A Modular Projector System: Modeled Versus Measured Performance

James Crawford
Ultra Electronics Maritime Systems
40 Atlantic Street, Dartmouth, Nova Scotia, Canada, B2Y 4N2
Phone: (902) 466-7491 ext 4112, fax: (902) 463-6098, email: jcrawford@ultra-uems.ca

Christopher Purcell
Defense Research and Development Canada Atlantic
P.O. Box 1012, Dartmouth Nova Scotia, Canada, B2Y 3Z7
Phone: (902) 426-3100 ext 389, email: chris.purcell@drdc-rddc.gc.ca

Bruce Armstrong
GeoSpectrum Technologies Inc.
30 Bel Ayr Avenue, Dartmouth, Nova Scotia, Canada, B2W 2E1
Phone: (902) 434-3906, email: bruce@geospectrum.ca

Abstract

Over the past several years, UEMS has developed the Modular Projector System (MPS), an invention by Bruce Armstrong. MPS exploits acoustic interaction between closely-spaced underwater sound projectors to produce a compact low-frequency broadband source that is straightforward to reconfigure for specific resonance frequency, bandwidth, and source level by simply repositioning the basic building blocks from which it is composed. Previous papers on MPS described the concept and its extraordinary flexibility in configuration and performance, and compared modeled results for different configurations using the MAVART finite element software. This paper compares modeled and measured frequency responses of a two MPS prototypes comprising flexural disk transducer stacks in several configurations, validating the modeling and performance predictions. Planned future modeling enhancements include moving from axisymmetric to fully three-dimensional models of non-collinear arrays and our roadmap towards this goal is described. Interpretation of the physical test results offers new insight into this remarkably versatile transducer.

1 Introduction

The Modular Projector System (MPS) is a versatile method for manufacturing a low-frequency underwater sound projector. As its name suggests, a MPS is assembled from a number of small sound projectors that are mounted in close proximity to each other. By exploiting the acoustic interactions amongst the projectors, the transducer designer can choose the resonance frequency, bandwidth, and output power of the system within wide limits. The concept was previously introduced [1] at a time when there was some modeling and test data available to suggest that MPS would function as predicted, but little work that actually showed close correspondence between modeled and measured results. Recently, the production and calibration of MPS projectors at various configurations and extensive modeling work has bridged this gap, illustrating some surprising but explainable effects from some modeling assumptions. This paper presents these results.

In principle, many projector types such as rings or barrel-stave projectors could be used as the "building block" for a MPS, but for most applications the best choice will be a flexural disk projector, also known as a "bender". A bender is inexpensive, reliable and easy to build, but most of all, a bender's pancake-like shape permits milli-λ separations. As an illustration of the versatility of the MPS concept, eight identical benders, each with an 1800Hz resonance in the free field, can produce a MPS with a 600Hz resonance and source level greater than 200 dB re 1 μPa at 1m. This cylindrical MPS would have a mass of 8 kg, a length of 20cm, a diameter of 14cm, and an operating depth of 300 m without pressure compensation. A different quantity and spatial arrangement of the same 1800Hz benders could be used to produce a MPS with resonance frequencies ranging from 450 to 1600Hz with source levels exceeding 210dB.

The acoustic performance of a conventional underwater sound projector is fixed at the time the projector is designed. If this performance exceeds the specification, the projector will be heavier and larger than the end-user wants. Furthermore, if this projector is part of a towed system the tow body and its handling system must also be larger and stronger. On the other hand, if the performance of the projector does not meet the specification, the customer must either sacrifice a portion of the specification or pay for a costly and time-consuming redesign of the projector, if indeed a single projector can be made to meet the specification. Thus the versatility of the MPS benefits both the end-user and the transducer manufacturer. Moreover, this paper demonstrates that the MPS numerical models have high fidelity across a wide range of configurations, so the risk associated with the MPS solution is further reduced.

Ultra Electronics has substantial experience using conventional arrays of benders in its active sonobuoy programs. Ultra's Canadian subsidiary Ultra Electronics Maritime Systems (UEMS) in Dartmouth, NS, Canada has been developing the MPS and has applied for patent protection. This paper presents a brief description of benders and a history of the MPS invention, and then compares measured and finite element (FE) modeled results for a number of MPS configurations.

2 Bender Description

Benders were first studied in the 1950's (see Woollett [2]). Several decades later, John Delany at Ultra Electronics Sonar and Communications (S&CS) in the UK "rediscovered" the bender and developed versions for sonobuoys, decoys and other active sound projector applications. Recently, Bruce Armstrong, using DRDC Atlantic's MAVART finite element program, improved on the Delany design, making it low-cost, reliable, and easy to build. Figure 1 shows an isometric and cross-sectional view of the bender that Ultra Electronics uses in its active sonobuoys. It is this 100mm diameter bender that was used as the building block for all MPS work reported on in this paper.

The bender is comprised of thickness-poled circular piezoelectric ceramic plates bonded to two aluminum plates, one on each. The plates are held together at their perimeters largely by hydrostatic pressure acting on a flexible joint that approximates a free-edge condition, a design goal enunciated by Woollett. The ceramics are positioned on the outside of the plates. The air-filled gap between the plates is just wide enough to prevent the plates from touching at maximum depth. In sonobuoys, the bender is waterproofed by a flexible potting compound. For MPS, the bender can either be potted or left bare if an oil-filled boot is used. One electrical lead is connected to the two aluminum plates, which contacts the inner silver electrodes of the ceramics, and the second is connected to the outer silver electrodes of the ceramics (leads are not shown in Figure 1). Voltage applied to the electrodes causes the two plates to flex axially in opposite directions, thereby generating sound.

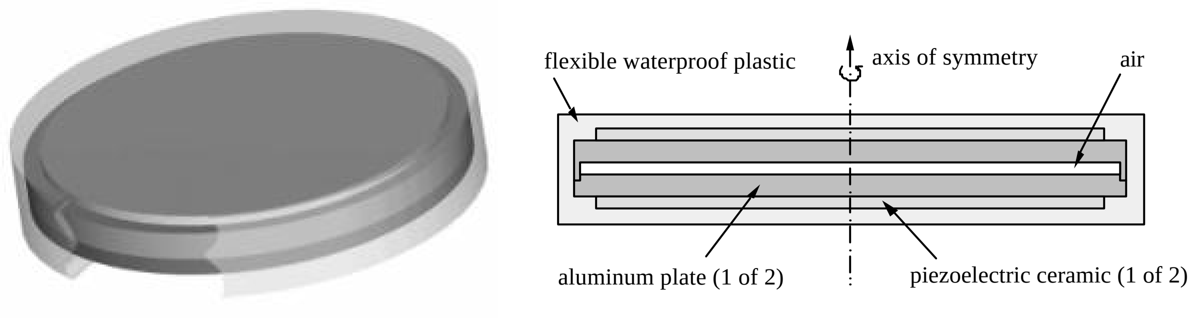


Figure 1 Isometric and Cross-Sectional Views of a Bender.

3 History of the Invention

Bruce Armstrong was the first to understand the physics behind MPS and its potential as a low frequency sound source. The dawn of understanding came gradually, with some serendipity. Ultra Electronics Maritime Systems in Dartmouth Nova Scotia had contracted Armstrong to develop a low frequency sound projector that had to fit within a constrained space. He realized that a single bender projector could not satisfy the power, size and depth requirements, but that four benders arranged axially could. Armstrong modeled an array of these benders with the MAVART code and saw an unexpected "bump" in the transmitting voltage response (TVR) at low frequency. He could find no problem with his model, and was relieved to see the bump in the measured calibration data. This bump was not in the acoustic band of interest for the intended application so was given no further attention.

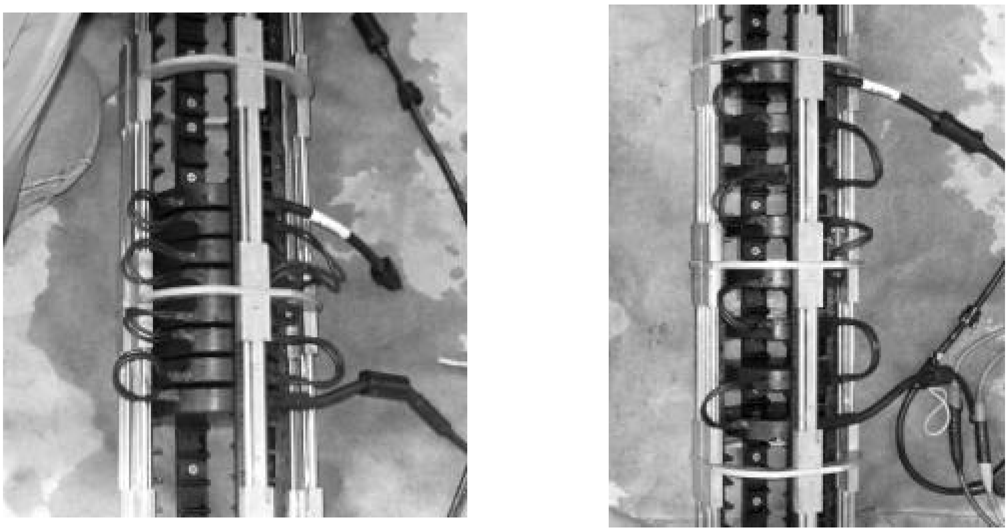
Months later, Armstrong was developing a high-power, low frequency sound source for deployment in an oil well. Again, the only way of generating high power with constraints on diameter was with a multitude of benders so he revisited the bump he had seen previously. It was only then that he realized that this was the fundamental resonance of the *system*, even though the fundamental resonance frequency of the benders in the free field was much higher. Bruce Armstrong has nearly three decades of experience in underwater transducer design so he realized that the strong acoustic interactions amongst the closely packed projectors were changing the radiation impedance seen by each bender, adding radiation mass and radiation resistance. It is this additional radiation mass that causes the resonance frequency of the projector system to be less than that of an individual projector in the free field. The number of benders and their spacing determines the radiation impedance, so the transducer designer can now adjust new degrees of freedom in the design to achieve the desired system performance. This near-field interaction has been dubbed the “MPS Effect”. It is interesting that prior to MPS, transducer designers feared acoustic interactions, attempting to minimize them and their deleterious consequences. In contrast, MPS relies on the interactions to achieve low frequency and broad bandwidth in the system response.

4 What Distinguishes MPS from a Conventional Array

Projectors have been used in conventional arrays for decades with typical separations between projectors a good portion of a wavelength, with $\lambda/2$ being a typical value. In contrast, the projectors in MPS typically have milli-λ spacings. In the MPS patent application [3], two criteria are listed that must be satisfied before an array can be considered a MPS.

1. The separation between projectors must be less than or equal to the characteristic size of the projector, and in preferred embodiments must be less than one-half the characteristic size. “Separation” is defined as the distance between the center of a projector and the center of its nearest neighbour. The “characteristic size” of an axially symmetric bender or sphere would be the diameter. In other words, characteristic size is a dimension that somehow represents the size of the projector.
2. The projector must be small compared to the wavelength of the acoustic wave at the resonance frequency of the system. At a minimum the characteristic size of a projector must be less than $\lambda/8$.

MPS is extraordinarily simple to reconfigure, even in the field. As an example, 12 different configurations of the potted-bender MPS were calibrated at the Acoustic Barge facility operated by Defence Research and Development Canada Atlantic (DRDCA) in Halifax harbour in a single morning. This has favourable ramifications for in-the-field refit and overhaul for MPS, something unheard of for conventional projectors like free flooding rings. Degradation over time is also graceful because benders will drop out one at a time. In fact, it has been found that a closely spaced MPS still operates at its low resonance frequency when several benders are not driven because they still resonate with the stack. Figure 2 shows examples of two configurations of an 8-element version of this MPS.



a) 25mm Spacing.

b) 50mm Spacing.

Figure 2 Configurable Spacing for the Potted Bender MPS.

Because the number of elements, their spacing (either uniform or non-uniform), and drive level can all be easily adjusted without redesign or additional fabrication, the acoustical performance can be readily tailored. Increasing the number of benders reduces the minimum operating depth limited by cavitation because the peak maximum local pressure goes down with *N* (the number of benders) for a given output level. Bender spacing can simultaneously be adjusted to move the resonance frequency by several octaves, with a practical lower limit near 400Hz for closely spaced 100mm diameter benders, and an upper limit near 2kHz. The bandwidth can be broadened considerably by increasing the number of benders or the spacing, and this coincides with an increase in efficiency. Increasing *N* or the spacing maximizes the peak acoustic output. While increasing the spacing to maintain the resonance frequency of the stack, doubling *N* increases the peak level by 1.8dB and the bandwidth by 80%. This is different from a conventional array with $\lambda/2$ spacing where doubling *N* adds 6dB to the output level, because MPS is a *compact* source.

5 Modeling MPS

As mentioned above, the finite element code MAVART played a key role in the invention of the MPS. MAVART is a family of linear, frequency domain finite element codes developed for DRDC Atlantic by industry, during the years 1975-2005. See [4] for a recent review. MAVART comes in several versions: axisymmetric, 2D and full 3D geometry, and also a version for 2D and 3D magnetics. It is a "conventional" FE code in the sense that it uses industry standard finite elements, but it was built from the ground up for solving coupled physics problems, in particular the wave equation in complex media, with anisotropic materials and Rayleigh damping. It has many features tuned to the requirements of transducer design, including the ability to calculate transmitting voltage response, admittance, directivity, efficiency and hydrophone sensitivity. MAVART is a finite element "engine" only, it does not build models, nor display results. A Mathematica™ package [5], called ModelMaker was developed at DRDC to provide these essential functions. ModelMaker is essentially a scripting language for creating parametric finite element models, and displaying results. Parametric models have their dimensions, material properties, boundary conditions, and meshing instructions defined by symbols, which are easily changed to redefine the model. This software environment was built to facilitate design optimization, and permitted evaluation of many variants of the MPS at low cost. All the analyses presented in this report were computed using the axisymmetric version of MAVART (Version 14).

The bender and collinear MPS designs are convenient to model in this environment because they are axisymmetric *and* symmetric about the plane cutting the system in half longitudinally, so only a quarter of the model is assembled and processed. Manufacturer's data sheets were used for the piezoelectric material constants (stiffness matrix, electroelastic matrix, and dielectric permittivity matrix). Handbook values for the density, Young's modulus and Poisson ratio of aluminum alloy were used, and typical published values for water were employed. Figure 3 depicts a typical mesh for an eight-bender MPS. Note that only the near field fluid is modeled, with interface elements to an infinite fluid surrounding the spherical space.

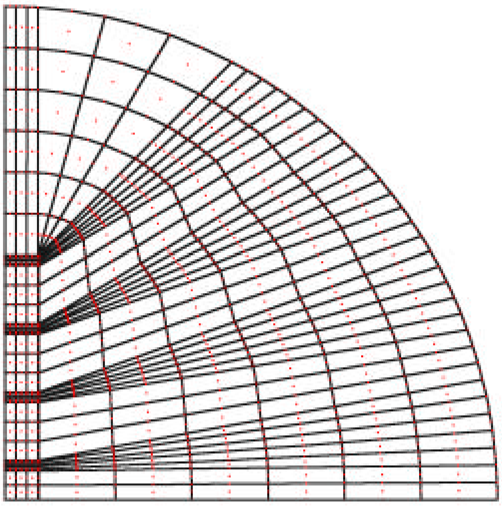
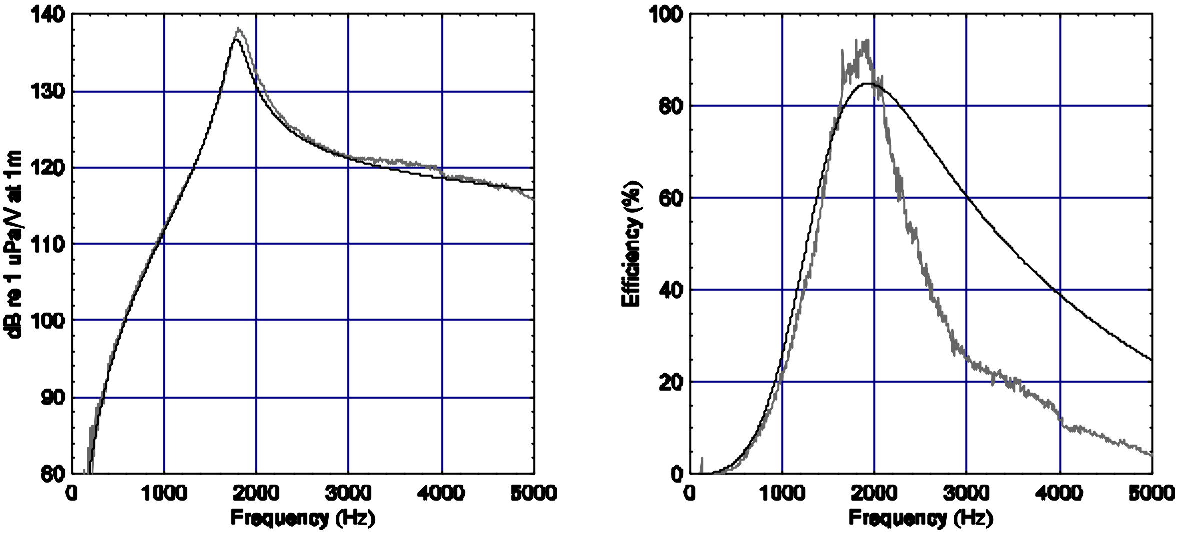


Figure 3 MAVART Finite Element Mesh for a MPS.

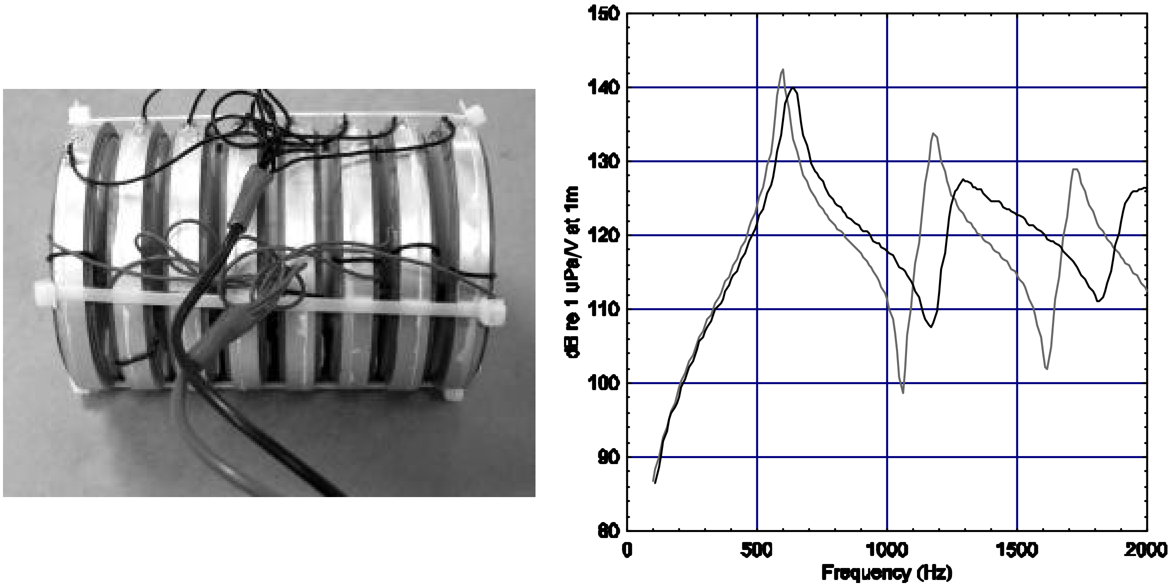
6 Modeled Versus Measured Results: A Single Bender

To begin with, the results of a single bender are reviewed. Note the close correspondence in Figure 4a between the modeled trace (smooth) and the measured trace (slightly noisy) TVRs. The bandwidth of interest for this and other comparisons in this paper is restricted to the lower frequency band where the benders and MPS operate omni-directionally. Note that our efficiency estimates (Figure 4b) are not reliable above resonance because we have simplified the contributions to material damping in our models. In this modeling work, and most projector and hydrophone modeling in MAVART in the past, the potting in which these transducers are typically encased is ignored. The assumption has been that the potting compound is soft compared to the ceramic, structural elements, or the fluid, so is essentially acoustically transparent. The results reaffirm that ignoring the potting is a valid assumption for this case.



a) TVR. b) Efficiency.

Figure 4 Single Bender: Modeled Versus Measured.

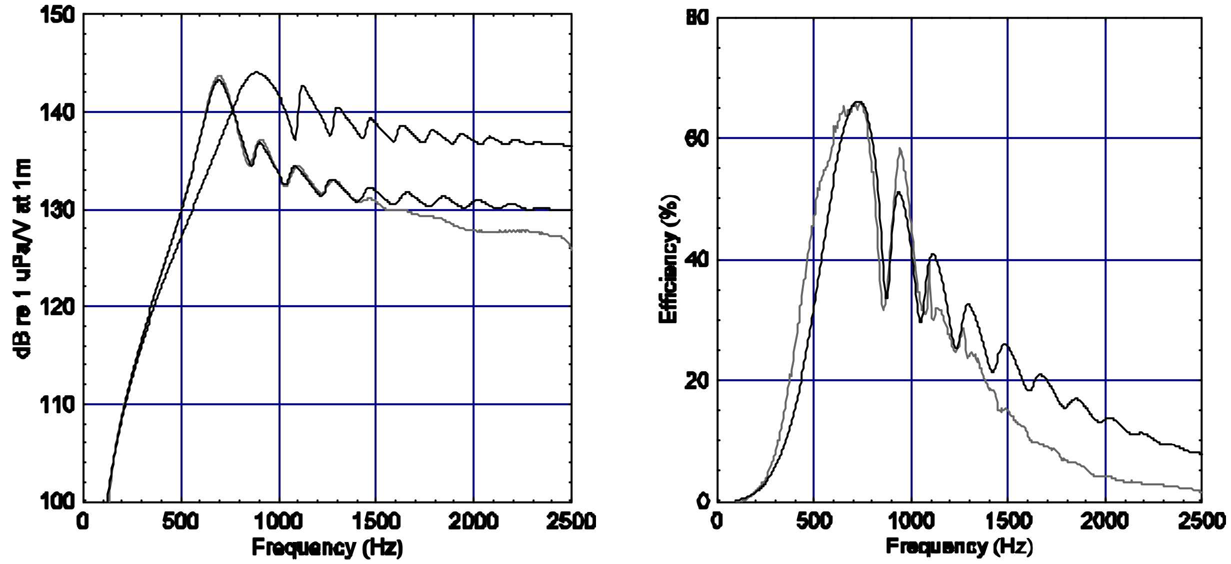


a) MPS Prototype. b) MPS TVR: Modeled vs. Measured.

Figure 5 Closely Spaced MPS: 8 Benders, 16mm Centre Spacing.

7 Modeled Versus Measured Results: MPS

Two different MPS types were calibrated. First, very closely spaced benders were assembled into MPS units that were filled with a non-conductive fill fluid and placed inside a boot because the benders were not potted (see Figure 5a above, boot not shown). These eight 100mm diameter benders were spaced only 1mm apart (equivalent to 16mm centre-to-centre). In the TVR for this test and model comparison (Figure 5b), the fundamental frequency seen in the model is slightly lower than was seen in the measured results. Future work includes modeling the boot and the fill fluid separate from the surrounding water to obtain better agreement. There was no model tweaking to artificially match the results. The dips in the response above the fundamental mode are a result of different benders in the stack operating in and out of phase, while at the fundamental resonance they all operate in phase. The dips in the TVR also coincide with a dip in efficiency.



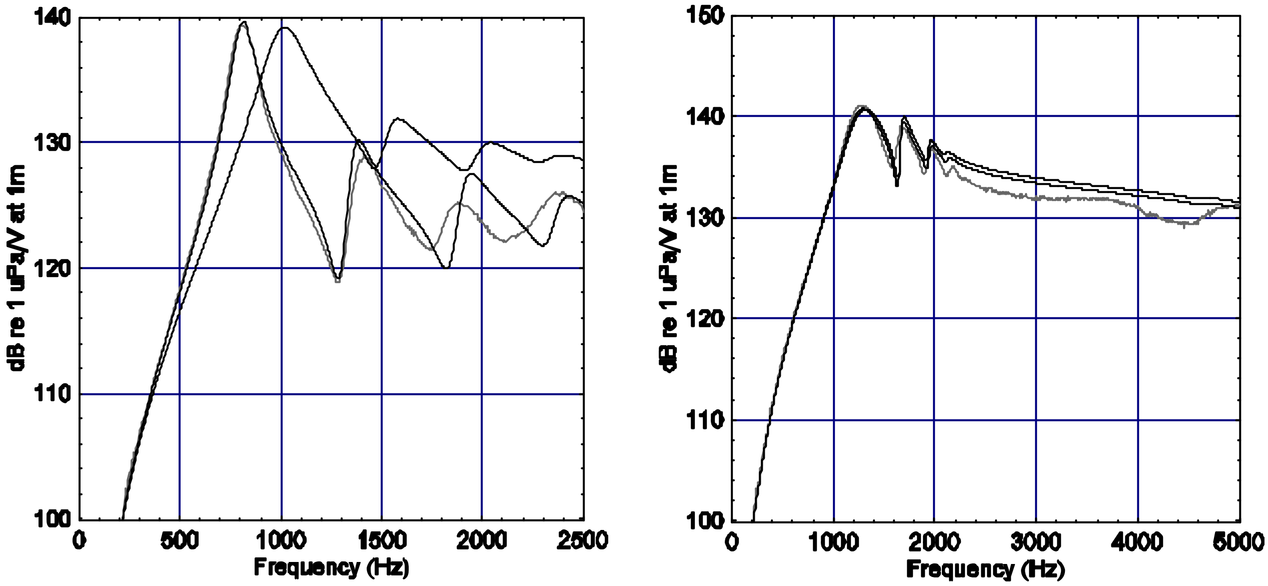
a) TVR.

b) Efficiency.

Figure 6 Potted Bender MPS: 24 Elements, 25mm Centre Spacing.

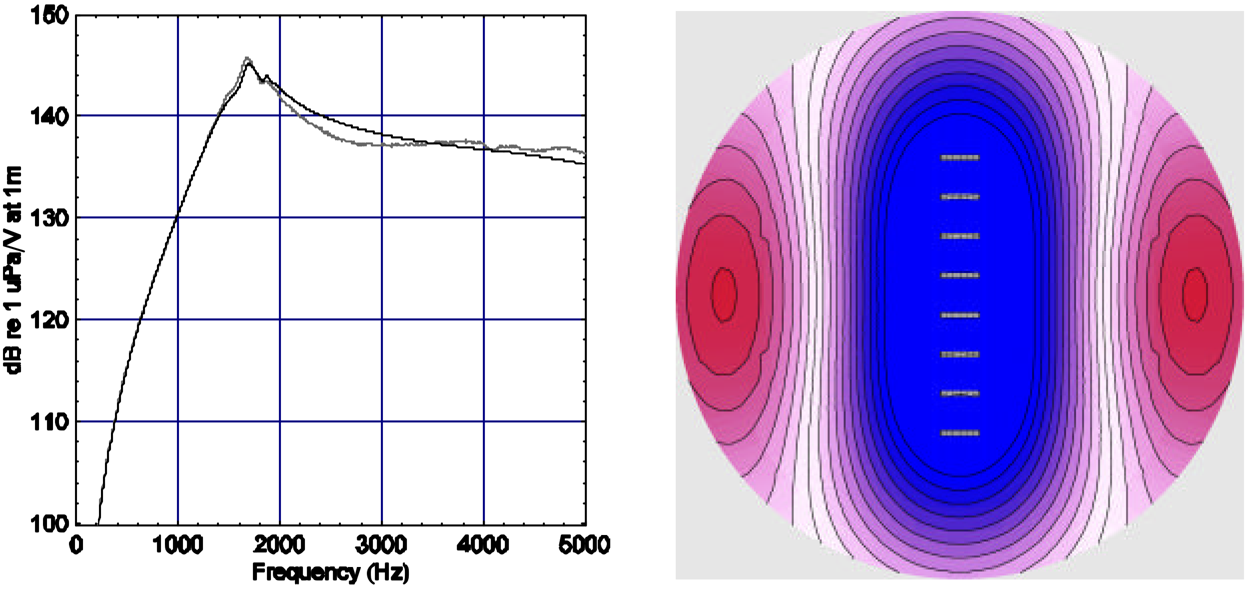
Meanwhile, for the potted-bender MPS that is open to water, a different effect emerges. Figure 6 shows the results of a 24-bender MPS, with uniform centre-to-centre spacing of 25mm. The figure shows modeled and measured (slight noisy trace) curves that correspond very closely up to about 1500Hz, and an additional modeled curve that is high in frequency and output level across the band. The poorly matched model curve has the same centre-to-centre spacing as the actual hardware but no potting, a modeling assumption carried through all the cases in this paper. The modeled curve that does match up well has been artificially spaced at 18.7mm giving the same face-to-face spacing between the non-potted modeled benders as exists in the actual potted benders. Obviously, the potting has a marked effect on the MPS when benders are close. While it appears as though it is not necessary to model the potting for the single bender (Figure 4), when benders are closely spaced the potting tends to take up some of the space between elements. This fluid space is where the MPS effect manifests itself, allowing the interactions between elements. The close correlation with the artificially spaced MPS tells us that potted benders behave like non-potted benders spaced more closely together. This holds for below, at, and above resonance until other more complex dynamics within the stack occurs. When the benders begin to operate out of phase in smaller groups, the overall length of the stack has a stronger bearing on the output levels. Looking back at the other modeled curve in Figure 6, we see that assuming no potting and keeping the same spacing effectively creates a MPS with larger spacing, i.e., higher frequency, output level, and bandwidth. The efficiency curve in the right of Figure 6 again shows good correspondence up to and slightly above resonance, where this depicts the artificially adjusted spacing in the model.

It was found, not surprisingly, that as the bender spacing was increased the difference between the adjusted and non-adjusted models decreased. To illustrate this, Figure 7 depicts the 8-element potted bender MPS cases of 25mm (a), 50mm (b) and 100mm (c and d) spacings. In these plots, the slightly noisy trace is the measured. In the 25mm case, the spacing-adjusted model matches the measured data well while the other trace is high in frequency and level, and in the 50mm case both models match reasonably well, with the adjusted model lower in level. There was no discernable difference between the two modeled TVRs in the 100mm spacing case. The fourth plot shows a pressure contour plot for the 100mm MPS operating at its peak level. This plot illustrates how the distribution of source pressure leads to a shallower cavitation depth by eliminating a concentration of pressure.



a) 25mm Centre-to-Centre.

b) 50mm Centre-to-Centre.

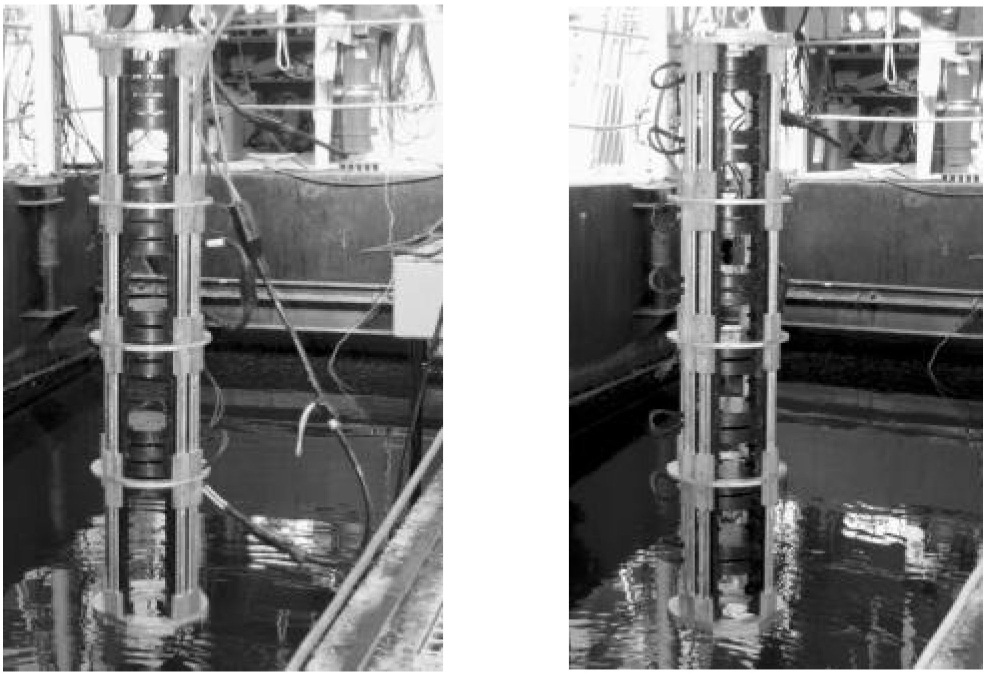


c) 100mm Centre-to-Centre.

d) 100mm Spacing: Contour at Resonance (1575Hz).

Figure 7 Potted Bender MPS: 8 Elements.

The modeling lessons learned here are that the oil and boot should be specifically modeled for the filled (non-potted) MPS to further increase model fidelity, and that the potting around the benders for the other MPS type must be modeled, although very good correspondence is attained near resonance when the model uses artificially adjusted spacing. The good news is that these results build high confidence in the modeling thus far, and clearly point to short-term future work. Even now before this work continues, this modeling can clearly be used for predicting the TVR of new configurations, serving as a design tool before hardware is actually put together and tested.



a) 4 Groups of 4 Benders. b) 8 Groups of 2 Benders.

Figure 8 Photographs of Non-Uniform Spaced MPS Configurations.

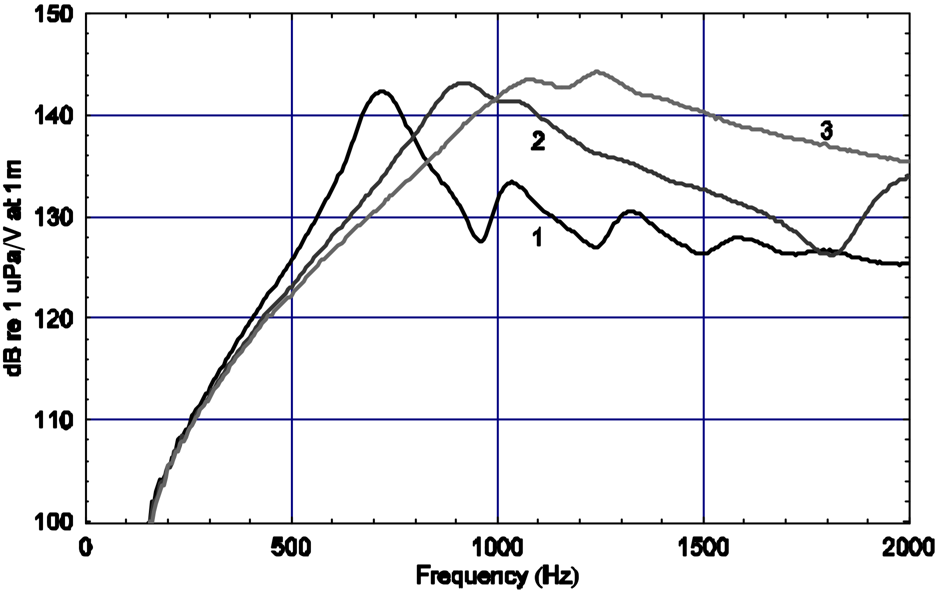


Figure 9 Comparison of MPS 16 TVR, Uniform and Non-Uniform Spacing.

1: 16 benders spaced at 25mm (uniform),
2: 4 groups of 4 benders spaced 25mm within groups, 175mm between groups,
3: 8 groups of 2 benders spaced 25mm within groups, 100mm between groups.

8 Non-Uniform Spacing

So far, uniform spacing of the bender MPS has been investigated. Another option available for this projector is non-uniform spacing. Some different configurations were tested that featured groupings of benders. The photographs in Figure 8 show two such examples, both using 16 benders. The left photograph shows four groups of four benders with elements in a group spaced at 25mm centre-to-centre and groups spaced 175mm. The right photograph shows eight groups of two benders with elements in a group spaced at 25mm and groups spaced 100mm. While this is still considered a single projector, one can appreciate how the distinction between a projector and a conventional array becomes obscured. What sets these MPS examples apart is that the spacing, even between groups, is still small compared to conventional arrays. Figure 9 shows a measured TVR comparison between a 16 bender MPS with elements uniformly spaced at 25mm (trace 1), the MPS configured as in the left photograph (trace 2), and the MPS configured as in right photograph (trace 3). Most notably, the increasing distribution of bender groups tends to expand the bandwidth of the peak response, the same trend seen in uniform spacing when the spacing is increased. However, the advantage of maintaining the close spacing within groups is that the resonance frequency is still relatively low. By comparison, a 16 bender, 50mm uniform spacing has a peak response at 1420Hz and a narrower bandwidth than traces 2 and 3, albeit with a 146dB peak level. These results further demonstrate how easily adaptable MPS is. Although it has not yet been explored, these groups-of-groups MPS configurations show promise of interesting and useful beam patterns at higher frequencies as inter-element resonance response goes through different phases. While this brief look at non-uniform spacing does not exhaust the possibilities, it demonstrates that application-specific designs can be rapidly conceptualized, accurately modeled, prototyped and tested, and delivered.

9 Summary

Previously, the MPS concept was introduced by describing how a stack of simple closely spaced flexural disk projectors is a promising approach for a low cost, light weight, underwater acoustic source easily configurable for a very broad range of acoustical specifications. This paper extends this by comparing modeled with measured results for two different MPS prototypes: a very closely spaced version packed with fill fluid in a boot, and a version that operates in open water made with potted benders. For both cases and for various configurations of the potted case, very close correlation between measured and modeled results is demonstrated. This verifies the modeling approach used, and suggests that the design cycle for a made-to-order MPS with customer-specified performance will be rapid, low risk and low cost. Test results show resonance frequencies as low as 650Hz, and suggest that even lower frequencies can be achieved using a bender small enough to withstand hydrostatic pressure at 300m depth while minimizing cavitation depth. With the inherent simplicity in the design, even the early MPS prototypes show amazing robustness and reliability, not to mention they are reconfigurable and repairable in the field.

Modeling the effects of the boot, the fill fluid and the potting on the benders is currently progressing. The MAVART codes do not presently have any provision for considering viscous damping in thin fluid layers, such as may be encountered in MPS configurations with very reduced spacing. Future work on MAVART may include such damping. The use of fully 3D configurations of the MPS can be modelled using the MAVART3D code, and as requirements for building 3D MPS systems arise, we intend to build a parametric 3D version of our MPS models. This will require substantial computer resources, but MAVART lends itself to a simple form of parallelization, where a number of processors are used with each one assigned to compute the system response over a given frequency band. The MAVART modeling and processing shows as much promise in modularity and adaptability as the MPS hardware itself, making it the ideal design and analysis tool.

10 Acknowledgements

The authors wish to thank Lou Boulanger of CFMETR for the loan of the potted-bender MPS hardware as a test specimen for this paper.

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