Extended Range Beryllium Dome Diaphragm Assembly for Large Format Compression Drivers

Marshall Buck[1], Peter Andrews[2], Gordon Simmons[2] and Sam Saye[2]

[1] Psychotechnology, Inc, Los Angeles, CA 90034, USA

[2] Materion Electrofusion, Fremont, CA 94538, USA

ABSTRACT

The development, manufacture, and testing of a new large format compression driver diaphragm using a beryllium dome and new type of polymer surround is detailed that exhibits improved performance. This design promises to give long life and good reliability with little or no change in performance anticipated over the life of the diaphragm. Design exercises include material properties comparisons, finite element analysis, and modal simulations. A comprehensive set of tests of beryllium, aluminum, and titanium diaphragm compression drivers is described including frequency response, distortion, wavelet time domain analysis on a 2 inch plane wave tube and laser scans of modes. Substantial differences were measured in the performance categories, particularly in the frequency range above 4kHz.

1. INTRODUCTION

This paper presents a rationale for the use of beryllium as the material for the diaphragm of a high frequency electroacoustic transducer. The material properties of beryllium are compared with aluminum and titanium and are found to be superior for this purpose. Other components of the assembly, which is designed to retrofit many standard two inch exit compression drivers, are also addressed for improvements, such as the voice coil and the surround. Manufacturing processes are described, and reliability testing results are given. Comprehensive acoustic testing data on a terminated tube are presented comparing the three materials. Laser scans show modal behavior of the three diaphragms.

2. HISTORY OF BERYLLIUM AS A DIAPHRAGM MATERIAL

Beryllium is a rare and unique metal which is used in a number of high technology industries including medical, aerospace, and high-energy physics. Applications for beryllium include x-ray components used in healthcare, scientific instruments used for advancing our understanding of the deepest laws of nature, satellite structures and aircraft components.

Beryllium has also played a significant role in high performance audio transducers. For many decades, it has been used in phonograph cartridges, and around 1977 a major Japanese audio company introduced loudspeakers containing beryllium. These beryllium transducers were used for several years in studio monitors and high performance home loudspeakers. They attained almost a cult status and are still sought after today.

At about the same time, another leading Japanese audio company introduced compression drivers and direct radiators which contained beryllium diaphragms, many of which are still widely used today. Both companies produced their beryllium diaphragms by a process called physical vapor deposition (PVD).

3. DIAPHRAGM MATERIAL PROPERTIES

The table below summarizes the key properties of aluminum, titanium, and beryllium. Note that different reference sources give some variations to the properties in this table. Descriptions of the key features are provided below.

Table 1: Comparison of Aluminum, Titanium and Beryllium

Property	**Aluminum**	**Titanium**	**Beryllium**
Density, ρ	2,700 kg/m^3	4,500 kg/m^3	1,850 kg/m^3
Young's Modulus, $\boldsymbol{E}$	71 x 10^9 Pa	116 x 10^9 Pa	310 x 10^9 Pa
Poisson's Ratio, ν	0.33	0.34	0.032
Speed of Sound, **c**	5,128 m/s	5,077 m/s	12,945 m/s
Tensile Strength	90 x 10^6 Pa Yield	140 x 10^6 Pa Yield	240 x 10^6 Pa Yield
Bending Modulus (re Al)	1.0	1.72	3.97
1st Bending Mode (re Al)	1.0	1.02	2.41

3.1 Density

The density of a material, ρ, is defined as the mass per unit volume or $\rho = \boldsymbol{m/V}$, where $\boldsymbol{m}$ = mass and $\boldsymbol{V}$ = volume. For a given transducer geometry, a lower-mass diaphragm allows greater acceleration of the moving system (F=ma), increasing both passband efficiency and high-frequency extension (Kinsler & Frey; Eargle).

3.2 Young's Modulus

This is the ratio of uniaxial stress to strain and is measured in units of pressure. It is defined as $\boldsymbol{E} = \boldsymbol{\sigma/\varepsilon}$, where $\boldsymbol{\sigma}$ = stress and $\boldsymbol{\varepsilon}$ = strain. A higher Young's Modulus equates to a stiffer diaphragm, all other things being equal. A stiffer diaphragm, of course, does not bend as much in response to an applied force. Thus, at high frequencies, the bending modes are shifted up in frequency, extending the useful bandwidth of the transducer (see further discussion below).

3.3 Poisson's Ratio

When a solid material is compressed in one direction, it tends to expand in the other two directions perpendicular to the direction of compression. This phenomenon is called the Poisson Effect. The Poisson's Ratio ν (nu) relates the contraction or transverse strain (perpendicular to the applied load), to the extension or axial strain (in the direction of the applied load). Assuming that the material is stretched or compressed along the axial direction:

$$\nu = - d\varepsilon_{transverse} / d\varepsilon_{axial}$$

Where

ν is the resulting Poisson's Ratio,

$\varepsilon_{transverse}$ is transverse strain (negative for axial tension, positive for axial compression)

ε_{axial} is axial strain (positive for axial tension, negative for axial compression).

The Poisson's Ratio of beryllium is unusually low. For acoustic applications, a low Poisson's Ratio results in reduced coupling of sound waves from one mode of propagation to another. For example, an axial wave will remain an axial wave transferring less energy to transverse modes of wave propagation. This ability to keep the different modes of propagation separated can be of great importance in acoustics, especially at higher frequencies, or in imaging or surface wave devices (Materion Electrofusion). In other words, a lower Poisson's Ratio better preserves the direction of the applied force.

3.4 Speed of Sound

The speed of sound is the rate of travel of a sound wave through an elastic medium. The speed of sound waves in solids is determined by the material's stiffness and density and may be described by the equation $c = \sqrt{E/\rho}$. This is generally understood to be the speed of a longitudinal wave along the x-axis of a long bar (where x >> y or z). For the purposes of this discussion, we are interested in the bending modes of a thin plate (x and y >> z) where the displacement of the wave is in the z-axis. The bending stiffness causes the bending wave speed to be different than c. These relationships are detailed below.

3.5 Tensile Strength

Tensile Strength is the property of a material that measures its ability to withstand tensile stress without failure. A material with a higher tensile strength allows a thinner dome to maintain equivalent strength, giving a lower moving mass.

3.6 Bending Modulus (relative to aluminum)

This property describes the stiffness of a thin plate in response to bending forces (similar to Young's Modulus, but in two dimensions). Of course, the actual bending stiffness of a dome shape is highly dependent on the details of that geometry. For this discussion, we separate the material's inherent bending stiffness from the geometry's stiffness by assuming the same thin plate geometry for all materials. For the sake of clarity in the table, these results have been shown relative to the Bending Modulus of the aluminum plate.

3.7 1st Bending Mode (relative to aluminum)

For a given geometry, the frequency of the first bending mode (break-up frequency) is related to the speed of sound in the material. More accurately, the first bending mode varies as $\sqrt{(E/\rho\,(1-\nu^2))}$, according to Euler-Bernoulli plate theory (Kinsler & Frey). For the sake of clarity in the table, these results have been shown relative to the 1st Bending Frequency of the aluminum plate.

The approximate shape of the 1st bending mode is shown in Figure 1 below.

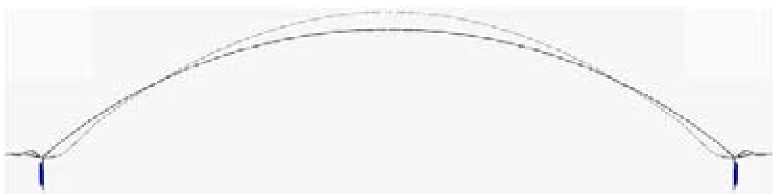


Figure 1. 2D Mode Shape at 1st Bending Frequency of a Dome Diaphragm.

3.8 Summary

In summary, from the material properties table above, one can readily see that beryllium has the lowest mass, the highest stiffness, the lowest Poisson Effect, the highest speed of sound, and the highest tensile strength of the acoustically useful light metals. This excellent combination of properties results in a much higher bending stiffness for any given geometry, and thus a marked increase in the first bending mode frequency of the diaphragm. What this means to the designer of large format compression drivers is more than an octave of useful frequency range from the same driver geometry.

4. MANUFACTURING PROCESSES

Beryllium is inherently a hard metal, and has a reputation for being brittle in thin structures. However, manufacturing processes can have significant effects on the ductility of beryllium. There are two processes that are currently used to manufacture beryllium acoustic components.

4.1 PVD Beryllium

PVD is a process performed in a vacuum and is a general term used to describe any of a variety of methods to deposit thin films by the condensation of a vaporized form of the material onto various surfaces. The coating method involves purely physical processes such as high temperature vacuum evaporation or plasma sputter bombardment. The process used to vapor deposit beryllium produces a relatively coarse grain structure with grains oriented perpendicular to the plane of the deposited layer. The PVD process also places physical limits on the thickness of the finished diaphragm.

4.2 Rolled Beryllium Foil

Rolled beryllium foil is produced using a process which creates a fine metallic grain structure with grains oriented parallel to the direction of rolling. Precise control of the rolling process produces beryllium foil with a highly uniform grain structure while minimizing residual strains in the finished product. For many years, rolled beryllium foil was not used for acoustic applications due primarily to the high price of the material. However, Materion Electrofusion developed a much more cost effective rolling process and has been supplying the acoustic market with beryllium foil for over a decade.

4.3 Comparison of PVD Beryllium vs. Rolled Beryllium Foil

The differences in the grain structure and grain orientation result in significant improvements in the functional properties of rolled beryllium foils vs. PVD beryllium materials. When a moderate normal force is applied to PVD beryllium it is subject to catastrophic failure, whereas if the same moderate normal force is applied to rolled beryllium foil, it displays ductility similar to titanium and aluminum domes (i.e., it deforms). PVD beryllium typically fails by shattering into multiple pieces of various sizes. However, rolled beryllium foil typically tears or splits when it fails, remaining cohesive if not functional. Currently, rolled beryllium foil is used in several high performance transducers including near field studio monitors, consumer and professional compression drivers, and direct radiating tweeters for both home and automobile applications.

5. ADDITIONAL IMPROVEMENTS TO THE LARGE FORMAT COMPRESSION DRIVER DIAPHRAGM ASSEMBLY

The use of a rolled beryllium foil diaphragm has been shown to offer exceptional improvements to large format compression driver performance regardless of geometry. However, there are several other aspects of the diaphragm assembly that also have room for improvement.

5.1 Voice Coil

The voice coil is commercially pure aluminum that is fully annealed before flattening to allow for uniformity and minimal elongation during the wire flattening process. A Kapton® former minimizes mass and mechanical losses while maintaining high rigidity between the coil and the diaphragm. The coil is bonded to the former using a high temperature aerospace adhesive typically not used in the speaker industry. Electrical connections to the voice coil are accomplished with two copper-beryllium lead out strips. These are soldered directly to the coil stack using special water-based flux which boils out during the subassembly curing cycle. Experience over the last 20 years with many thousands of coils has proven that this process provides reliable solder connections with an extremely low number of voice coil failures in the field.

In order to maximize packing density, increase coil rigidity, and minimize mass, it is already well-known that edgewound flat aluminum wire is the best solution, giving a theoretical 27% greater packing density than round wire (Eargle), although realizable improvements may be more like 17%. Most modern high performance compression drivers take advantage of this geometry. We have developed a proprietary winding method that enables even greater packing density, achieving additional gains of up to 3% to 7% over commercially available coils. The resulting increase in $B\ell$ is well known to increase efficiency in a compression driver.

Table 2 below compares the packing density of our improved coil with that of two commercially available voice coils.

Table 2: Comparison of Three Edge-Wound Flat Wire 16-Ohm Compression Driver Voice Coils

Coil Type	Average Packing Density	Relative Packing Density
Brand X	218.5 turns/in	100%
Brand Y	227.3 turns/in	104%
Improved Coil	232.9 turns/in	107%

5.2 Surround

There are two surround designs typically used for large format compression drivers. The most common is to use the metallic dome material for the surround. These integral dome/surround designs typically have some geometric relief provided to the surround portion such as a half roll, pleats, or indentations to reduce flexing stress and distortion. This type of surround has been employed with good performance results since the early development of compression drivers by Western Electric in the 1920s. Careful forming methods are required in order to prevent the metallic foil material from work hardening during the forming process, potentially cracking under subsequent use. Molding of the foil membrane is usually accomplished by pressure forming in a die. Early efforts spun the dome portion into the mold to provide different properties in the dome and surround areas. The single material membrane + surround is the least expensive design, but does have certain limitations.

A second more recent method is the use of a polymer surround. Kapton and Mylar® are the most common materials used as their mechanical properties allow greater flexing and minimize the work hardening effects suffered by metallic surrounds. Some designs use a special moldable Kapton that wraps around the voice coil making it part of the surround assembly and provide greater protection of the voice coil. Most polymer surrounds do not need geometric relief as the material can flex sufficiently to provide the needed movement. While Kapton and Mylar show a marked improvement over a metal surround, they do not represent the best technology available today.

A special polymer surround material was selected for use in the diaphragm assembly presented here. This polymer material was chosen specifically for its mechanical properties including excellent damping which contributes to the exceptionally smooth response of the diaphragm. In addition, the outstanding fatigue resistance of the surround material enables the diaphragm assembly to provide long life and excellent reliability with little or no change in performance anticipated over the life of the diaphragm.

Figures 2 and 3 show response curves taken before and after a 100-hour accelerated life test, comparing a popular high-performance titanium diaphragm assembly and the improved beryllium diaphragm assembly of this presentation. As mentioned above, a metal surround will work harden with the flexing of continued use, causing the performance degradation that can be seen in both the frequency response and the 3rd harmonic distortion curves for the titanium diaphragm assembly. An average of 1.5dB is lost in the output below 3kHz, and there is an increase of 5% in the 3rd harmonic at 1kHz.

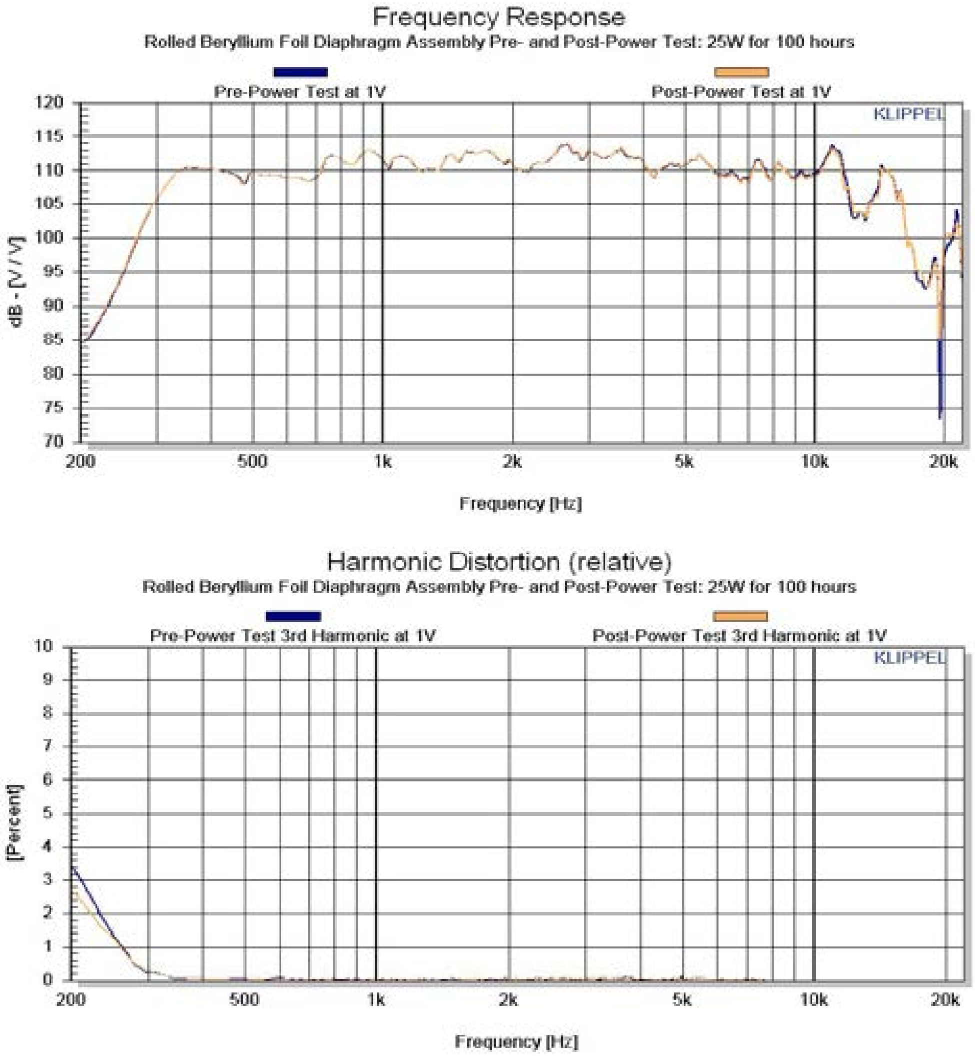


Figure 2. Accelerated Life Test Data; Rolled Beryllium Foil Diaphragm Assembly. 500Hz – 5,000Hz Pink Noise, 6dB CF, 12dB/octave slope. Note very small changes in frequency response and minimal increase in distortion after 100 hour test.

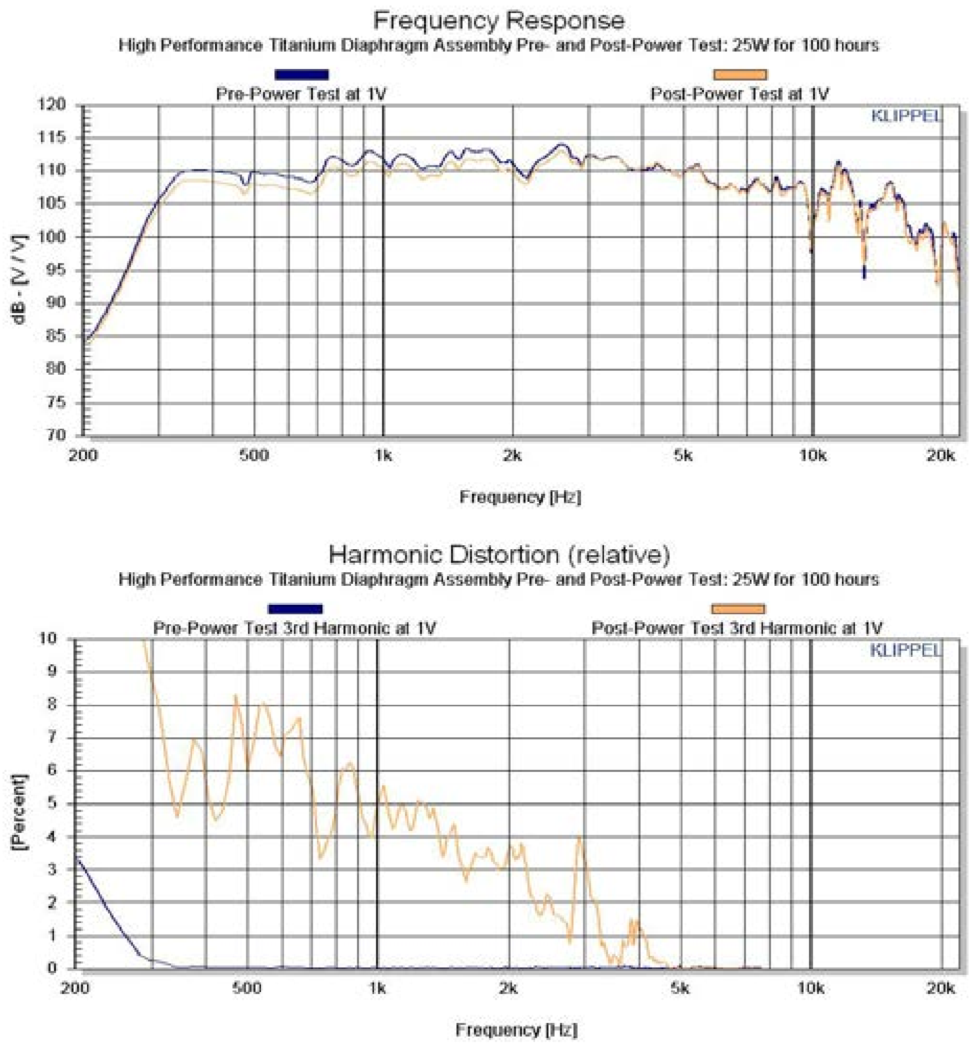


Figure 3. Accelerated Life Test Data; Titanium Diaphragm Assembly.
500Hz – 5,000Hz Pink Noise, 6dB CF, 12dB/octave slope. An average of 1.5dB is lost in the output below 3kHz, and there is an increase of 5% in the 3rd harmonic at 1kHz after 100 hours.

5.3 Final Assembly

Special tooling has been built to facilitate the final assembly of the dome and surround to the coil/former subassembly. The tooling uses novel techniques to apply precise pressure on all adhesion surfaces of the diaphragm assembly.

Further, two aluminum clamp rings are employed to ensure high precision alignment of the surround to the dome and coil in all directions during cure. An extended cure cycle is used with slow temperature ramp times to give the greatest and most reliable adhesive cure strength.

6. VIBRATION MODELS AND MEASUREMENTS

6.1 Finite Element Modeling

A finite element model was constructed using the geometry of the Truextent® brand 4 inch (100mm) diaphragm assembly. To resolve the natural frequencies of each material, this analysis intentionally ignores acoustic loads from the compression driver itself (no rear cap, no phase plug, no horn), essentially modeling the dome in a vacuum. Each material's properties are fed into the model without changing the geometry. The first 6 bending modes are shown on the following page.

The mode shapes are, of course, similar for all the materials however the frequencies of these modes vary significantly. Table 3 below summarizes these natural frequencies.

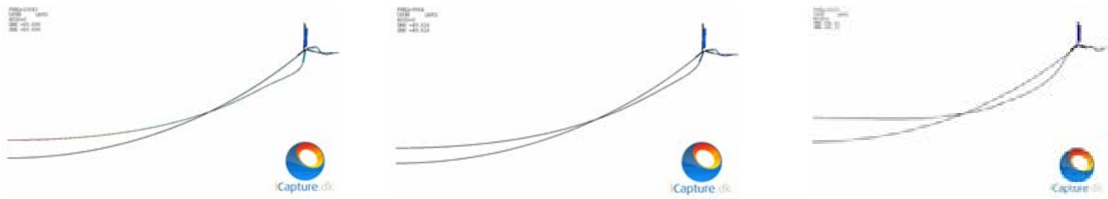
Table 3: Predicted Bending Mode Frequencies

Natural Freq(kHz)	Aluminum	Titanium	Ti_n / Al_n	Beryllium	Be_n / Al_n
1st mode	10.04	9.98	**0.99**	26.16	**2.61**
2nd mode	10.44	10.36	**0.99**	26.64	**2.55**
3rd mode	10.56	10.46	**0.99**	26.79	**2.54**
4th mode	10.62	10.52	**0.99**	26.90	**2.53**
5th mode	10.68	10.58	**0.99**	27.05	**2.53**
6th mode	10.76	10.66	**0.99**	27.28	**2.54**

First, notice that the Finite Element Model confirms the analytical solution above; if geometry is held constant, beryllium's bending modes occur at roughly 2.5x higher frequency than those of the other materials.

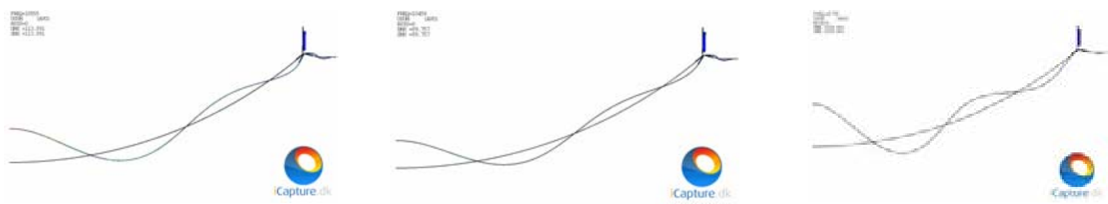
Perhaps even more interesting is the acutely non-harmonic relationship of the modes above the first. Classical plate theory hints at this, but flat plates and membranes do not exhibit such closely-spaced modes. While beyond the scope of this study, it is certainly worth noting that the relationship between the natural frequencies is drastically affected by the geometry of the dome. The modal density above the first bending mode is much higher than that predicted by classical (flat) plate theory. Essentially, this lends greater importance to the first bending mode frequency, since adjacent modes set in so quickly and densely above that frequency.

Aluminum	Titanium	Beryllium



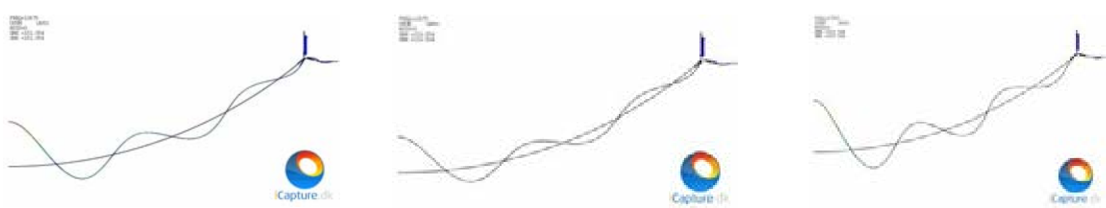
1st bending mode = 10.04kHz 9.98kHz 26.16kHz

2nd bending mode = 10.44kHz 10.36kHz 26.64kHz



3rd bending mode = 10.56kHz 10.46kHz 26.79kHz

4th bending mode = 10.62kHz 10.52kHz 26.90kHz



5th bending mode = 10.68kHz 10.58kHz 27.05kHz

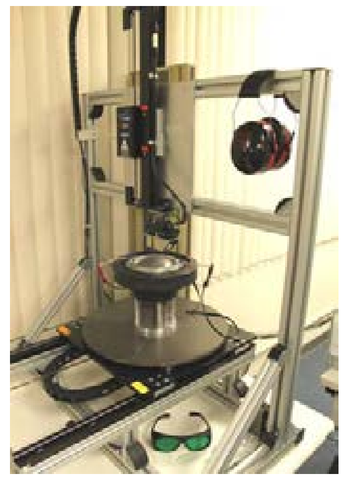
6th bending mode = 10.76kHz 10.66kHz 27.28kHz

Figure 4. Bending Modes of 4" Compression Domes in Vacuo.

6.2 LASER VIBROMETRY MEASUREMENTS

Using a Klippel SCN laser scanner, geometric and vibration scans of compression driver domes were made of the three materials discussed herein; aluminum, titanium, and beryllium. While these real domes are not the same thickness or profile, the relative performance characteristics and properties discussed above are clearly evident.

These scans were made on an open compression driver (JBL® 2446 with back cover removed) using a custom fixture that insures repeatable position of the DUT. To minimize the effects of different suspension methods, these scans were limited to a 51mm radius, 1mm outside the nominal voice coil radius. This restricts the measurements to the metallic part of each assembly.



Note that this test setup does not provide a complete as-used acoustic load to the diaphragm (i.e., mounted on a horn with the back cap in place). However, we submit that these results can relatively quantify the performance of these materials, and confirm the empirical analysis above. Future work will include tests both in vacuo and in situ.

For simplicity, both 2D (cross-section) and 3D measurements of each dome's total vibration are shown at 4 frequencies: 5, 10, 15, and 20kHz. From these snapshots, it can be readily seen that the beryllium dome is better-behaved at high frequencies than either the aluminum or titanium domes.

First, at only 5kHz, simple bending occurs on all the domes, some more than others. Going up in frequency, bending waves become visible on each dome's surface. As expected, the number of wavelengths increases with frequency. The brief table below simply counts the number of wavelengths up one side of each dome. As discussed above, the speed of sound in beryllium is roughly 2.5x the speed of sound in aluminum or titanium. Even with such crude analysis, this is apparent.

Table 4: Number of Wavelengths of Modes Up One Side of the Dome

Frequency	Number of bending waves (/radius)		
	Aluminum	Titanium	Beryllium
5kHz	~1	~1	<1
10kHz	~3.5	~3.5	<1
15kHz	6+	6+	~2.5
20kHz	~9	~9	~3.5

Perhaps more importantly, the aluminum and titanium both show large areas of anti-phase motion even near 10kHz. These destructively interfere with the in-phase motion, producing sharp peaks and dips evident in the Acoustic Performance Testing section of this paper. Further work will include analysis of these anti-phase motions and their effects on the measured response of the assembly.

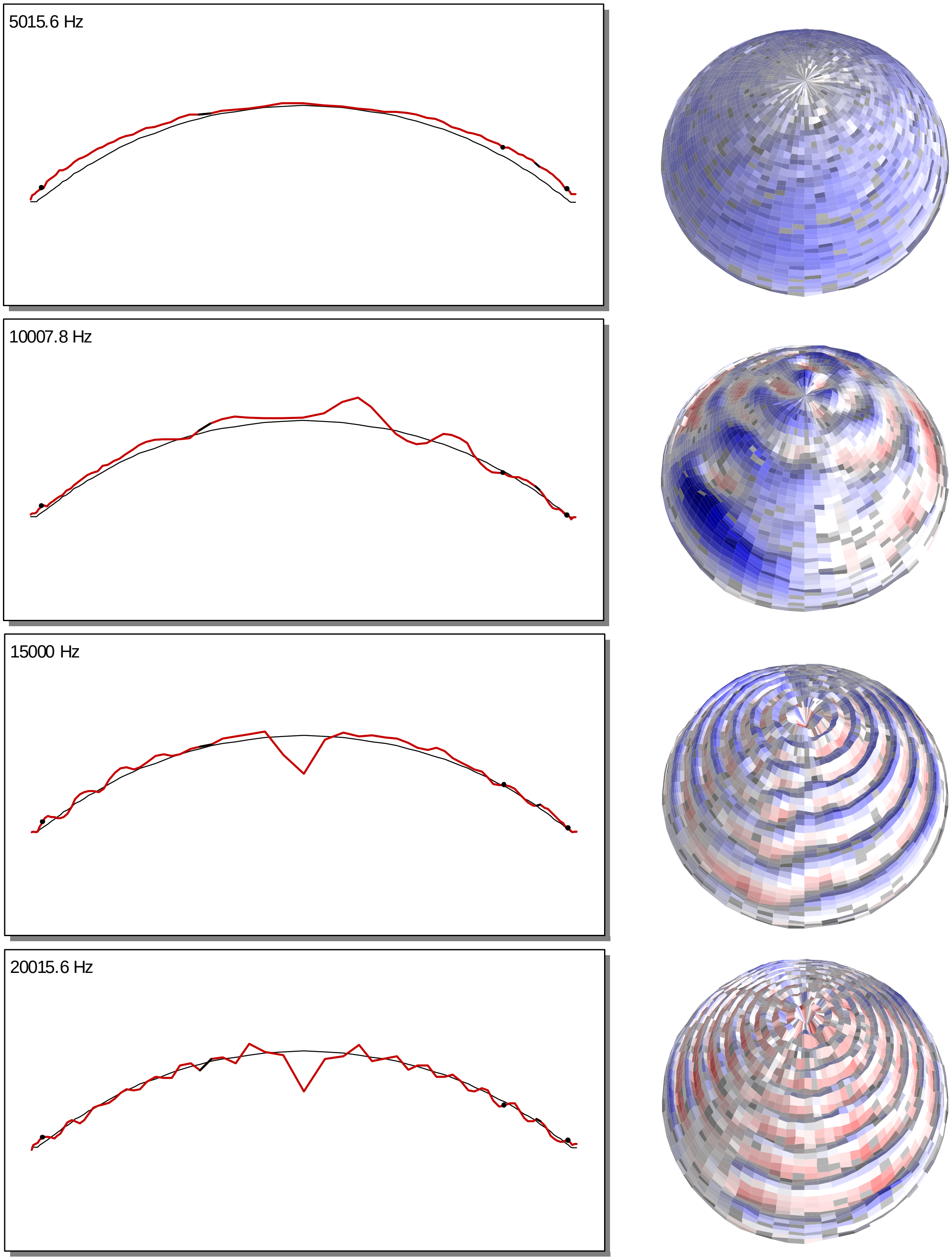


Figure 5. Aluminum Dome Total Vibration at 5kHz, 10kHz, 15kHz, and 20kHz.

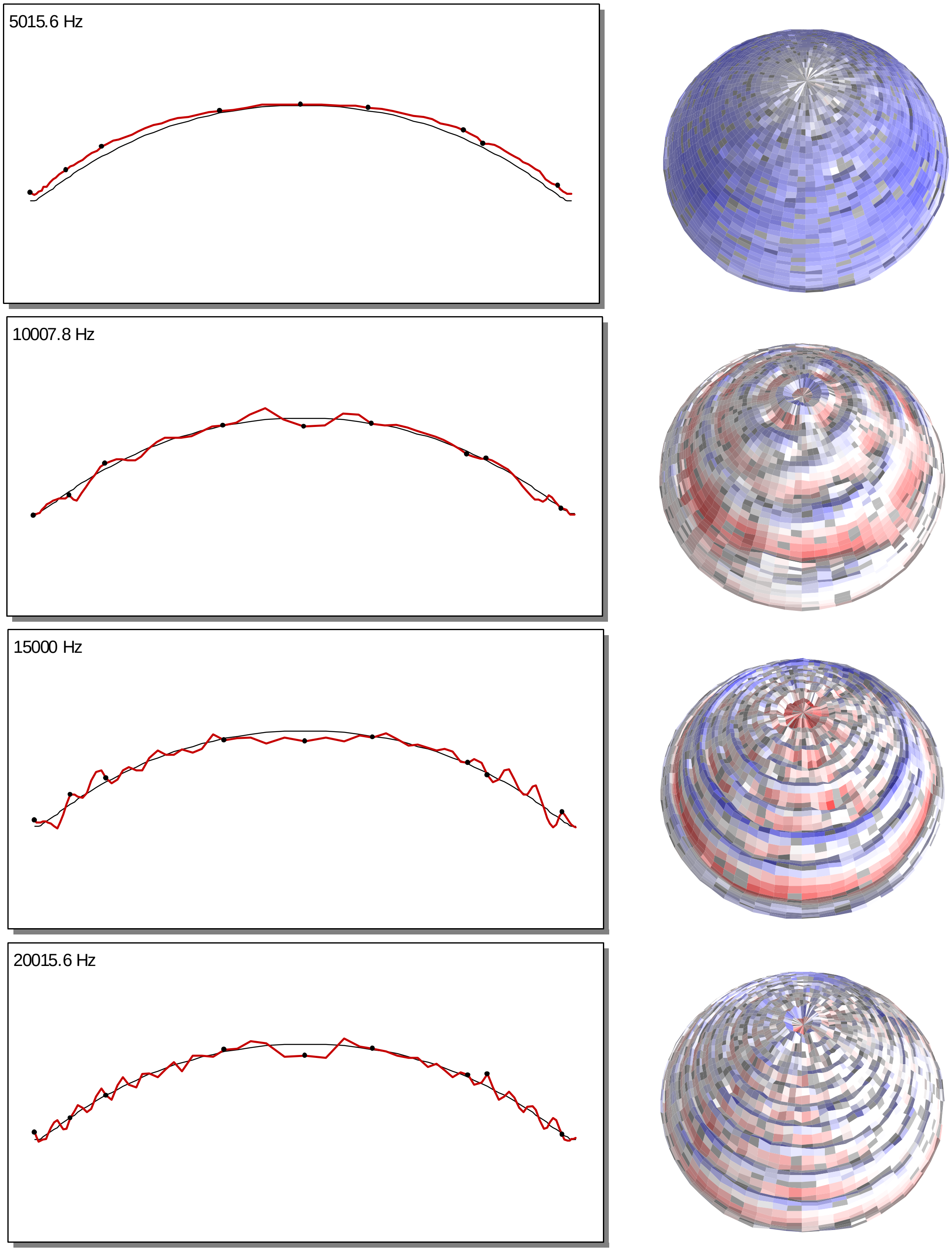


Figure 6. Titanium Dome Total Vibration at 5kHz, 10kHz, 15kHz, and 20kHz.

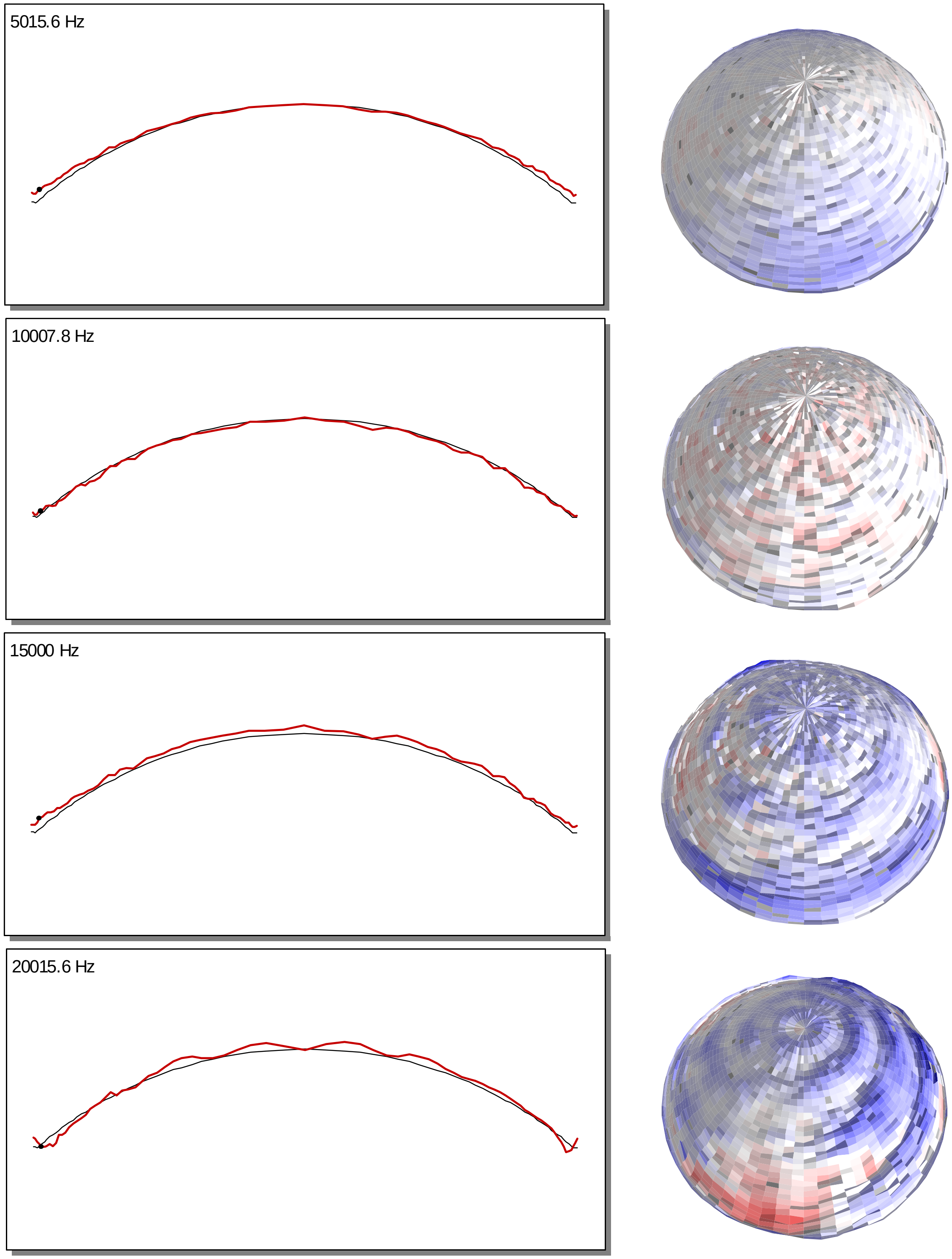


Figure 7. Beryllium Dome Total Vibration at 5kHz, 10kHz, 15kHz, and 20kHz.

7. ACOUSTIC PERFORMANCE TESTING

7.1 Test Equipment and Methods

All of the following tests were performed with a test setup that included a 2 inch terminated plane wave tube (Buck), using a Bruel & Kjaer 1/4 inch microphone, Bruel & Kjaer 2619 preampifier, 2801 power supply and an Audiomatica CLIO 10 QC Firewire PC Windows XP® measurement system with 192kHz sampling rate. System pressure calibration was performed using a Bruel & Kjaer 4231 Calibrator. The nominal 16 Ohm drivers were driven with 4 Volts RMS for a 1 Watt power level, except where noted. A comparison of frequency response, distortion, and time domain behavior of four diaphragms will be presented below.

7.2 Frequency Response and Harmonic Distortion

The first data set is frequency response and distortion. Each curve is an average of three measurements taken at 120 degree rotation intervals on the PWT. This smooths out effects of slight non plane wave behavior typical of large format compression drivers with 4 inch diaphragms, particularly at and above 10kHz. All tests used a JBL 2450 driver assembly, with the 1.5 inch to 2 inch throat adaptor in place. The 2nd and 3rd harmonic distortion curves were raised 20dB to fit the graph. In all cases, the BLACK curve is the fundamental response, the GREEN curve is the 2nd harmonic distortion, and the RED curve is the 3rd harmonic distortion. The highest curve is the fundamental, the next one is the 2nd harmonic and the lowest is the 3rd. The distortion curves are displayed at the excitation frequencies. Scales and axis ratios follow IEC recommended practice of 25 or 50dB/decade.

Figure 8 shows the response and distortion of the aluminum diaphragm. Aluminum has long been the material of choice for compression driver diaphragms. It exhibits frequency response above 10kHz, unlike phenolic diaphragms, and is easy to form. Sound quality has been good.

Figure 9 shows the response and distortion of the titanium non-ribbed diaphragm. The use of titanium in compression driver diaphragms gained in popularity in recent decades due largely to its ruggedness. It also provides a high frequency output improvement over aluminum. There were some reports that sound quality was not as good as aluminum. (Murray)

Figure 10 shows the response and distortion of the ribbed titanium diaphragm. The ribbing and diamond pleat surround add stiffness, thus extending the high frequency response. The tradeoff is higher Q resonances above 10kHz.

Figure 11 shows the response and distortion of the beryllium diaphragm. The beryllium diaphragm exhibits a smooth, extended frequency response, and the distortion is comparable to the other materials.

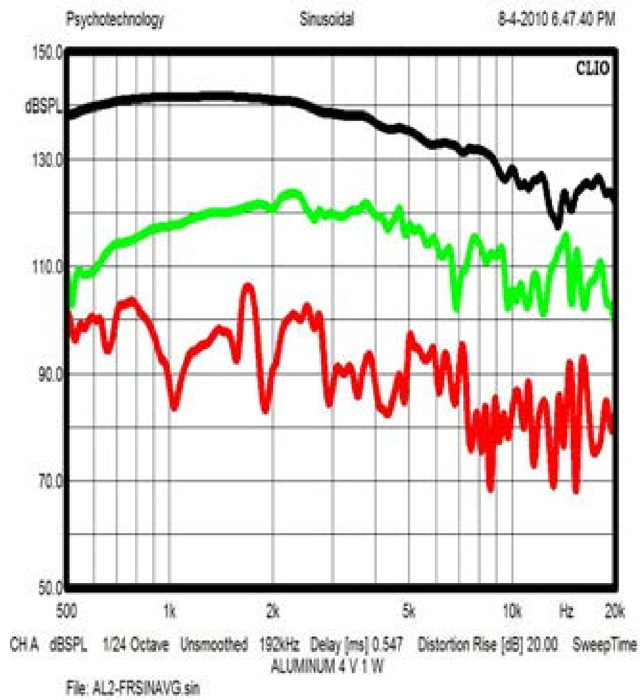


Figure 8. Response and Distortion - Aluminum Diaphragm.
(Fundamental-Black; 2nd Harmonic-Green; 3rd Harmonic-Red)

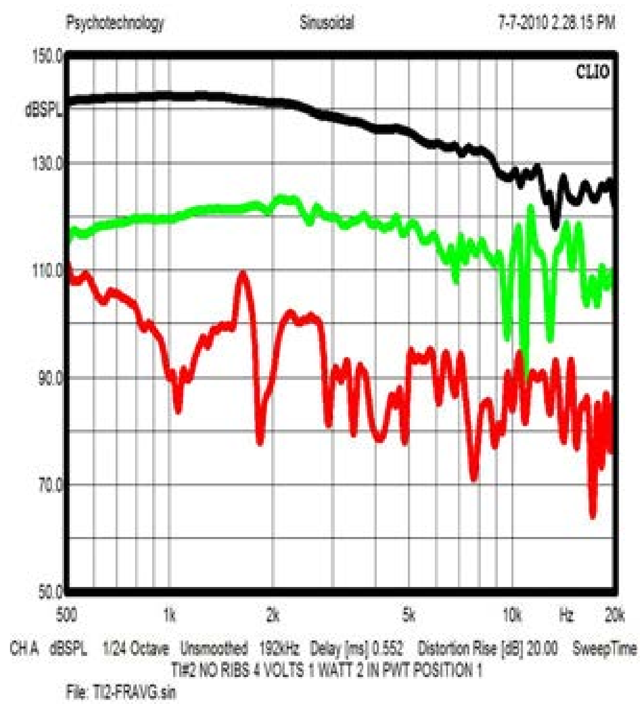


Figure 9. Response and Distortion - Titanium Nonribbed Diaphragm.
(Fundamental-Black; 2nd Harmonic-Green; 3rd Harmonic-Red)

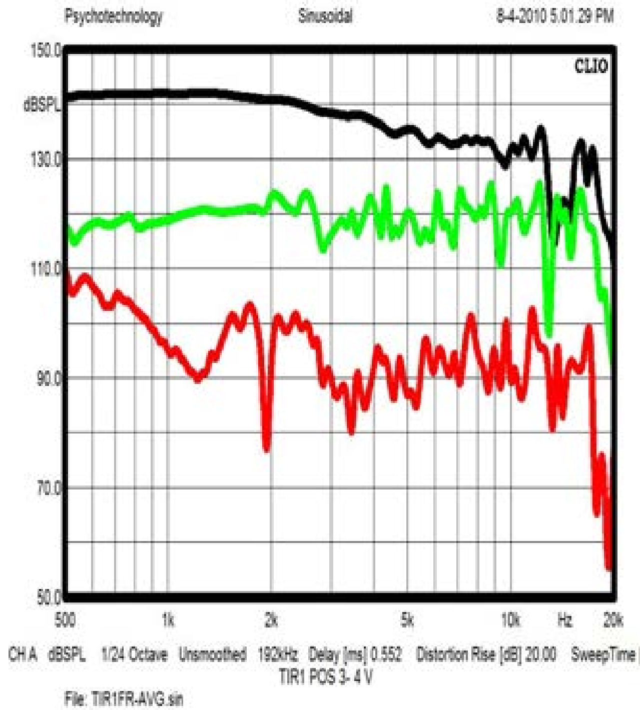


Figure 10. Response and Distortion - Ribbed Titanium Diaphragm.
(Fundamental-Black; 2nd Harmonic-Green; 3rd Harmonic-Red)

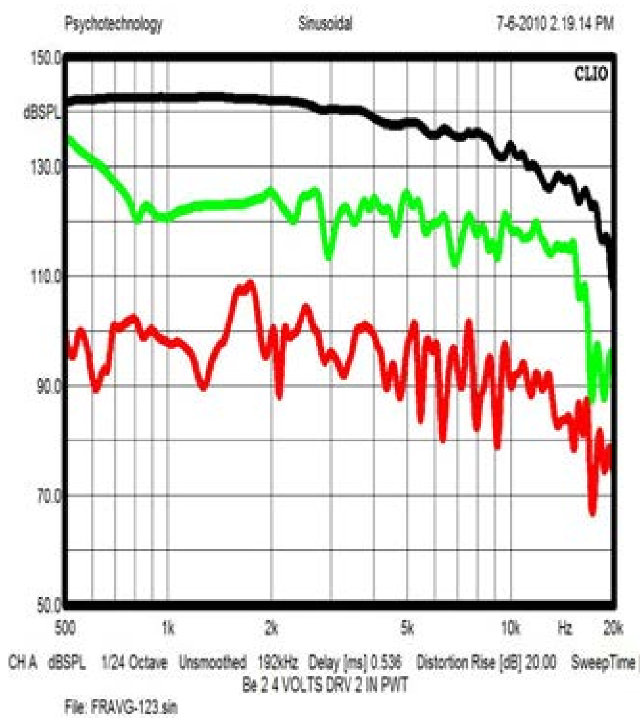


Figure 11. Response and Distortion - Beryllium Diaphragm.
(Fundamental-Black; 2nd Harmonic-Green; 3rd Harmonic-Red)

7.3 Discussion of the Response and Distortion Tests

The four reponse and harmonic distortion plots above are traditional measurements, taken on a plane wave tube. The four diaphragms show differences in high frequency response, above 4kHz, while the lower frequency sensitivities are essentially equal. The distortion plots are similar, and are largely a function of the compression of the air in the phase plug. Low frequency distortion is related to suspension performance.

7.4 Direct Response Comparisons

The following frequency response graphs are on an expanded vertical scale to show in more detail the differences between beryllium and the three competing technologies.

Figure 12 shows the response of the beryllium diaphragm versus the aluminum diaphragm. The beryllium diaphragm has substantially more output than the aluminum one from 4 to 18kHz, with a solid 6dB advantage at 10kHz.

Figure 13 illustrates that the beryllium diaphragm has substantially more output than the nonribbed titanium one from 3 to 18kHz, with a solid 6dB advantage at 10kHz.

Figure 14 shows the response of the beryllium diaphragm versus the ribbed titanium diaphragm. The beryllium diaphragm has substantially more output than the titanium one from 3 to 11kHz, with an average of 2.5dB advantage at 5 to 10kHz. The response of the beryllium diaphragm is also much smoother in the top octave.

Figure 15 shows the responses of all four diaphragms on a 100dB scale. The midrange effciency is essentially equal with +/- 0.5dB at 2kHz. However, significant differences appear above 4kHz.

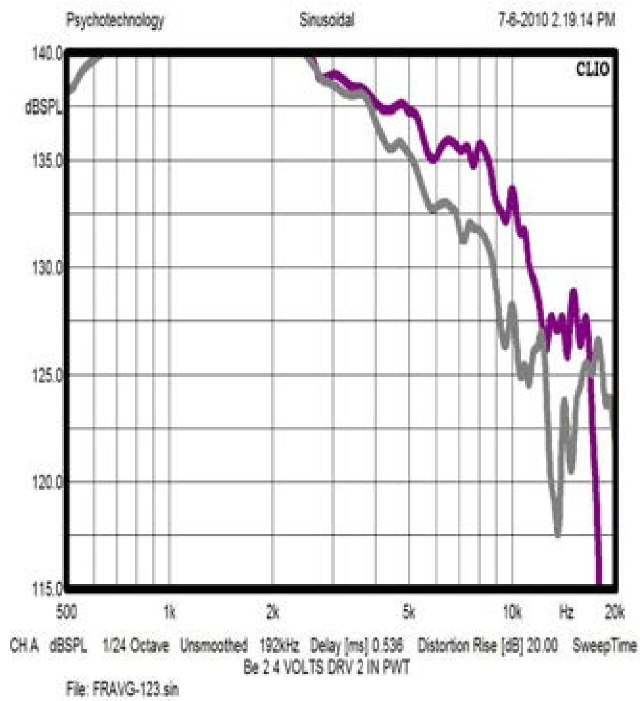


Figure 12. Response - Beryllium (purple) vs. Aluminum (grey) Diaphragm.

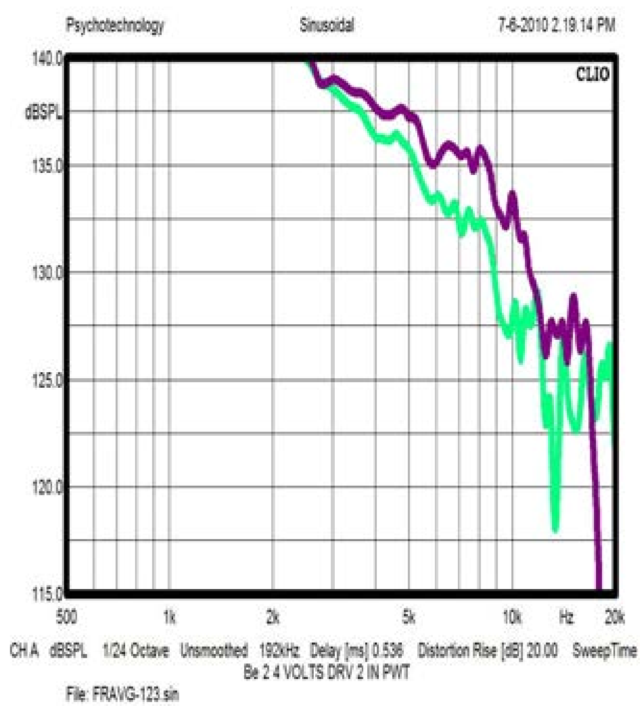


Figure 13. Response - Beryllium (purple) vs. Nonribbed Titanium (lime) Diaphragm.

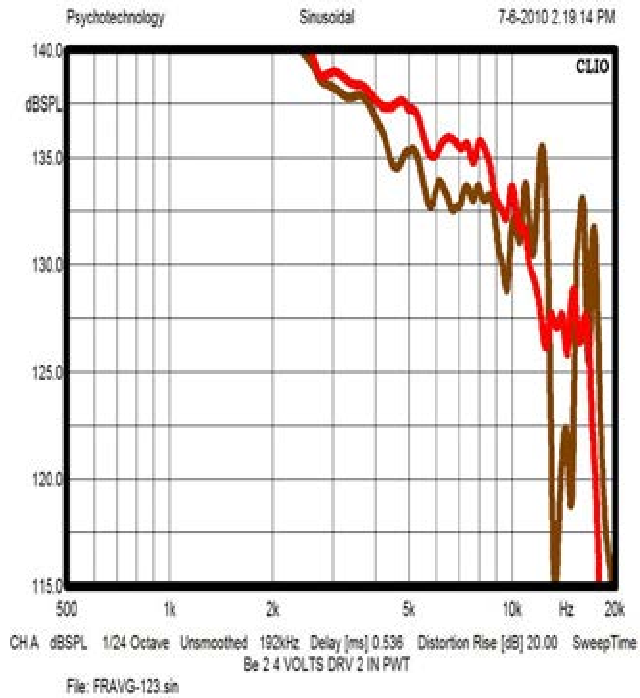


Figure 14. Response of Beryllium (red) vs Ribbed Titanium (brown) Diaphragm.

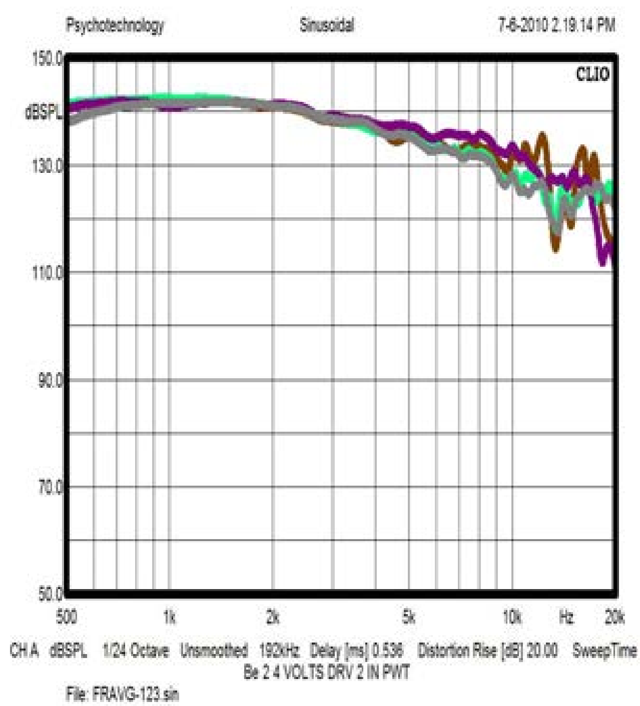


Figure 15. Response - All Four Diaphragms on a 100dB Scale.
(Beryllium-purple; Aluminum-grey; Nonribbed Titanium-lime; Ribbed Titanium-brown)

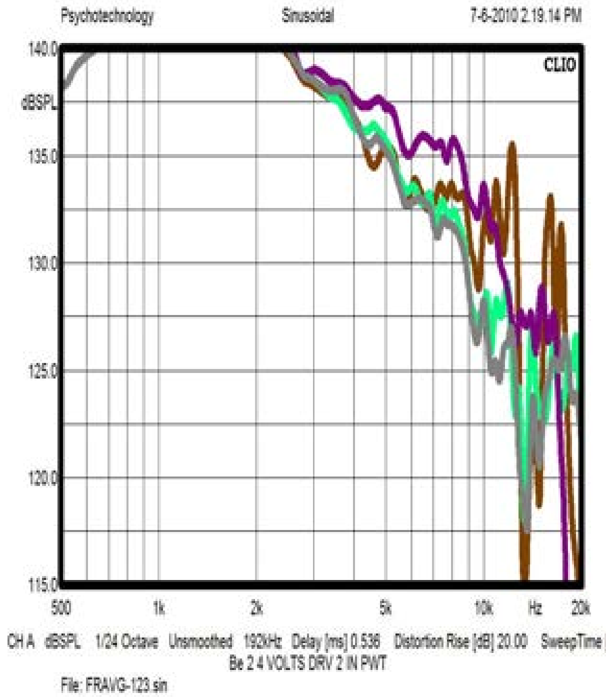


Figure 16. Response - All Four Diaphragms on a 25dB Scale.
(Beryllium-purple; Aluminum-grey; Nonribbed Titanium-lime; Ribbed Titanium-brown)

7.5 Summary of Frequency Response Differences

In these comparisons, the beryllium diaphragm exhibits substantially more output in the two octaves from 3 to 12kHz than all of the standard materials. Only the ribbed titanium diaphragm has some additional energy over the beryllium in the highest octave, but it is decidedly rougher.

In professional audio, especially at larger venues, the top octave is less important as it tends to be attenuated quickly with distance. However, if the user wants to boost that octave, it would be preferable to do that on the smoother unit with the beryllium diaphragm.

7.6 Wavelet Analysis of Time Domain Behavior

In an attempt to address the sound quality issues voiced by some audio professionals, it was decided to look closely at the time domain behavior of each of these diaphragms. It is known that peaky frequency response is associated with a longer decay time. Perhaps the following results will provide insight into the relative performance of these materials in these applications.

CLIO 10 QC has the capability of doing a wavelet analysis on the impulse response of the transducer. The impulse responses were taken using the Maximum Length Sequence analysis mode, and truncated to 11 milliseconds for the analysis.

CLIO's wavelet analysis tool is implemented using a kernel of modified complex Morlet wavelets and can be interpreted as a constant Q analysis. Time resolution is high at high frequencies and not too low at low frequencies. Thus, the wavelet analysis overcomes the fixed time/frequency resolution limitations of an FFT analysis.

Here we used a Q of 3 and plotted the Scalogram relative to the peak energy in each spectral slice. This provides a detailed view of the energy decay of the transducer as a function of frequency.

These data are presented in Figures 17 - 21 on the following pages. The color bar on the right shows the hues over the 50dB scale of the energy, while the spectrum is on the vertical axis. The horizontal axis is time in milliseconds, from 0 to 11.

Figure 17: Perfect Wavelet

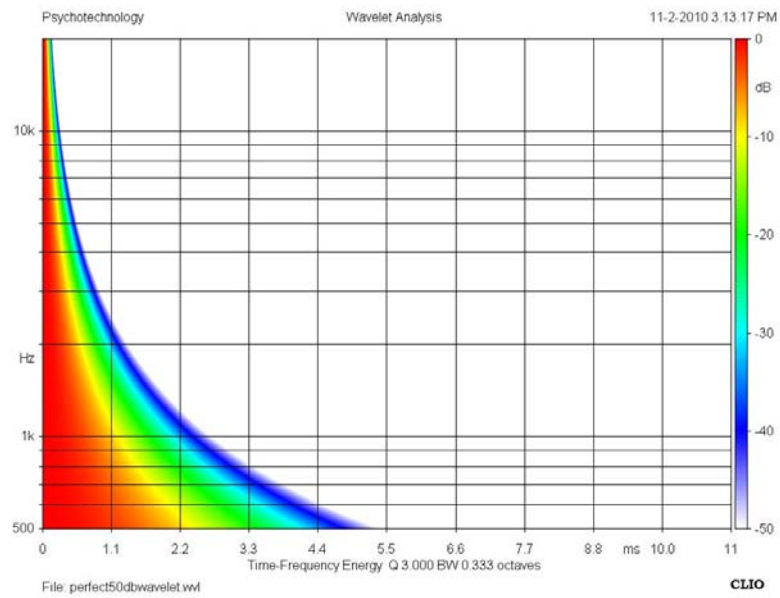


Figure 17. Perfect Wavelet.

Figure 17 shows a wavelet that was calculated from a direct electronic loopback through CLIO. The decay is approximately 1/f for each frequency.

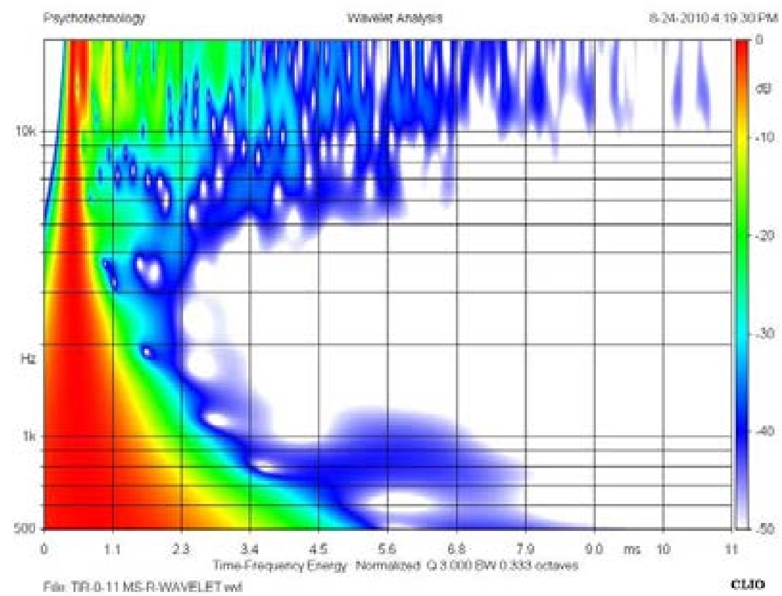


Figure 18: Titanium Ribbed Diaphragm (Diamond Pleat Surround).

Figure 18 shows that the titanium ribbed diaphragm shows the worst ringing of the four diaphragms, exhibiting long decay at both the upper two octaves and at 1kHz.

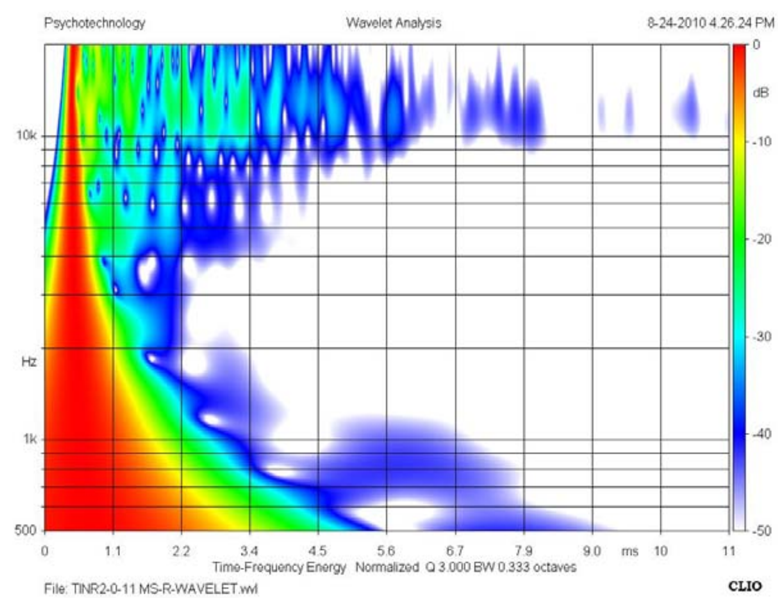


Figure 19: Titanium Nonribbed Diaphragm.

Figure 19 shows that the titanium diaphragm with no ribs is the second worst performer on the wavelet decay test, it suffers from the top octave and 1kHz ring.

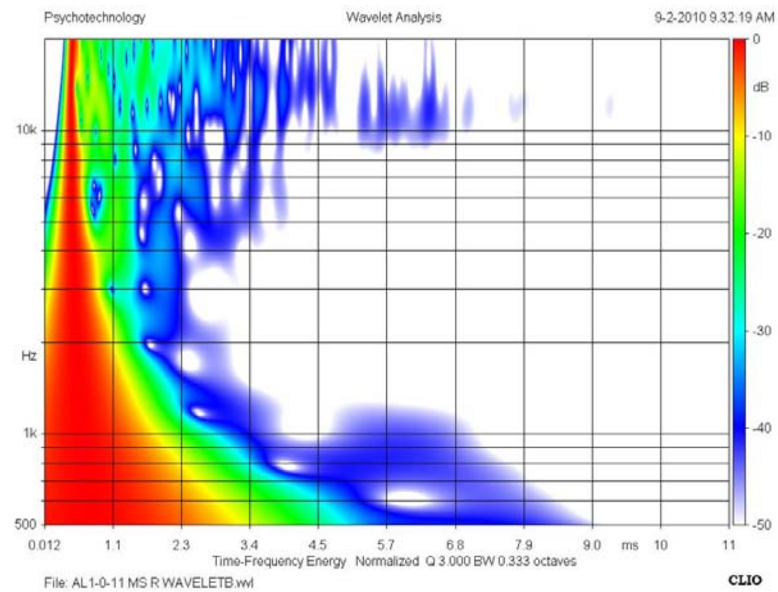


Figure 20: Aluminum Diaphragm.

Figure 20 indicates that the aluminum diaphragm has good decay behavior, both in the upper two octaves and at 1kHz.

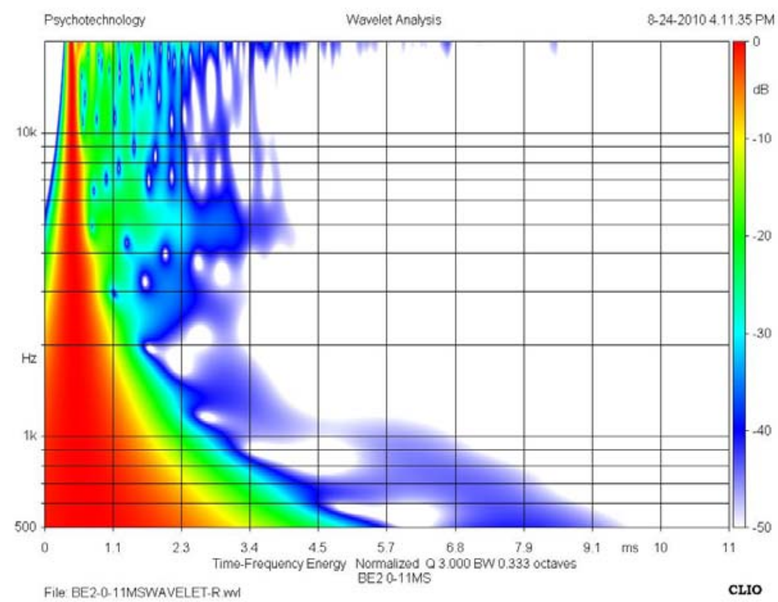


Figure 21: Beryllium Diaphragm.

Figure 21 illustrates that the beryllium diaphragm has the best top octave decay characteristics of the four materials and shapes.

There is a connection between the time domain behavior and the frequency domain behavior. When there is a rough and peaky frequency response, then the time domain response will show a long decay. This effect is particularly evident in the top octave response and decay differences between the smooth, fast-decaying beryllium driver and the peaky, long-ringing ribbed titanium driver.

Although we have done no formal listening tests of this effect, it has long been stated by audio professionals that the titanium diaphragms do not sound as good as the original aluminum ones, but they are prized for their reliability (Murray).

Note that when displayed in a grey scale instead of color, it is more difficult to assess the probable sound quality implications of these acoustic decay scalograms. At least, it appears that the aluminum and the beryllium diaphragms have similar decay characteristics, and both are better than titanium in that regard.

With the new development of a beryllium device that combines reliability with a smooth extended high frequency response, the pro audio industry has an additional option in its toolbox.

8. CONCLUSIONS

There are still many opportunities for improvement in today's professional compression drivers. New materials and processes can contribute to better performance, more part-to-part consistency, better reliability, and longer life cycles. The rolled beryllium foil gives clear performance and durability advantages over other available diaphragm materials. New suspension materials and adhesives maintain that performance over a longer life, and carefully controlled manufacturing processes using precision parts ensure consistency and reliability. State of the art testing methods including use of terminated tubes, scanning laser displacement vibrometry, accelerated life testing, and experimentation with new engineered materials for flexible suspensions will facilitate continued progress in this field.

9. ACKNOWLEDGEMENTS

This work was supported by Materion Electrofusion. The authors would like to acknowledge the assistance of Martin Wolf, Edward Hefter, and Mr. Ulrik Skov of iCapture.dk who performed the Finite Element Modeling.

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