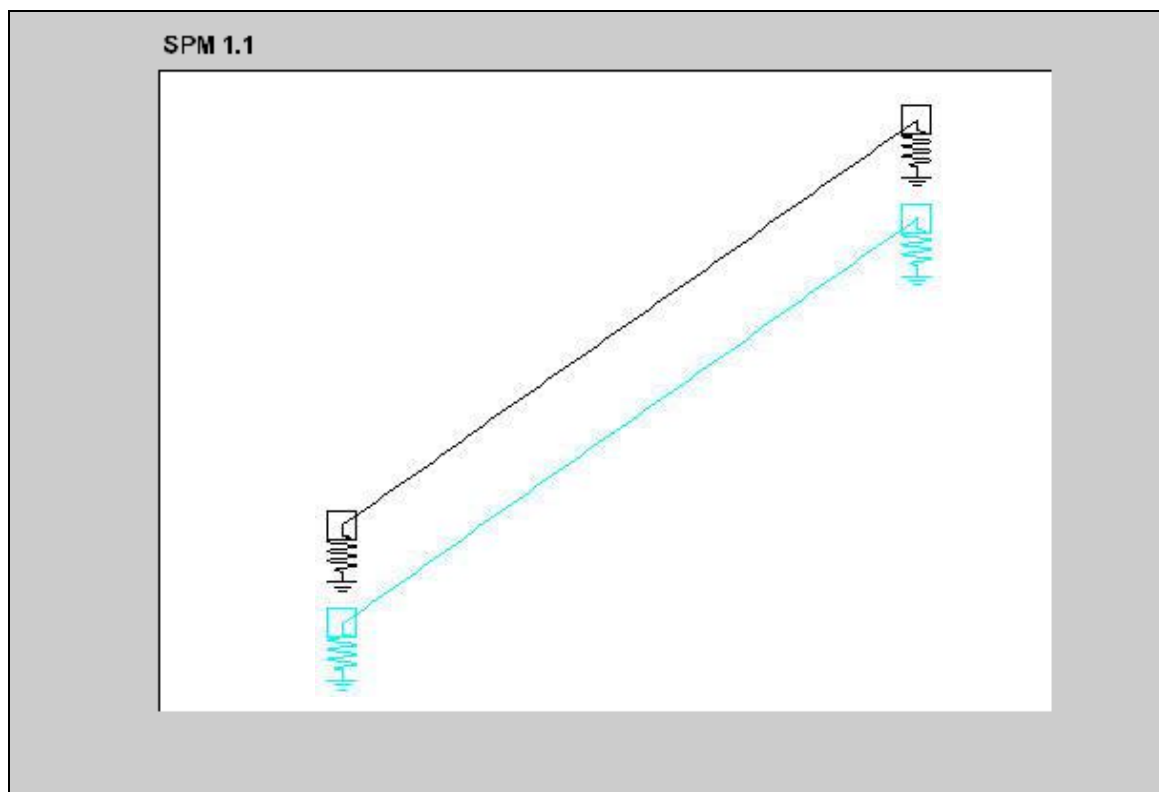
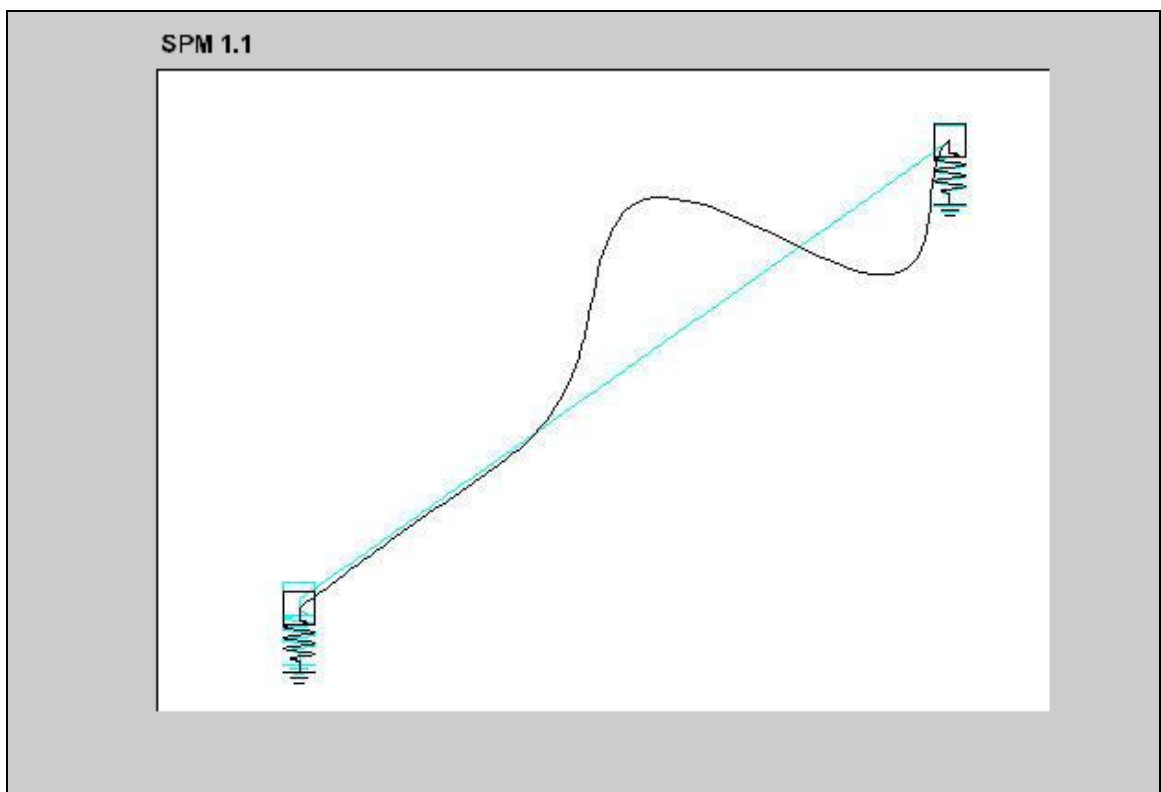
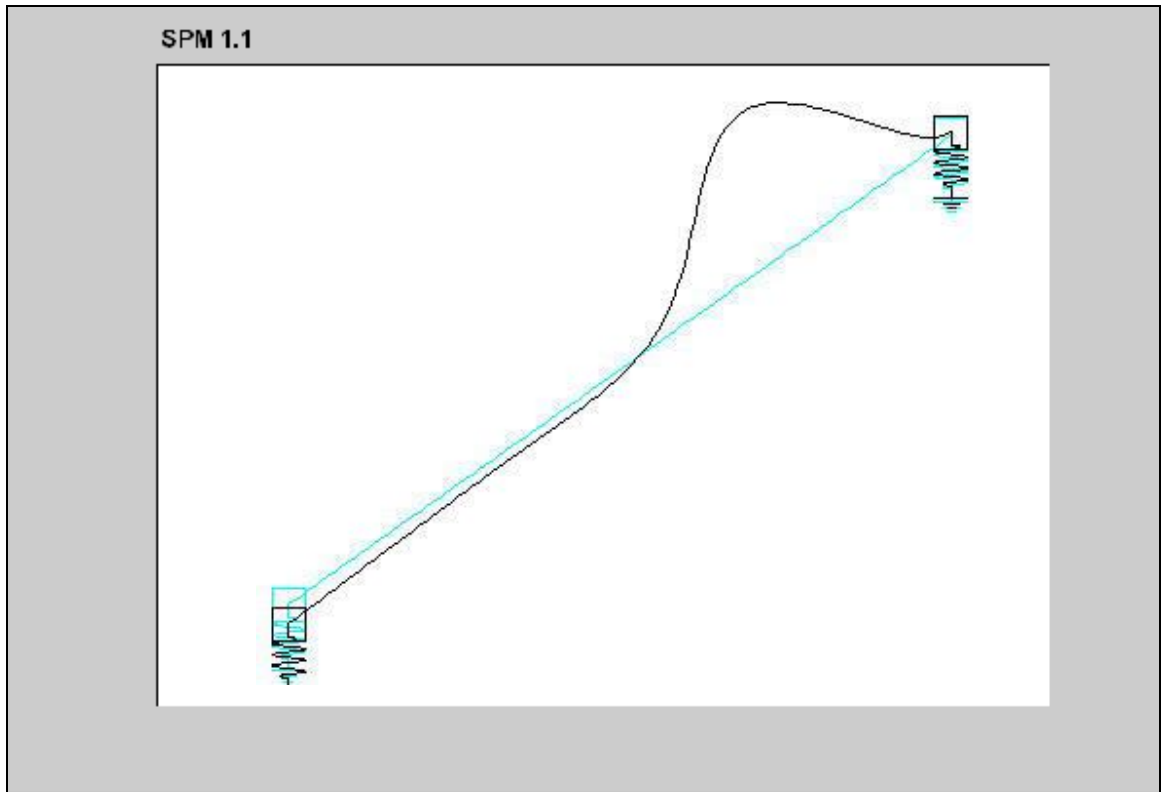


FIGURE 11. MODE SHAPE @ $f_0 = 145$ Hz



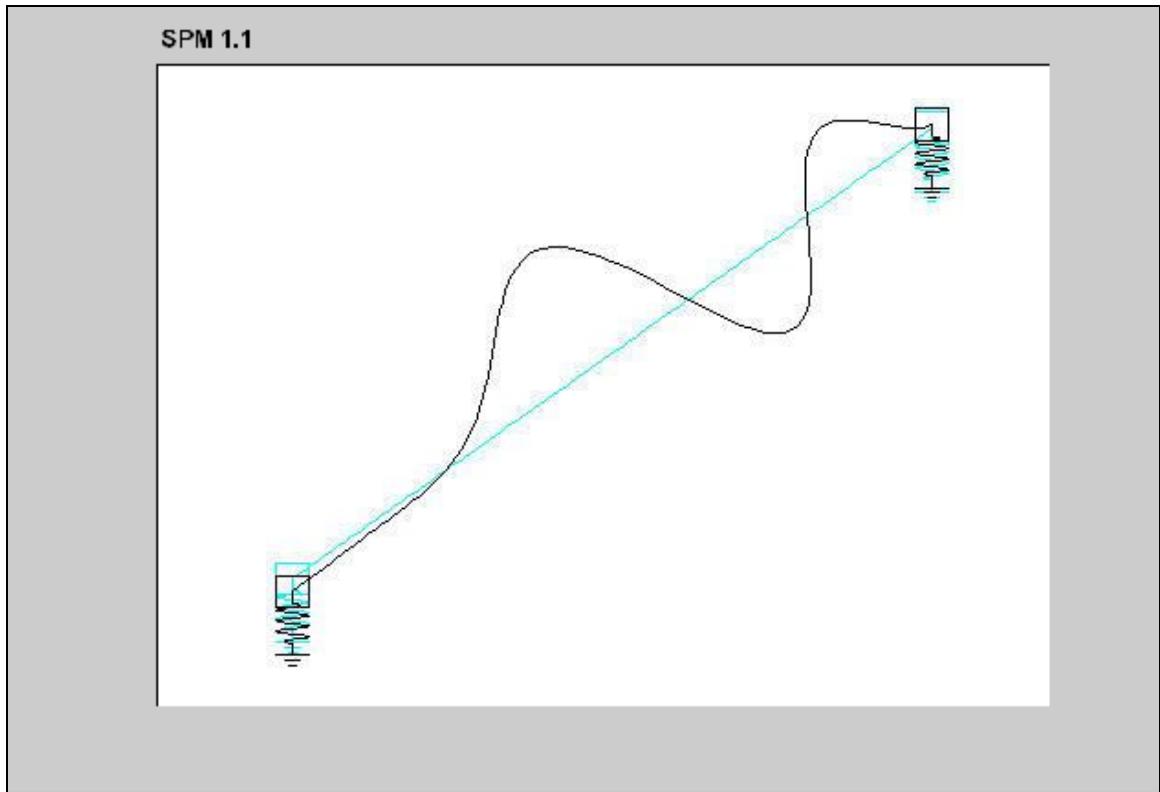


FIGURE 14. MODE SHAPE @ $f_3 = 7.2$ kHz, DAMPING = 0.006

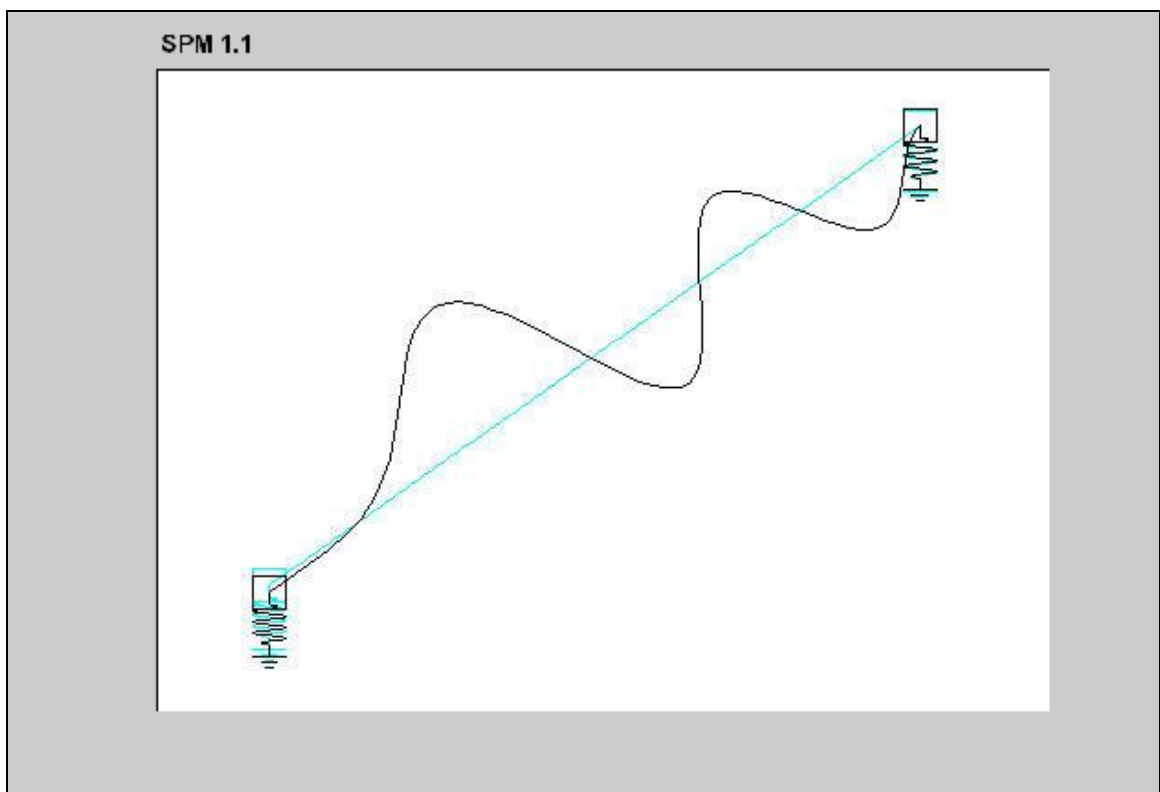


FIGURE 15. MODE SHAPE @ $f_4 = 8.0$ kHz, DAMPING = 0.006

The Metal Matrix cone with the ceramic core is an improvement over the first magnesium cone that was simulated; however, falls somewhat short of the performance of the Deep Anodized magnesium cone. Frankly, the process is

quite complicated. The magnesium must be molded over the ceramic core and secondary machining maybe required. This molding or casting of such a thin structure could be simplified by using carbon as filler within the mold. This carbon could be subsequently easily removed from the magnesium. Some minor secondary machining may still be required and the cone must finally be plated to prevent oxidation. This cone would most likely be cost ineffective.

The next simulations are of Sandwich Composites. Figures 16 through 20 illustrate the axis-symmetric mode shapes of the Mg / SiC-foam / Mg Sandwich Composite cone, while figures 21 through 25 illustrate the ultra hi-tech Mg / Poly-foam / Mg Sandwich Composite cone.

Geometric Properties:

CONE # 4: 5 μm Ceramic / 25 μm Mg / 0.45 mm SiC Foam / 25 μm Mg / 5 μm Ceramic

Material Properties:

Silicon Carbide (8%) Foam:

Modulus of Elasticity, $E_{SC} = 2.75 \times 10^9$ Pa

Mass Density, $\rho_{SC} = 0.24$ g cm⁻³

Poisson's Number = 0.2 Unit-less

Inner Loss, $\tan\delta = 0.03$ Unit-less

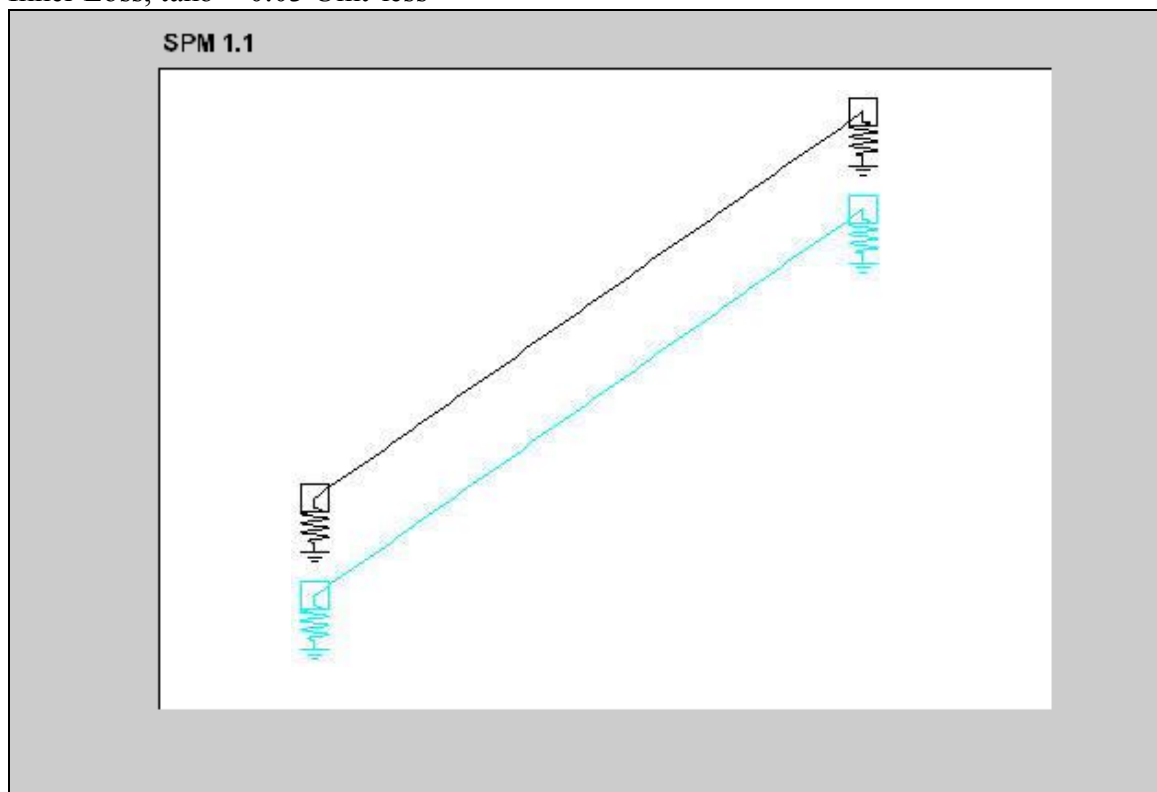


FIGURE 16. MODE SHAPE @ $f_0 = 145$ Hz

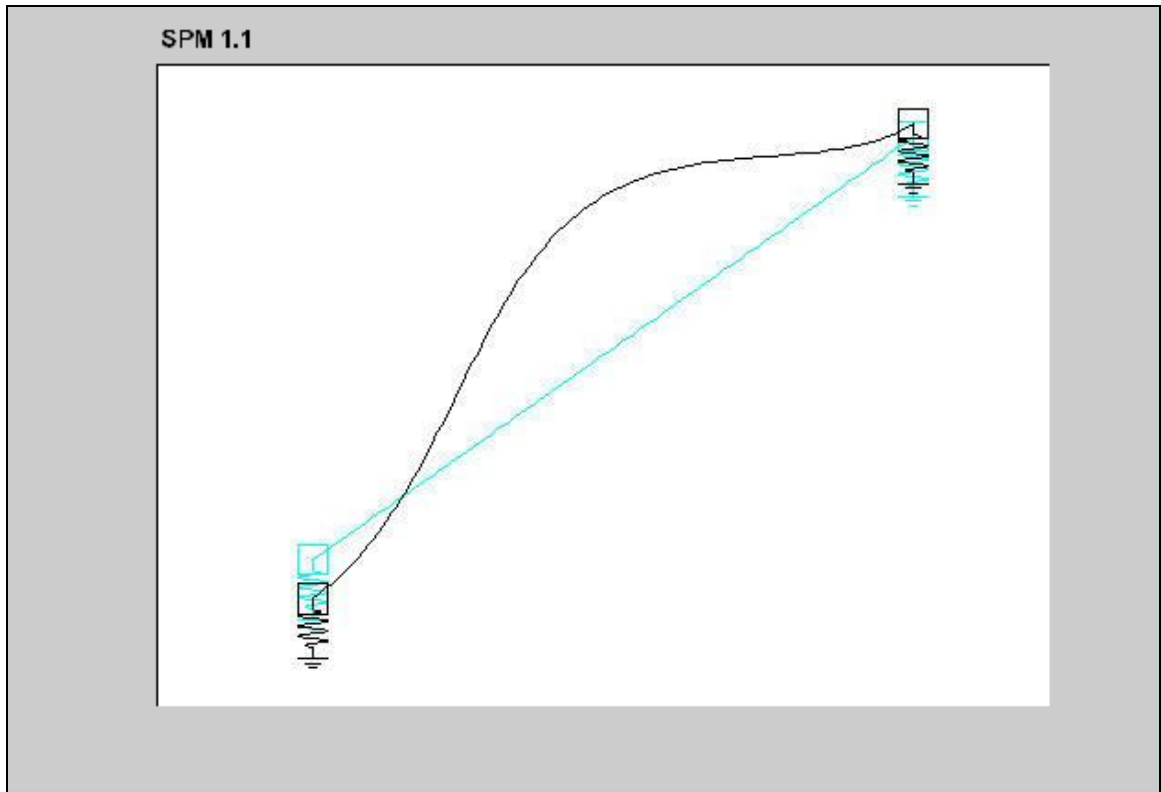


FIGURE 17. MODE SHAPE @ $f_1 = 4.9$ kHz, DAMPING = 0.01

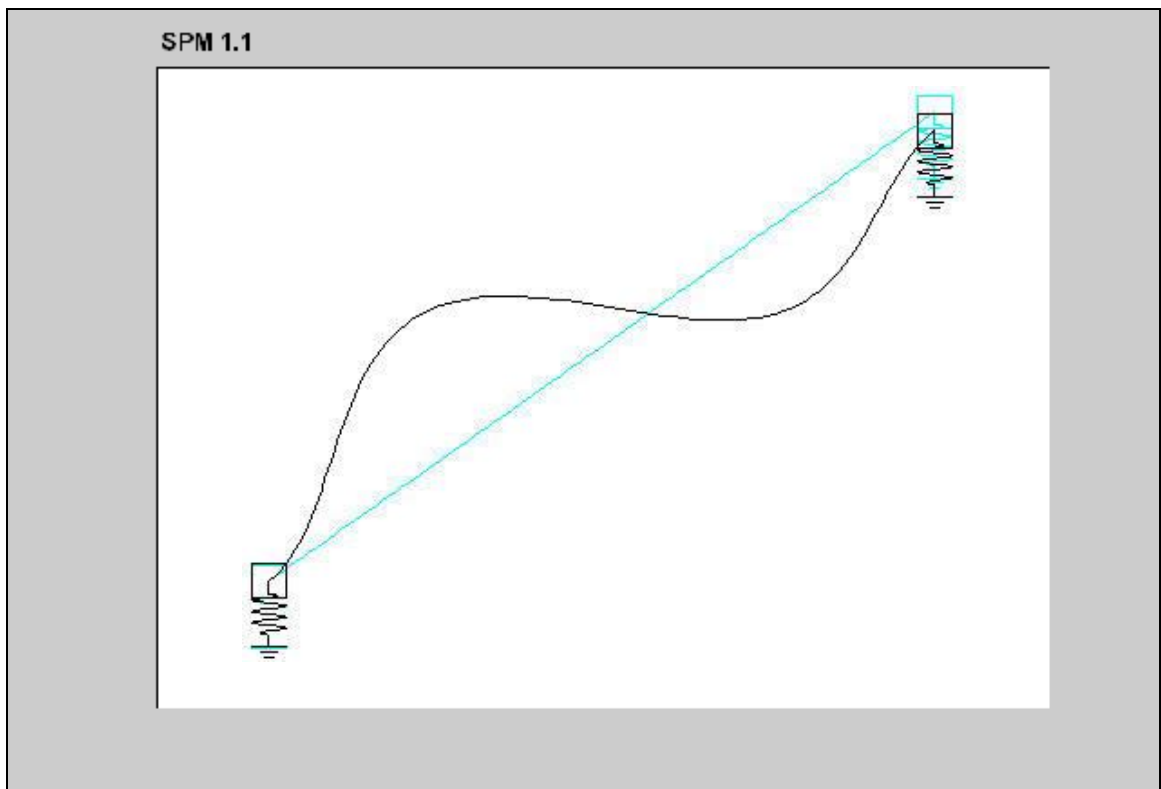


FIGURE 18. MODE SHAPE @ $f_2 = 7.1$ kHz, DAMPING = 0.01

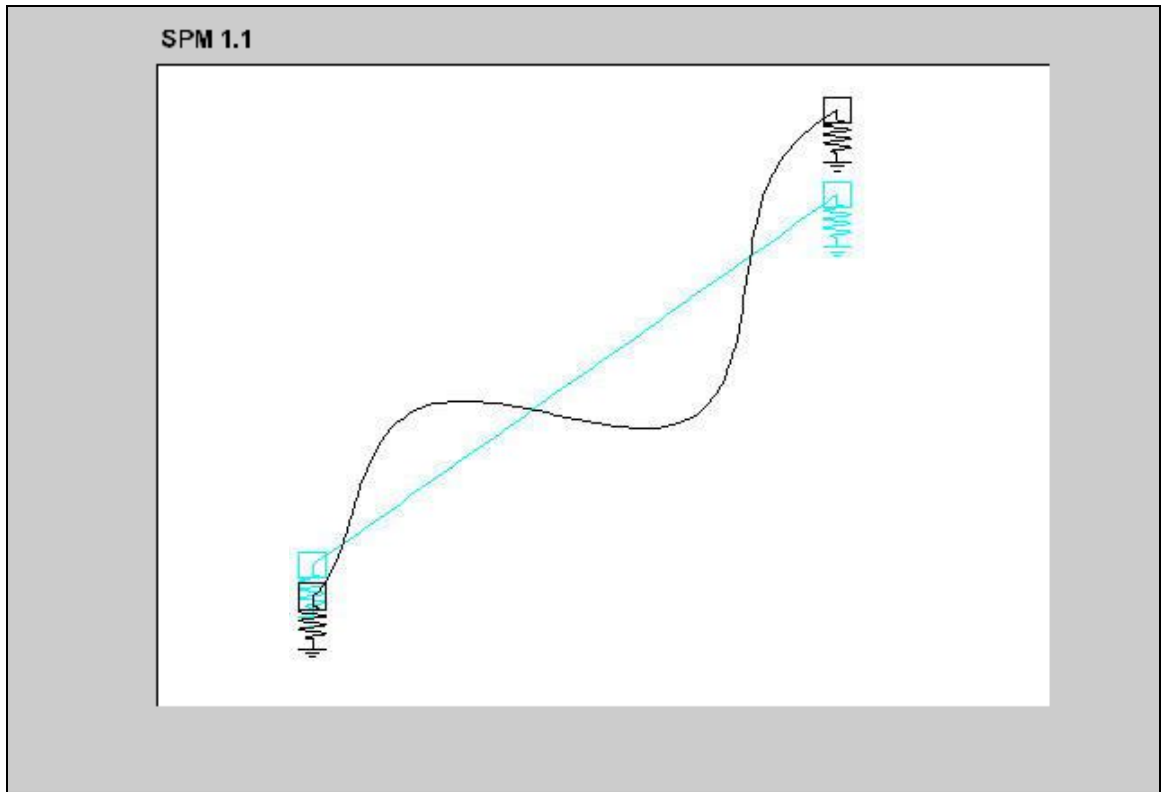


FIGURE 19. MODE SHAPE @ $f_3 = 9.2$ kHz, DAMPING = 0.01

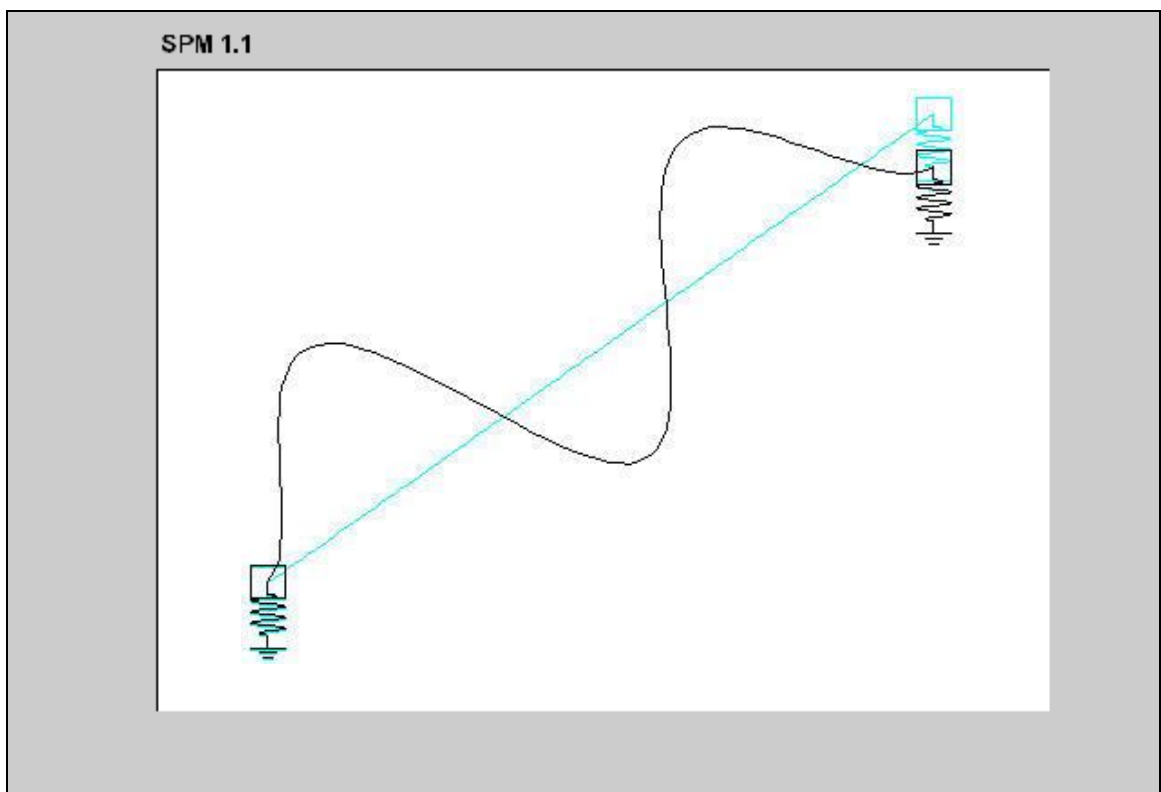


FIGURE 20. MODE SHAPE @ $f_4 = 12$ kHz, DAMPING = 0.01

Geometric Properties:

CONE # 5: 5 μm Ceramic / 25 μm Mg / 2 mm Poly-foam / 25 μm Mg / 5 μm Ceramic

Material Properties:

Structural Poly-foam:

Modulus of Elasticity, $E_P = 6.90 \times 10^7 \text{ Pa}$

Mass Density, $\rho_P = 0.052 \text{ g cm}^{-3}$

Poisson's Number = 0.4 Unit-less

Inner Loss, $\tan\delta = 0.03$ Unit-less

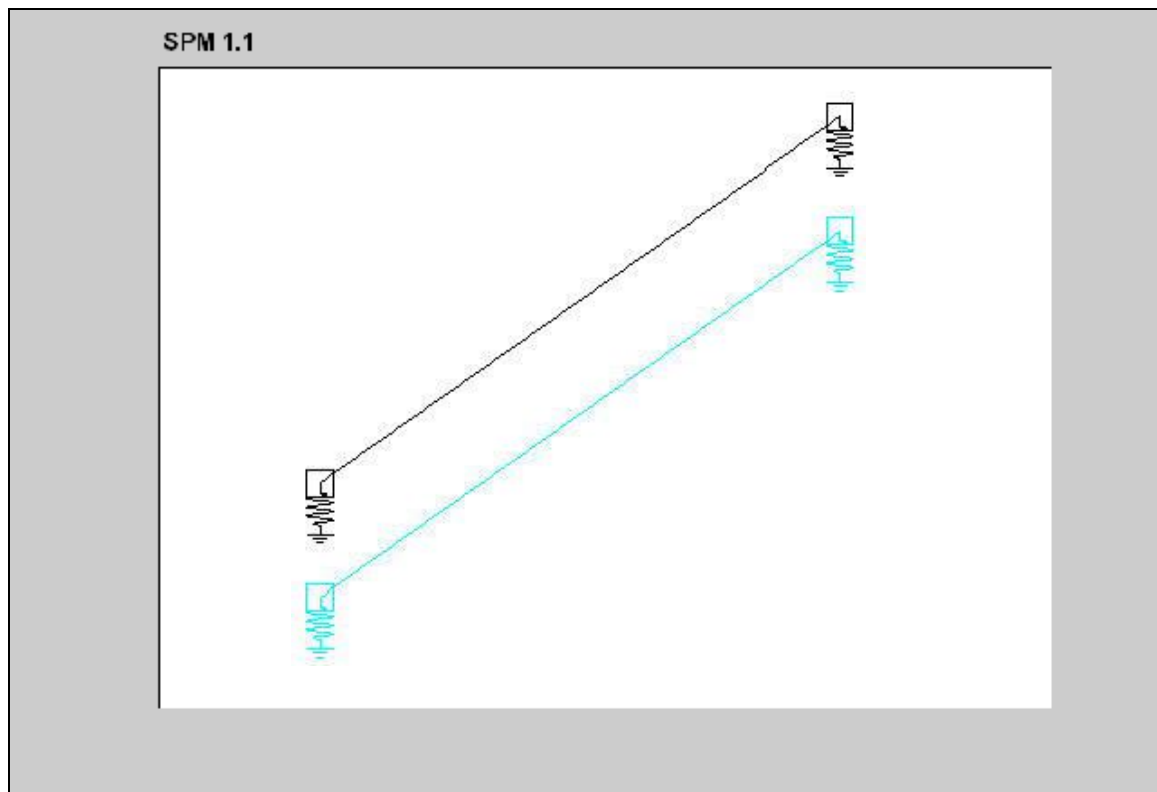


FIGURE 21. MODE SHAPE @ $f_0 = 145 \text{ Hz}$

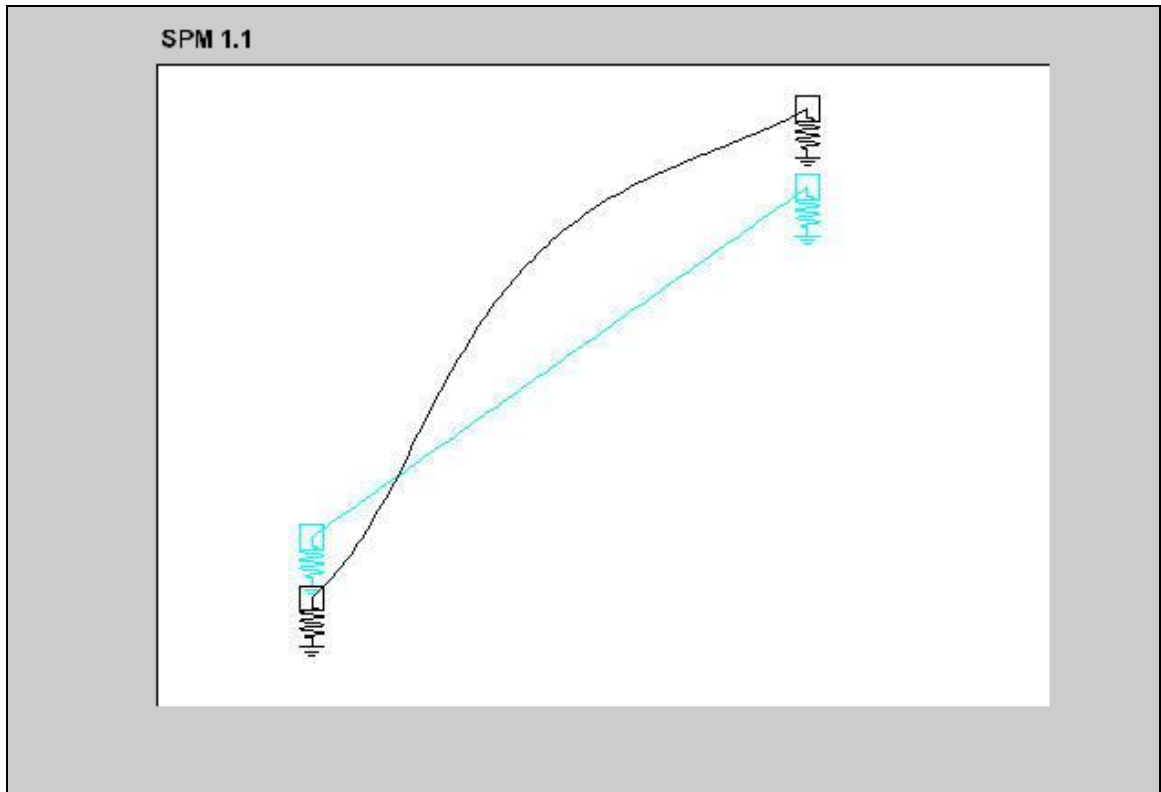


FIGURE 22. MODE SHAPE @ $f_1 = 6.4$ kHz, DAMPING = 0.02!

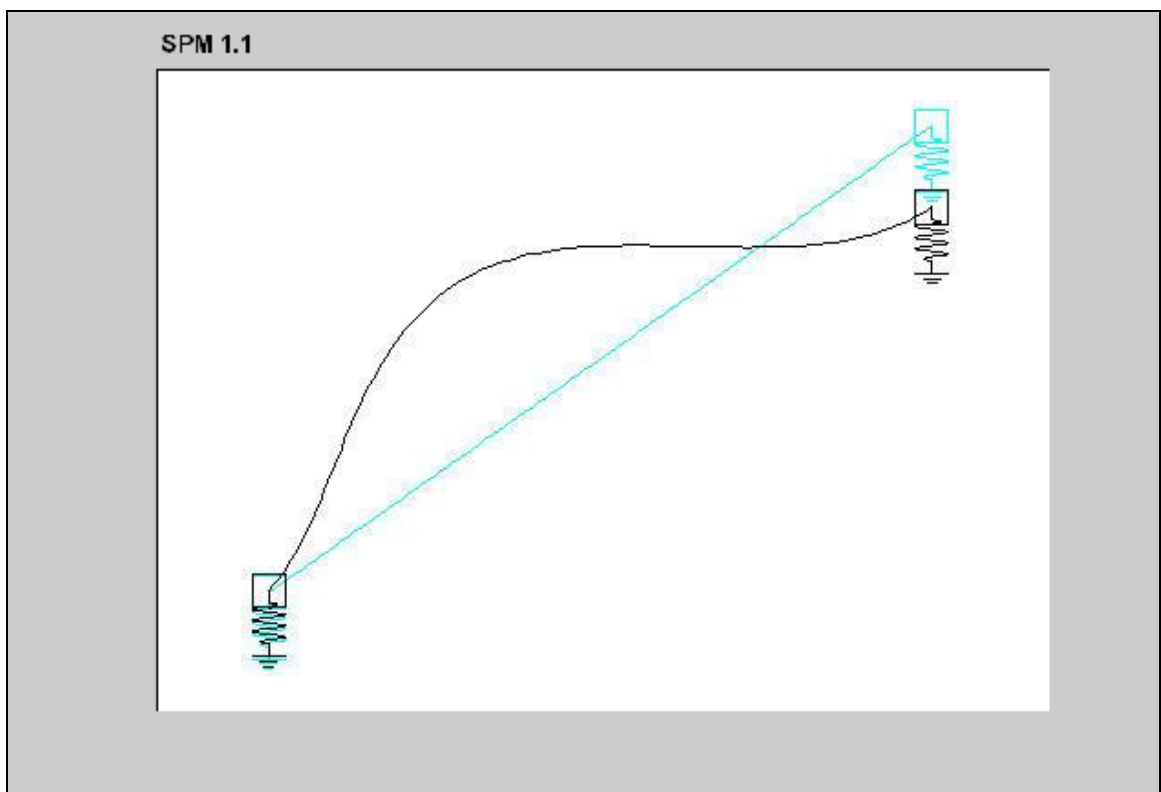


FIGURE 23. MODE SHAPE @ $f_2 = 10$ kHz, DAMPING = 0.03!

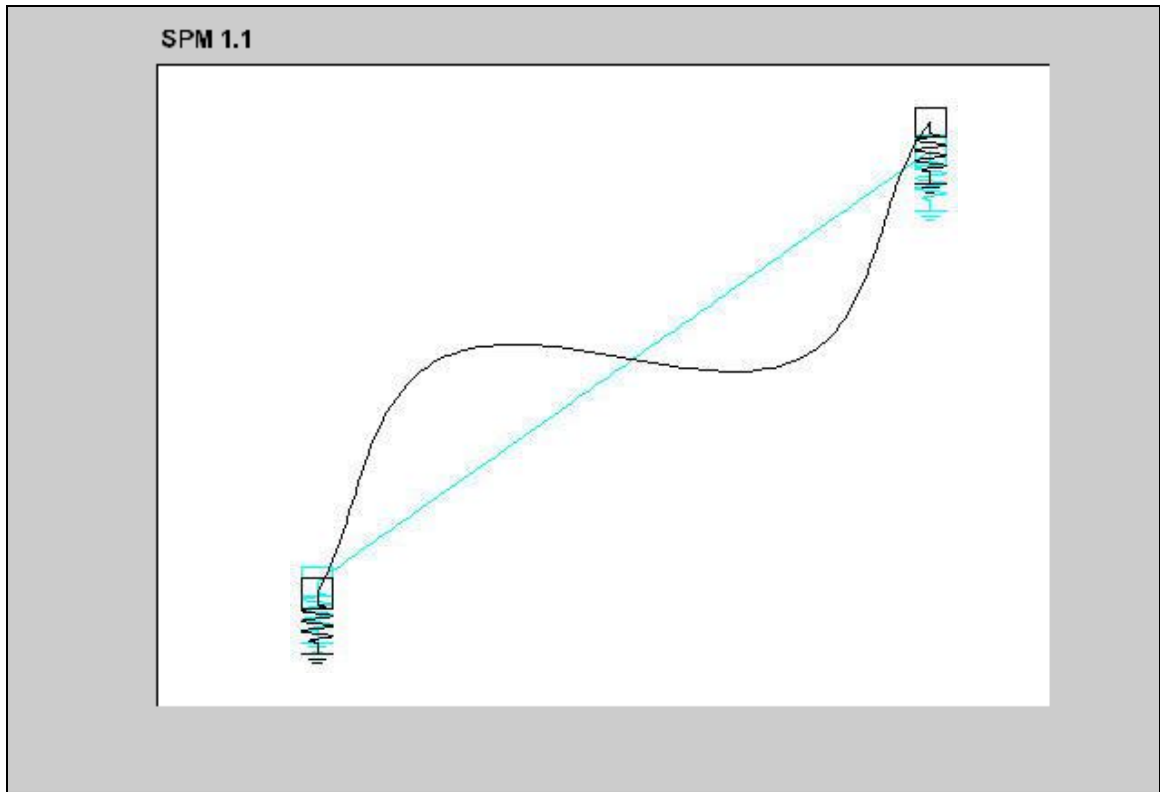


FIGURE 24. MODE SHAPE @ $f_3 = 19$ kHz! DAMPING = 0.04!

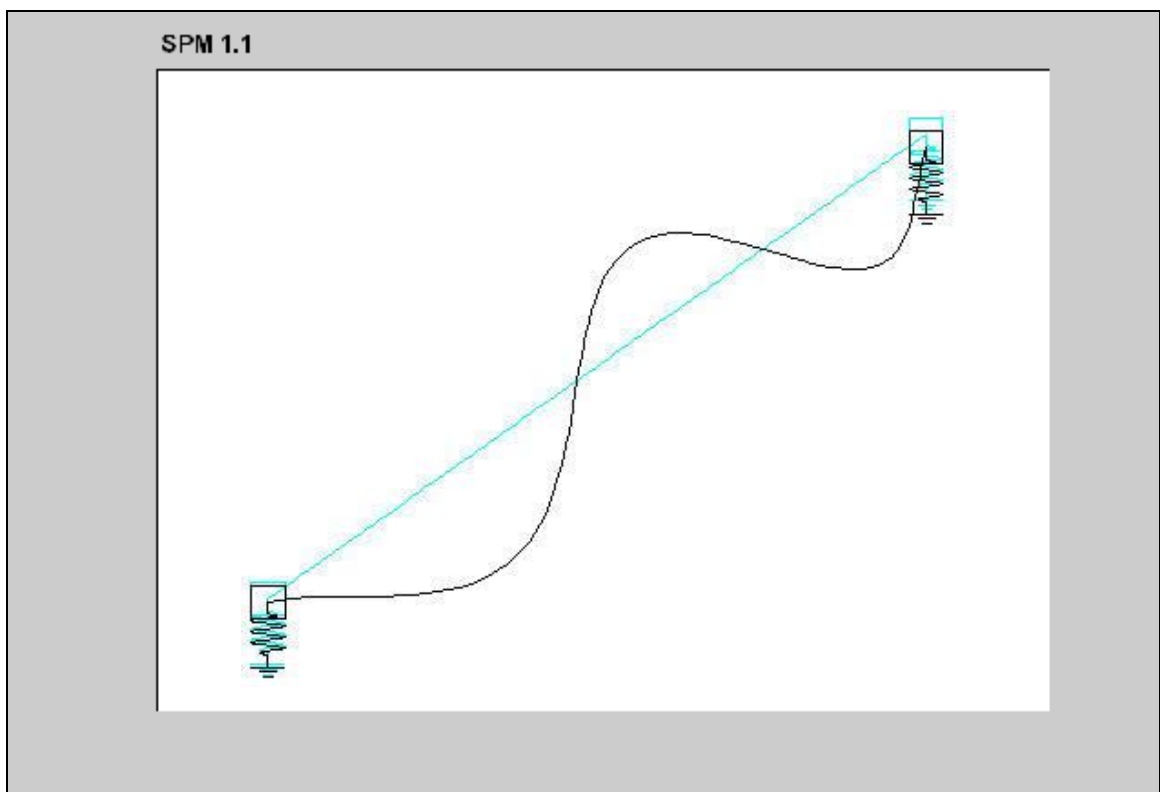


FIGURE 25. MODE SHAPE @ $f_4 = 30$ kHz! DAMPING = 0.04!

The Foam Sandwich Composite cone appears to have outstanding behavior. Of the five cone simulations, this one is by far the highest performer. It has the same piston bandwidth as the Deep Anodized magnesium cone with

damping comparable to paper but with mode shapes that are very well controlled. Is this the ideal metal cone? I believe it is. I call this the “Stealth Cone”. The simulation indicates that this cone is suitable for use up to 15 kHz or higher. Crossover design with this type of cone should also be greatly simplified. Expect no narrow band peaks and/or dips in the response. It really does not get any better than this.

In all the 2D axis-symmetric illustrations, the flared beam analogy can be seen. It is this I-beam analogy that explains the behavior of the Sandwich Composite cones that are illustrated in figures 15 through 25. When vibrated, the mode or load is distributed along the surface of the cone or I-beam within the analogy. Inherently for non-sandwich configuration, the cone will tend to bend first at the outside diameter. This should be intuitive and is characteristics of most cones. The exception is the Sandwich Composite with the I-beam analogy. The modulus of elasticity of the skins is much higher than the core. Wide spacing of the skins seems to be desirable; however, there was a self-imposed mass budget within all five of the cone models. Please note that f_0 is quite consistent from cone to cone. This indicates fairly consistent mass of the respective cones. The lumped spring/mass boundary conditions that implement the voice coil, spider, neck joints and surround are identical in each model as are the ID and OD dimensions.

Looking at figures 21 through 25, it is no wonder that similar topology is used to implement helicopter propellers, military rifle barrels and several other R&D intensive applications. There are several companies worldwide that develop and manufacture Sandwich Composites but I could not locate any companies that were familiar with the preferred harmonic characteristics of a transducer’s diaphragm. Most if not all of these companies utilize structural Finite Element Analysis to design the required composite part and/or assembly; however, it is unusual for harmonic analysis to be performed.

With the much of the development of the Sandwich Composite materials discussed within this article being for defense and aerospace application, the costs are high. The suppliers of these composites typically have customer bases that include General Dynamics, GE, Lockheed Sanders, Boeing and Air Bus to name a few. More information on composites can be obtained at <http://www.composite.about.com/>.

To be able to utilize these composite materials to raise the state of the art for transducers and loudspeakers will require R&D and capital investment, preferably within Asia where manufacturing costs are low and raw materials are readily available. Economies of scale could also have a significant impact on cost reduction. Purchasing departments know that the three most important elements of transducer piece part price are quantity, quantity and quantity.

What is required is for venture capital to flow into R&D for the development of cost effective manufacturing processes for implementation of composite cones and diaphragms. The raw materials themselves are not cost prohibitive for transducer cone and diaphragm applications.

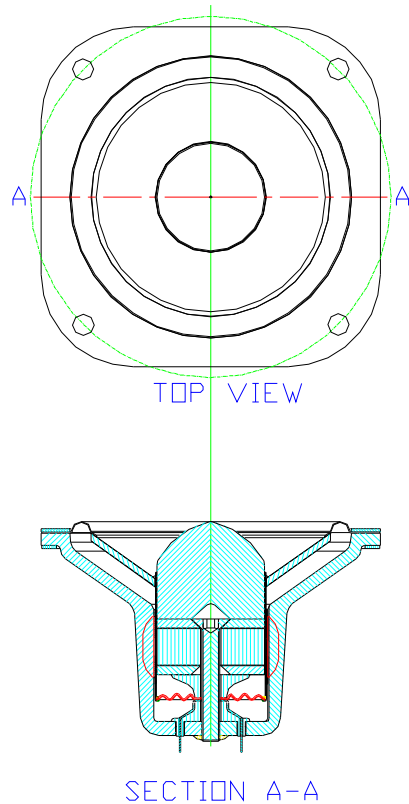


FIGURE 26. AN EXAMPLE 4 INCH FULL RANGE TRANSDUCER ASSEMBLY UTILIZING A SANDWICH COMPOSITE CONE.

With regards to all the moving assembly simulations and with respect to figure 26, after break-in f_0 will be reduced by approximately 20% due to a reduction in spider and surround stiffness. This will result in an f_0 of less than 120 Hz. In a ported enclosure tuned to 80 to 100 Hz, this transducer could be used over a very wide bandwidth. A cone with the performance potential of the Sandwich Composite requires that the additional components of the transducer's acoustic package should also be designed to the highest standards to exploit the full potential of this cone. In this case, a full range, mid/bass or midrange application is suitable.

If the bandwidth of the transducer requires operation above f_1 , there must be a phenomenon that I refer to as controlled or well-damped breakup. This relates to both mode shapes and damping. There is a clear trend with the Sandwich Composites that result in the increased spacing of the vibration modes with respect to frequency. This allows the system engineer to equalize any reasonable peaks and dips. The more typical modes of a cone are closely spaced, narrow band, and are difficult or impossible to be corrected with EQ. The response at or below f_1 is simply rolled-off by a low pass filter, preferably 4th order.

Finally, if a fairly large cone stays piston to the limits of audibility, then the response will beam and the power response will be poor at high frequencies and will follow the fundamental 'ka' law of acoustics, where

$$ka = \frac{2\pi \cdot \text{frequency}}{345} \cdot \text{cone radius} < 2. \text{ Above } f_1 \text{ the acoustic output from the}$$

diaphragm is somewhat randomized and the power response is typically

improved. The surface area and mass of the diaphragm within breakup are effectively reduced.

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