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Breathing-Mode DSP^2 High Frequency MMPP

Richard Fleming

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2007-313

November 2008

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Principal Author

Original signed by Richard Fleming

Richard Fleming

Approved by

Original signed by David Hazen

David Hazen

Head/Technology Demonstration Section

Approved for release by

Original signed by Ron Kuwahara for

Calvin Hyatt

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Abstract

The high frequency multi-mode pipe projector (HF MMPP) transducer has been employed in many applications since its inception. With its wide bandwidth, one of its uses has been as an acoustic source for underwater communications. The digital spread-spectrum with digital signal processing (DSP^2) project identified the need for a more efficient underwater communications acoustic projector in the 35 kHz to 60 kHz band. Two versions of a new breathing-mode DSP^2 HF MMPP were developed using finite element design techniques and initial testing has demonstrated design objective conformance.

Résumé

Le transducteur du projecteur à tube multimodes haute fréquence (MMPP HF) a servi à de nombreuses applications depuis sa conception. Grâce à sa grande largeur de bande, il a servi de source acoustique de communications sous-marines. Le projet d'étalement numérique du spectre avec traitement numérique des signaux (DSP^2) a fait ressortir le besoin d'un projecteur acoustique de communications sous-marines plus efficient dans la bande de 35 kHz à 60 kHz. Deux versions d'un nouveau MMPP HF DSP^2 en mode hermétique ont été mises au point à l'aide de techniques de conception par éléments finis, et l'essai initial en a démontré la conformité à l'objectif de conception.

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Executive summary

Breathing-Mode DSP^2 High Frequency MMPP:

Fleming, R.; DRDC Atlantic TM 2007-313; Defence R&D Canada – Atlantic; November 2008.

Introduction or background: The digital spread spectrum with digital signal processing (DSP^2) project identified a requirement for a version of the high frequency multimode pipe projector (HF MMPP) that was highly electro-acoustically efficient from 30-55 kHz. It was hypothesized that by preferentially operating the HF MMPP in the modes that contribute most significantly to acoustic output in this band, a more efficient design would result. Finite element modelling has shown that output over this band is dominated by waveguide and drive motor radial modes. A design study followed that centered on changing the drive motor from a longitudinally-poled d_{33} style drive motor to a radially-poled d_{31} motor in order to investigate tailoring the HF MMPP to operate most efficiently in the 30-55 kHz band.

Results: Using tandem stock lead-zirconate-titanate-5 (PZT-5) radially-poled cylinders and optimized waveguide dimensions, the new breathing-mode DSP^2 HF MMPP was designed, constructed and tested. This new projector was built in two versions. One version, with a single active cylinder, met the DSP^2 project's design performance requirements with greater than 140 dB re 1μPa/V @ 1m from 30 kHz to 55 kHz from its broadside aspect with a power factor of greater than 0.9. The other unit, with both cylinders active, has shown broadside transmitting voltage response of greater than 146 dB re 1μPa/V @ 1m over the same band. In both units, the endfire acoustic radiation is of approximately 3 dB greater than the broadside which is a significant improvement over the 30X35 HF MMPP.

Significance: This new version of the HF MMPP is a significant improvement over the previous version in this application and will enable low-power and efficient underwater communications over nearly an octave of bandwidth. This design will provide the DSP^2 project a marked increase in operational effectiveness both through lower-power operation and greater data transmission rate.

Future plans: Follow-on work to characterize the beampattern of these devices as a function of frequency is planned. As well, maximum depth of operation and maximum drive voltage limits will be explored.

Sommaire

Breathing-Mode DSP^2 High Frequency MMPP:

Fleming, R.; DRDC Atlantic TM 2007-313; R & D pour la défense Canada – Atlantique; Novembre 2008.

Introduction: Le projet d'étalement numérique du spectre avec traitement numérique des signaux (DSP^2) a fait ressortir le besoin d'une version du projecteur à tube multimodes haute fréquence (MMPP HF) hautement efficient sur le plan électro-acoustique dans la bande 30-55 kHz. On a émis l'hypothèse qu'avec un fonctionnement préféré du MMPP HF dans les modes qui apportent la contribution la plus importante à la sortie acoustique dans cette bande, il en découlerait une conception plus efficiente. La modélisation par éléments finis a fait ressortir le fait que la sortie dans cette bande est dominée par les modes radiaux de moteur d'entraînement et de guide d'ondes. A suivi une étude de conception portant essentiellement sur le remplacement du moteur d'entraînement de style d_{33} à pôle longitudinal par un moteur d_{31} à pôle radial pour l'étude de la possibilité d'adapter le MMPP HF à un fonctionnement plus efficient dans la bande 30-55 kHz.

Résultats: On a conçu le nouveau MMPP HF DSP^2 en mode hermétique à l'aide d'un guide d'ondes à dimensions optimisées et de cylindres à pôle radial en titano-zirconate de plomb 5 (PTZ 5) en tandem, puis on l'a construit et mis à l'essai. Ce nouveau projecteur a été fabriqué en deux versions. Une version, dont un seul cylindre était actif, a satisfait aux exigences de performance de conception du projet DSP^2 à plus de 140 dB, rapportée à 1 µPa/V à 1 m dans la bande de 30 kHz à 55 kHz dans son aspect transversal avec un facteur de puissance supérieur à 0,9. L'autre unité, dont les deux cylindres étaient actifs, a donné une réponse en tension d'émission transversale supérieure à 146 dB, rapportée à 1 µPa/V à 1 m dans la même bande. Dans les deux cas, le rayonnement acoustique longitudinal est supérieur d'environ 3 dB au rayonnement transversal, ce qui représente une amélioration significative par rapport au MMPP HF 30X35.

Portée : La nouvelle version du MMPP HF représente une amélioration significative par rapport à la version antérieure dans cette application et permettra des communications sous-marines efficientes et à faible puissance dans près d'une octave de largeur de bande. Cette conception donne au projet DSP^2 une hausse marquée de l'efficacité opérationnelle par un fonctionnement à une puissance moindre et un débit supérieur de transmission de données.

Recherches futures : Des travaux de suivi sont prévus en vue de la définition des caractéristiques du diagramme de formation des faisceaux de ces dispositifs en fonction de la fréquence. En outre, on étudiera les limites maximales de la profondeur de fonctionnement et de la tension d'entraînement.

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1 Introduction

There existed in the Digital Spread Spectrum with Digital Signal Processing (DSP^2) project a requirement for a high frequency sonar projector that was small and capable of very efficient output from 30 kHz to 55 kHz. The existing 30X35 high frequency multi-mode pipe projector (HF MMPP) (see Figure 1 left) [1, 2] was considered but it lacked sufficient electro-acoustic efficiency and acoustic output over the entire band of interest (see Figure 2 and 3) for the project's power constraint. The design goal for the new DSP^2 transducer included a broadside transmitting voltage response of greater than 140 dB re 1μPa/V @ 1m from 30 kHz to 55 kHz and a power factor (cosine of the phase angle between the voltage and current) of greater than 0.8. In addition, since the endfire output of the 30X35 HF MMPP can be significantly higher than its broadside response (see Figure 4), it was thought that with a reduction in endfire output as compared to broadside output, this new design had the potential for reduced multipath distortion.

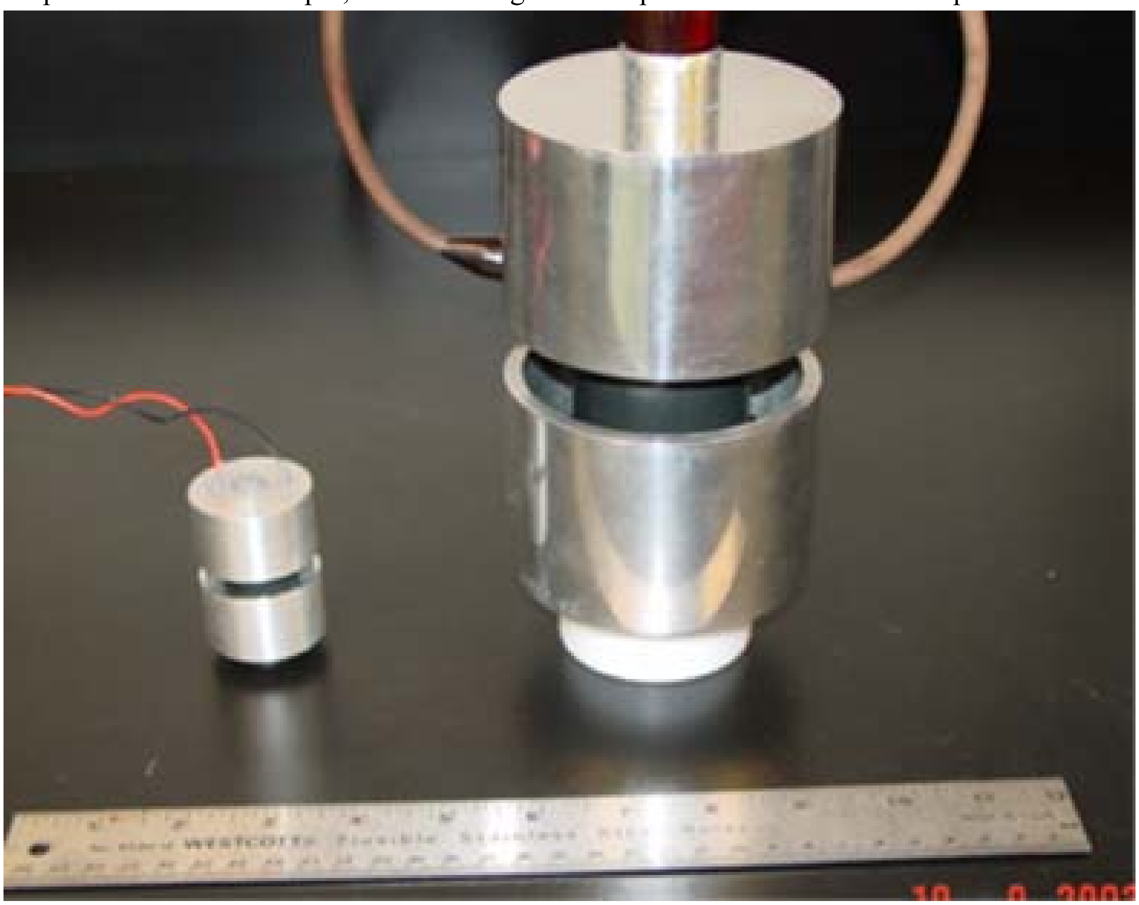

Figure 1 L-R assembled 30X35 HF MMPP and medium frequency MMPP.

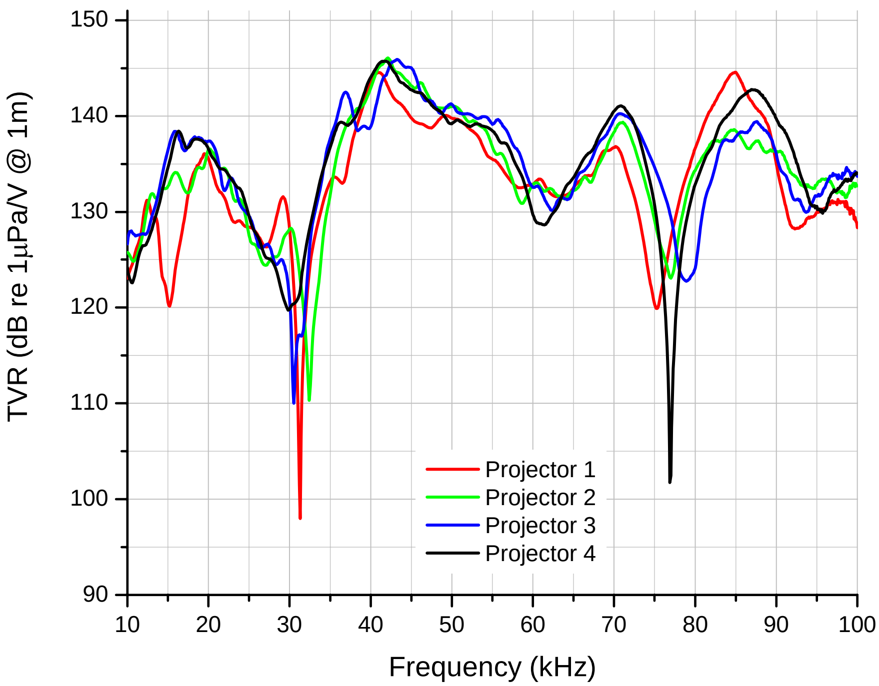

Figure 2 30X35 HF MMPP broadside TVR's.

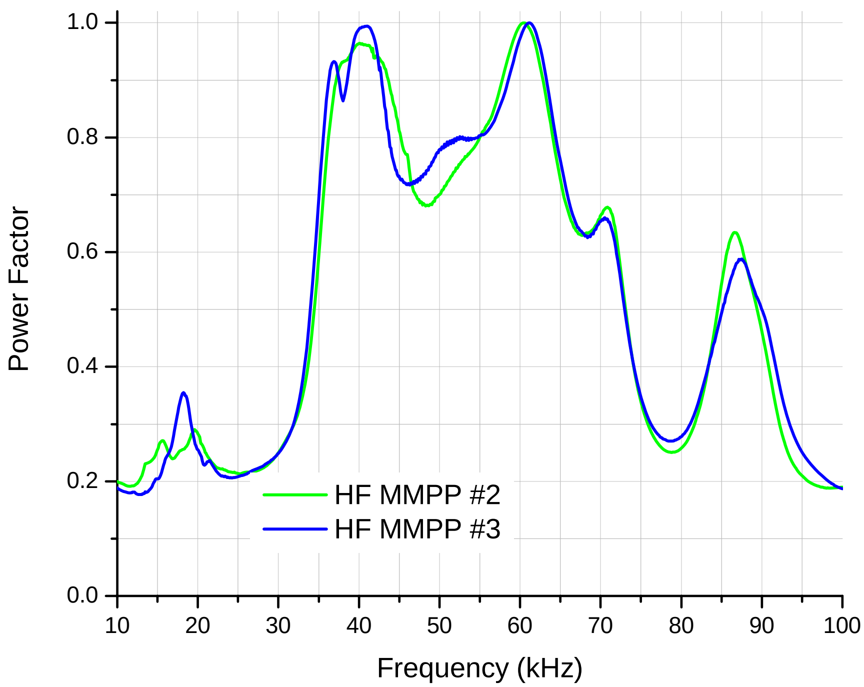

Figure 3 30X35 HF MMPP power factor with paralleled 1.64 mH tuning inductor.

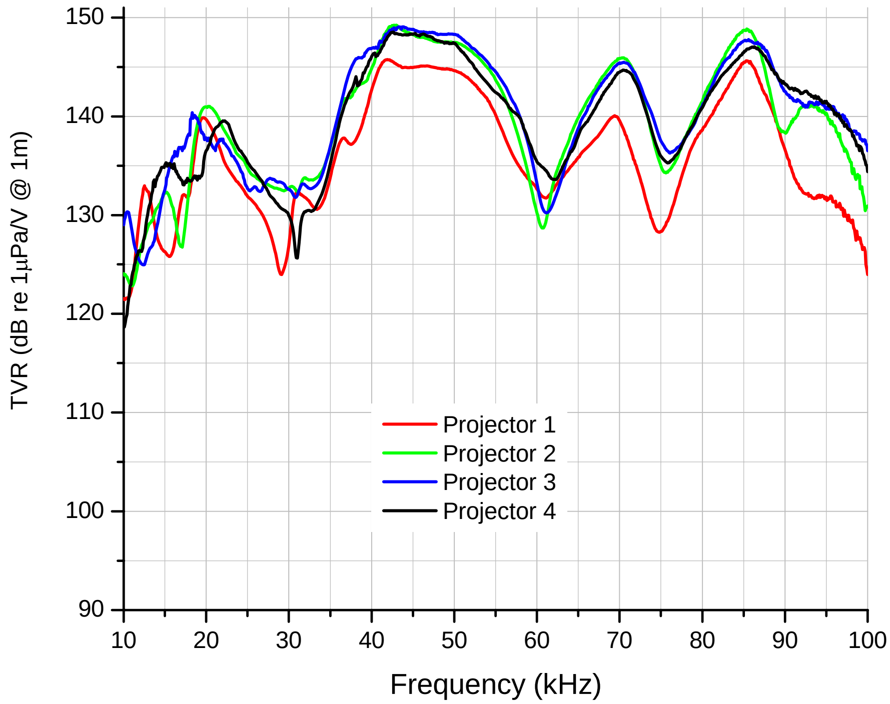

Figure 4 30X35 HF MMPP endfire TVR's.

2 DSP^2 transducer design

Using the 30X35 HF MMPP as a starting point for the DSP^2 transducer design seemed reasonable given its respectable performance in the 30-55 kHz band. Unfortunately this HF MMPP's power factor drops as low as 0.25 over this band (see Figure 3) and it exhibits a problematic notch in broadside transmitting voltage response at about 32 kHz (see Figure 2). It also exhibits excessive endfire radiation which can only be ameliorated with air-filled endfire attenuators [3].

Since it is the stack and waveguide wall breathing modes which contribute the bulk of the acoustic output above 20 kHz in the HF MMPP, it was thought that by enhancing this effect, greater efficiency and output could be realized for the DSP^2 application. In addition, the lower frequency modes of the 30X35 HF MMPP, which are predominately generated by longitudinal motions of the piezoceramic drive motor, were below the band of interest in this design and therefore superfluous. It was hypothesized that by driving the drive motor purely in the radial direction, more efficient transduction would occur over the 30-55 kHz band.

To test this hypothesis, a finite element model using DRDC-Atlantic's Model to Analyze the Vibration and Acoustic Radiation of Transducers (MAVART) code was generated (see Figure 5) that employed a breathing-mode drive motor with dimensions equivalent to those of DRDC Atlantic stock lead zirconate titanate -5 (PZT-5) items. PZT-5 is a soft piezoelectric ceramic typically used in low power hydrophone designs because of its high sensitivity, and was thought to be appropriate for this high sensitivity - low power design. The material used in the model for the waveguide is 6061T6 aluminum. The waveguide wall and endcap thicknesses were optimized for maximum output across the band from 30 kHz to 55 kHz. After dimension optimization, the finite element analysis showed that with this radially-poled piezoceramic drive motor arrangement, significant broadside acoustic output could be generated in the band of interest (see Figure 6). The endfire components of the acoustic radiation are on the order of or lower than the broadside response leading to the possibility of reduced multipath effects as compared to the similarly-size longitudinally driven 30X35 HF MMPP.

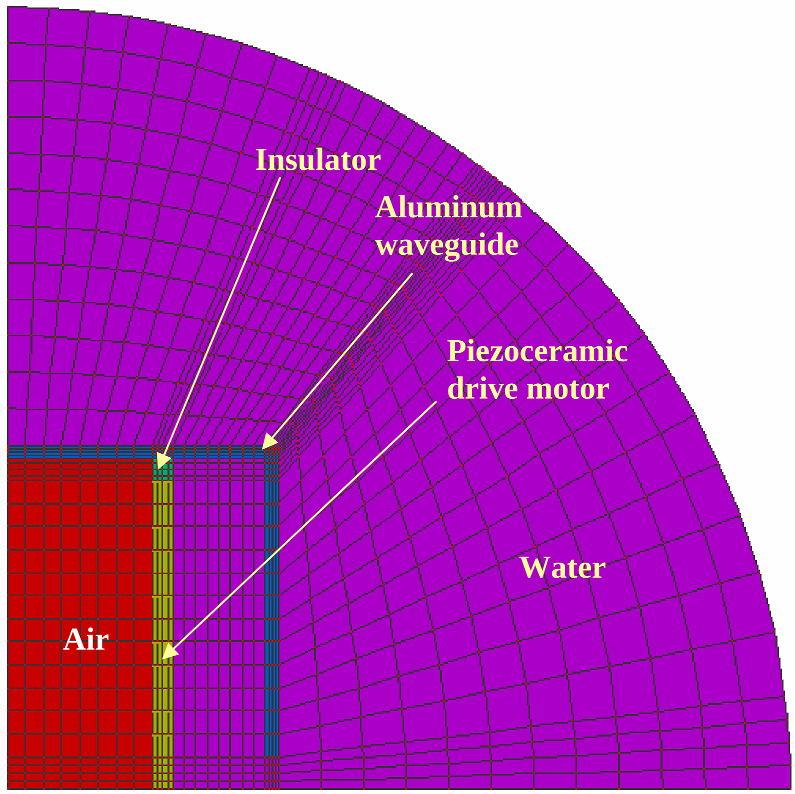

Figure 5 First quadrant axi-symmetric finite element model geometry of the DSP^2 HF MMPP.

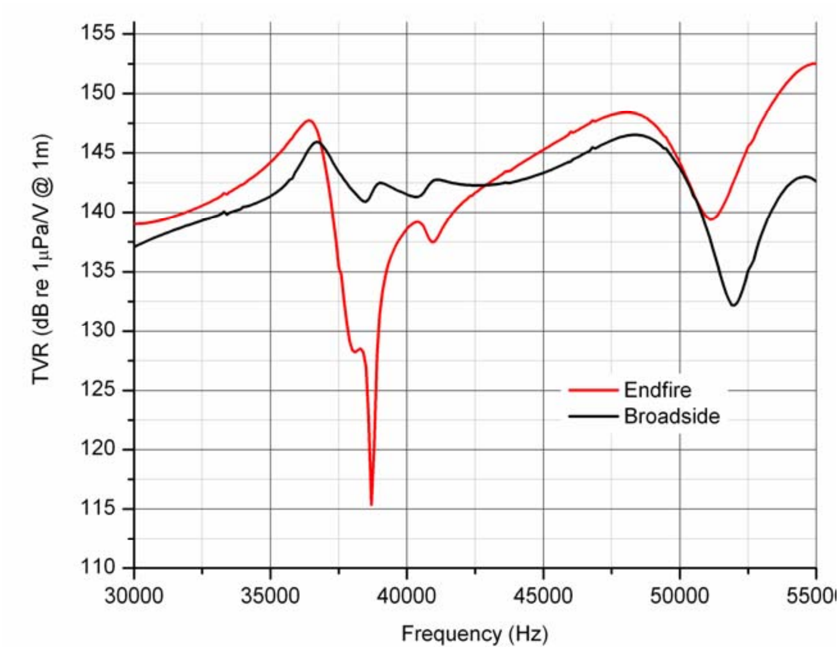

Figure 6 Mavart finite element predictions of broadside and endfire TVR's for the DSP^2 HF MMPP.

3 Construction and testing of DSP^2 MMPP prototypes

DRDC Atlantic's prototype development section generated drawings for subsequent manufacture of the DSP^2 MMPP endcaps and prestess rods from the finite element design optimization (see Figure 7).

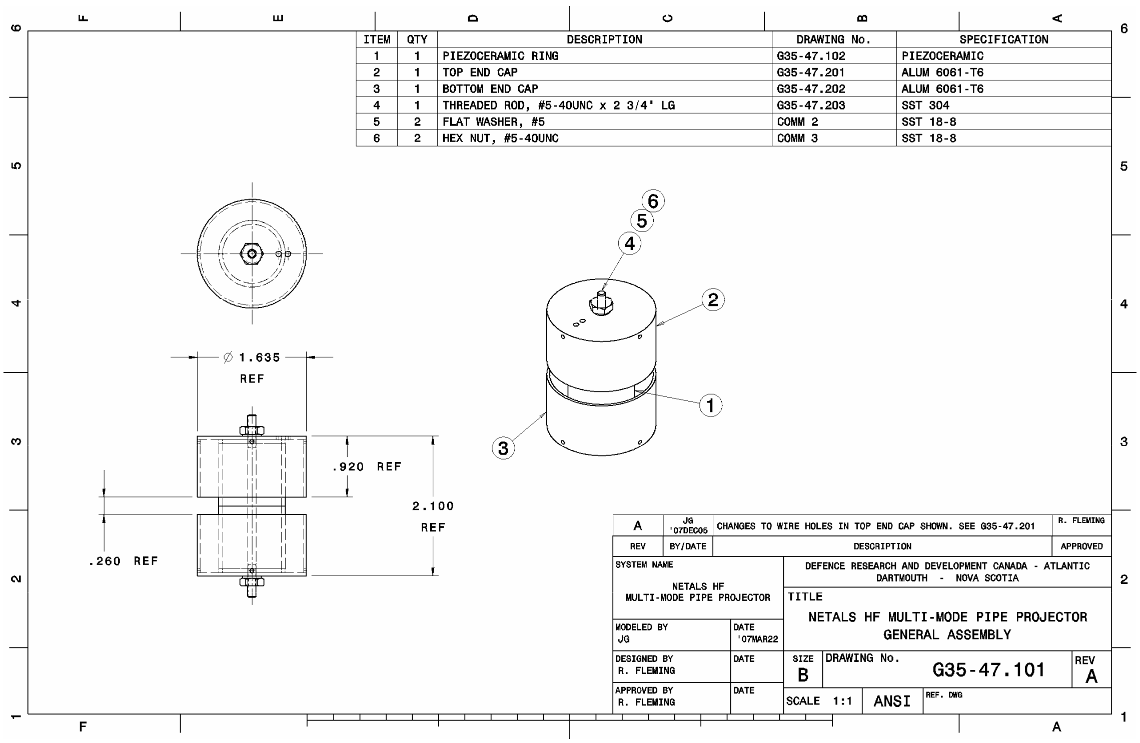

Figure 7 DSP^2 HF MMPP general assembly drawing G35-47.101.

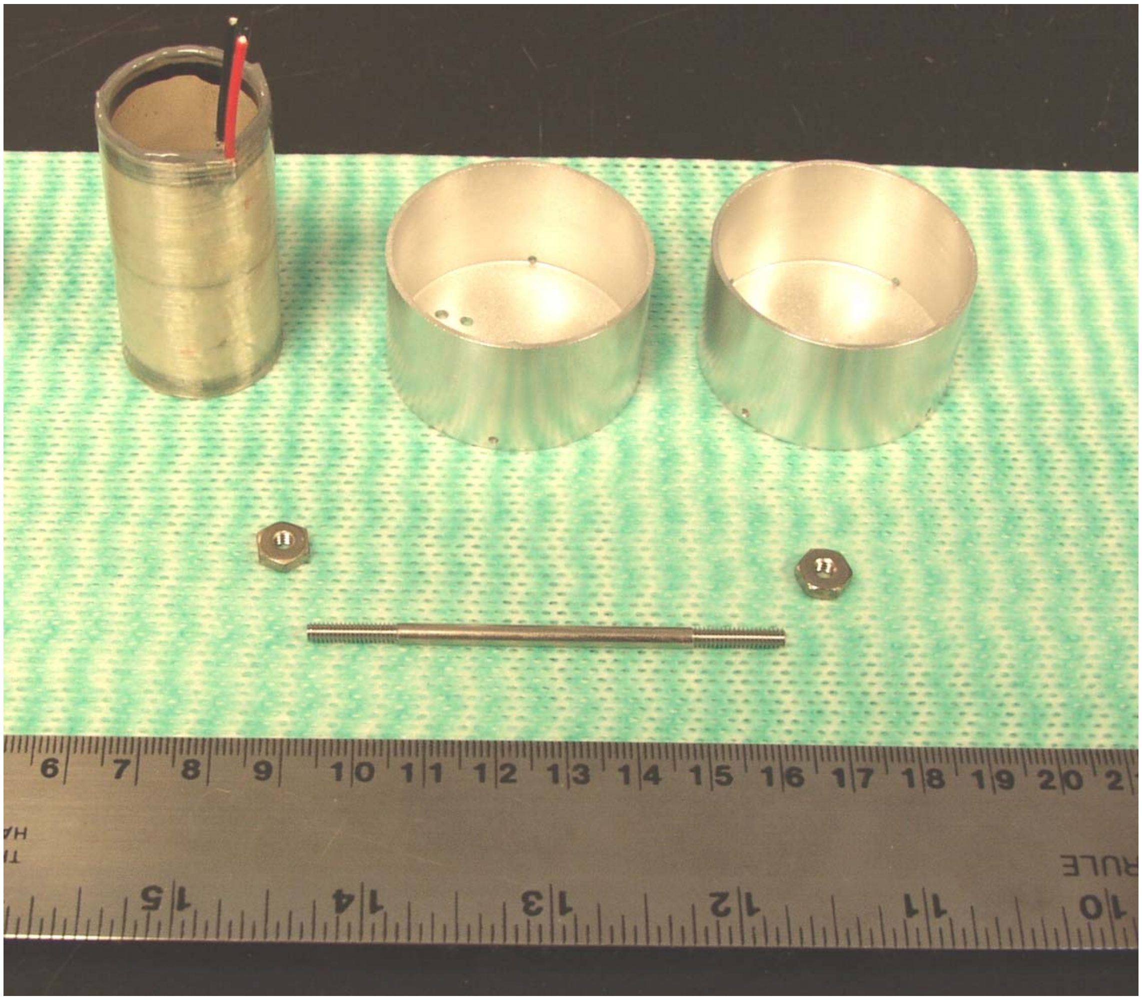

Figure 8 DSP^2 parts including PZT drive stack, stainless steel prestress rod and nuts and aluminum endcaps.

Four prototypes were originally constructed and tested. Two PZT-5 radially-poled cylinders were selected for the basis of the drive motor (see Figure 8). These cylinders were cemented together using Hysol 9460 epoxy, and 1.5mm of the electrode material was etched from the ends of the built-up stack with nitric acid in order to provide electrical insulation. The drive motor was wired with both positive and negative high voltage leads and subsequently wrapped with polyurethane-impregnated fibreglass in order to provide both electrical insulation and circumferential prestressing (to prevent tensile failure of the drive motor). A central prestress rod was installed in order to provide axial prestress and to keep the waveguide well proximated to the ends of the drive motor assembly. The total mass of the DSP^2 HF MMPP is 78 grams where the 30X35 HF MMPP is 156 grams. This reduction in mass comes about from a substantial decrease in radial thickness of the drive motor and reduced wall and end thickness of the waveguide. The outside diameter of the DSP^2 is 2.85 mm greater than the 30X35 and the overall length is similar (see Figure 9).

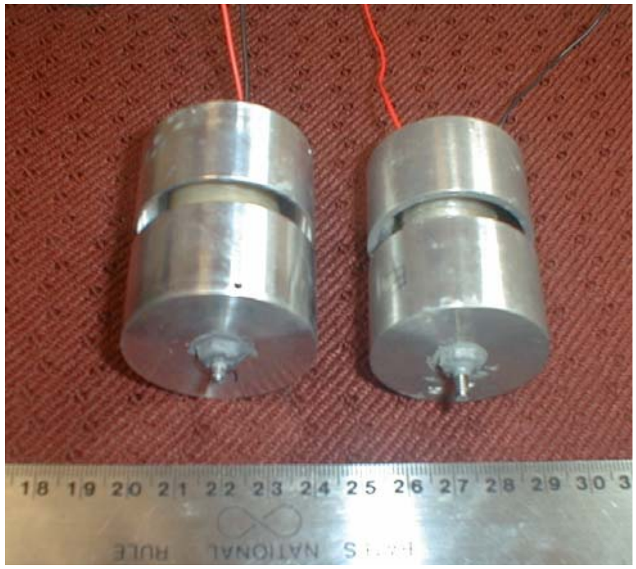

Figure 9 L-R DSP^2 HF MMPP and 30X35 HF MMPP.

These first four DSP^2 HF MMPP's were wired such that only one of the two PZT-5 elements was active. This was inline with the MAVART modelling. Since the impedance magnitude was higher than a fully-wired version, current draw could be kept low for the power supply envisioned. After construction, these four projectors were calibrated in DRDC Atlantic's acoustic calibration tank (ACT) using its proprietary transducer calibration (TRANSCAL) measurement suite. Transmitting voltage responses and impedance measurements (with and without tuning inductors) were carried out (see Figures 10 and 11). Measurements were made with drive voltage set at 100 Vrms which is a conservative safe limit for these thin-walled PZT-5 elements. Repeated measurements at this voltage showed no measurable change in performance.

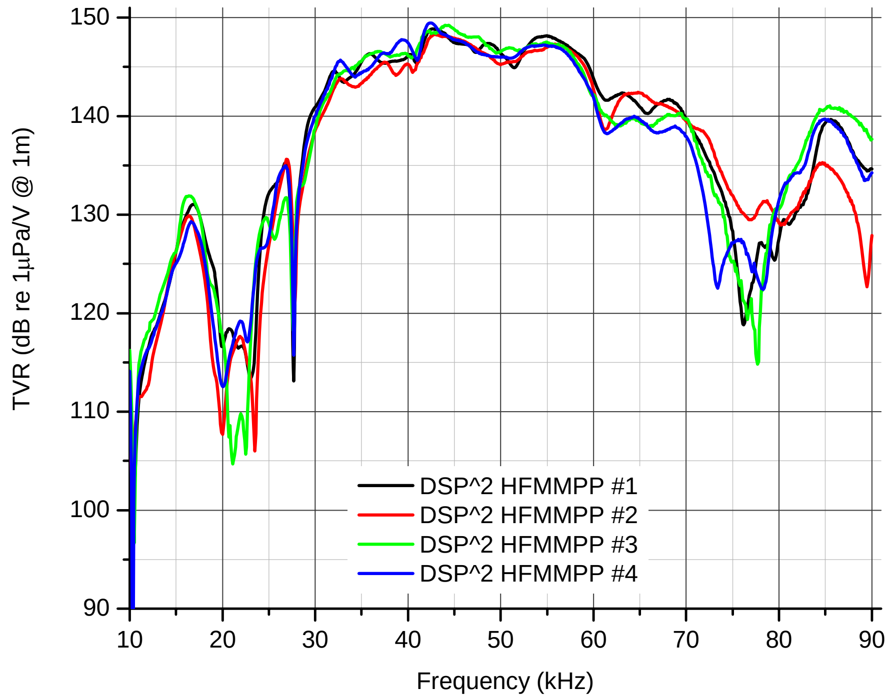

Figure 10 DSP² HF MMPP broadside transmitting voltage responses.

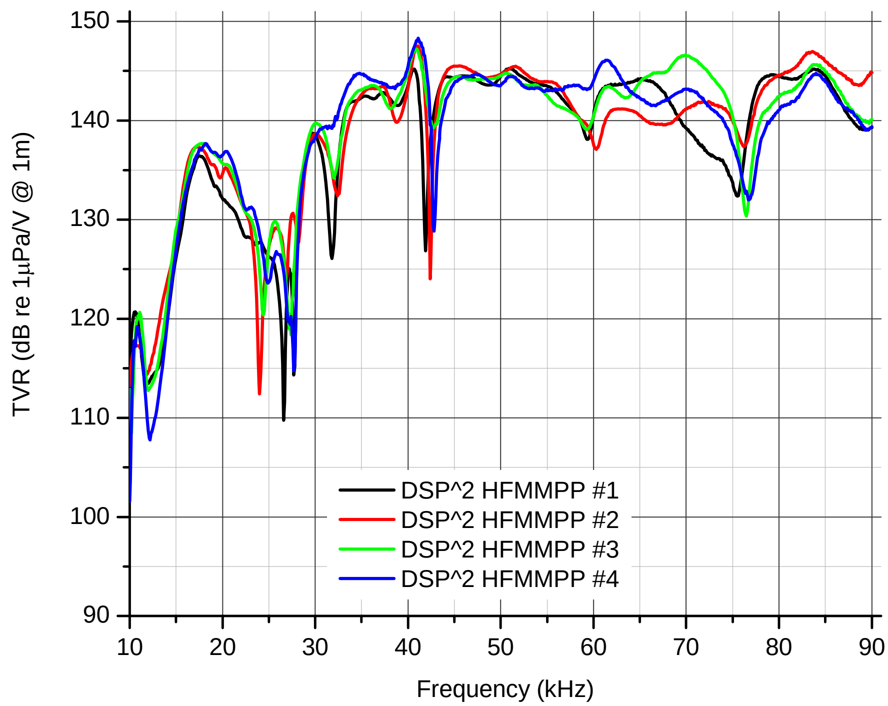

Figure 11 DSP² HF MMPP endfire transmitting voltage responses.

A single DSP^2 HF MMPP (#3) was used to test the effect of tuning both on transmitting voltage response and electrical load behaviour. Various tuning inductor values were used and an optimal value of 1.192 mH was selected based on the highest average power factor over the 30 to 55 kHz band (see Figure 12). This high power factor indicates that these units will provide a very efficient electrical load to a power supply and reduce the reflected power. Figure 13 shows the effect of tuning inductor value on impedance magnitude. Figure 14 demonstrates that the tuning inductor value does not significantly affect the transmitting voltage response.

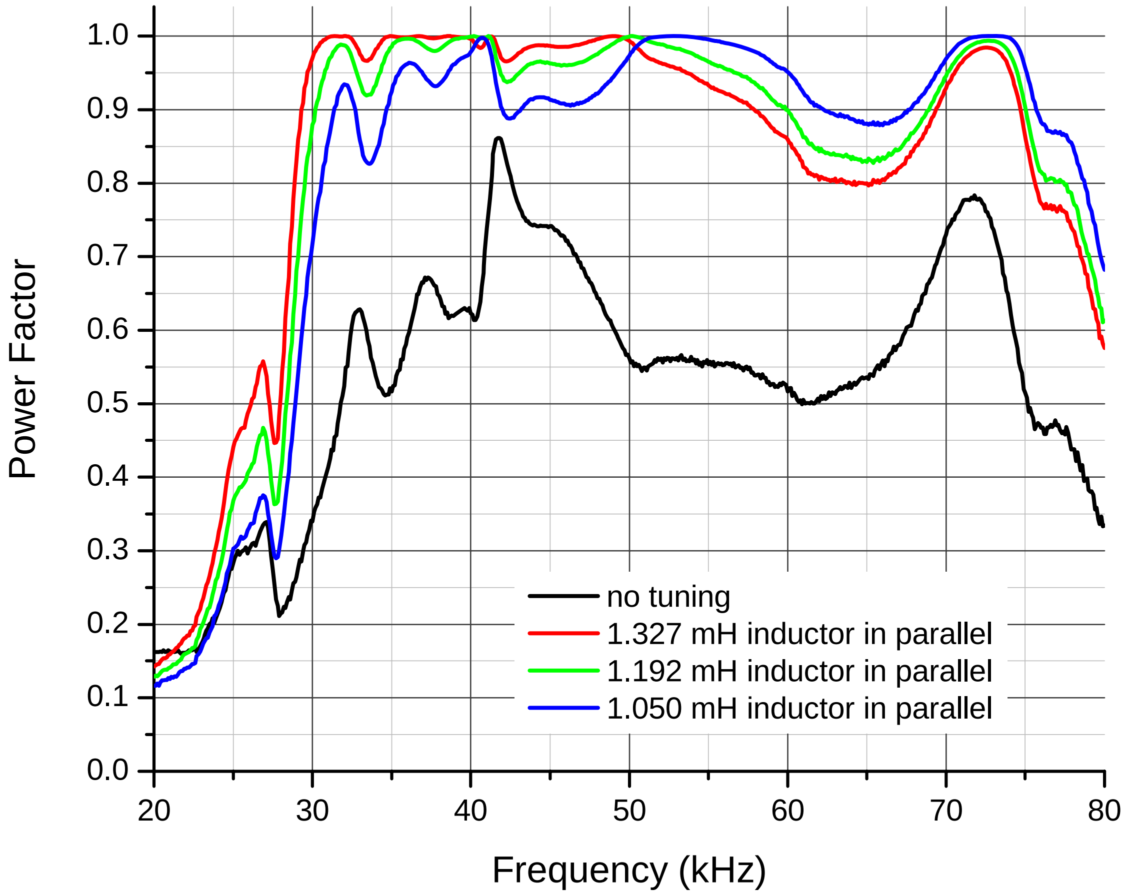

Figure 12 Power factor of DSP^2 HF MMPP#3 with various parallel inductor values.

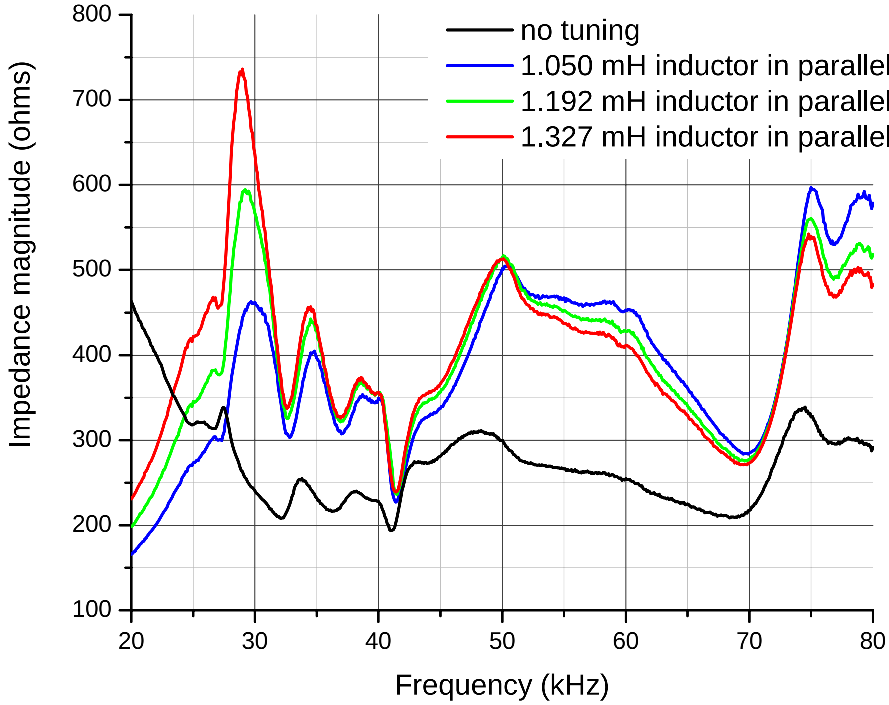

Figure 13 DSP[2] HF MMPP#3 impedance magnitude with various parallel tuning inductors.

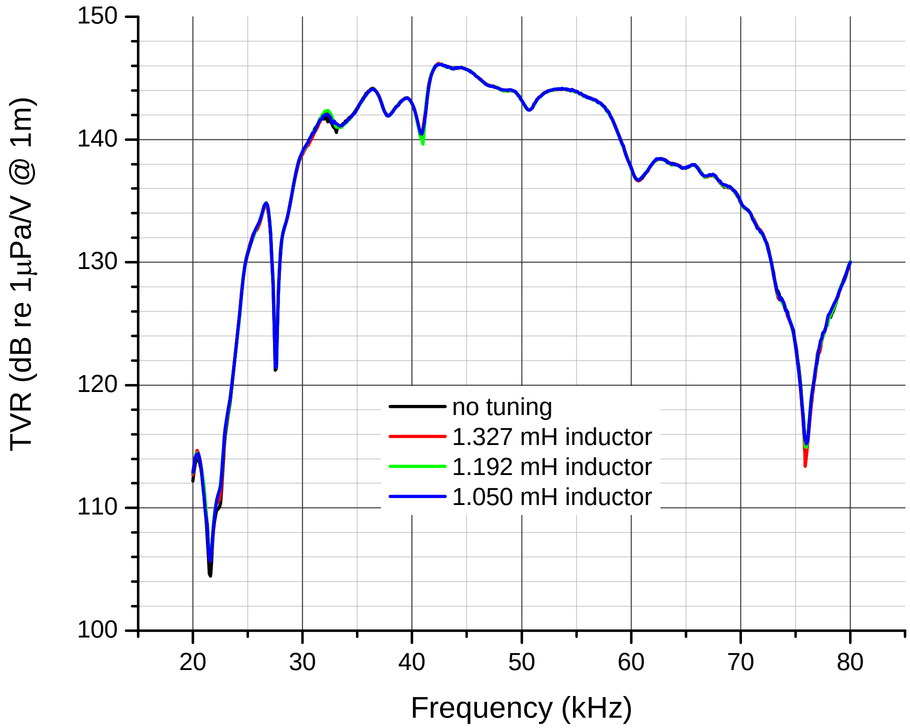

Figure 14 DSP[2] HF MMPP#3 broadside TVR's with various tuning inductors.

A subsequent fully-active DSP^2 HF MMPP (#6) was constructed and it has higher transmitting voltage response (on the order of 6 dB) than the single active cylinder versions (see Figure 15) but its impedance magnitude is indeed lower than that of the first four units (25 to 100 ohms) (see Figure 16). This unit will have greater specific output than the single active cylinder version but will require a power amplifier capable of producing higher current.

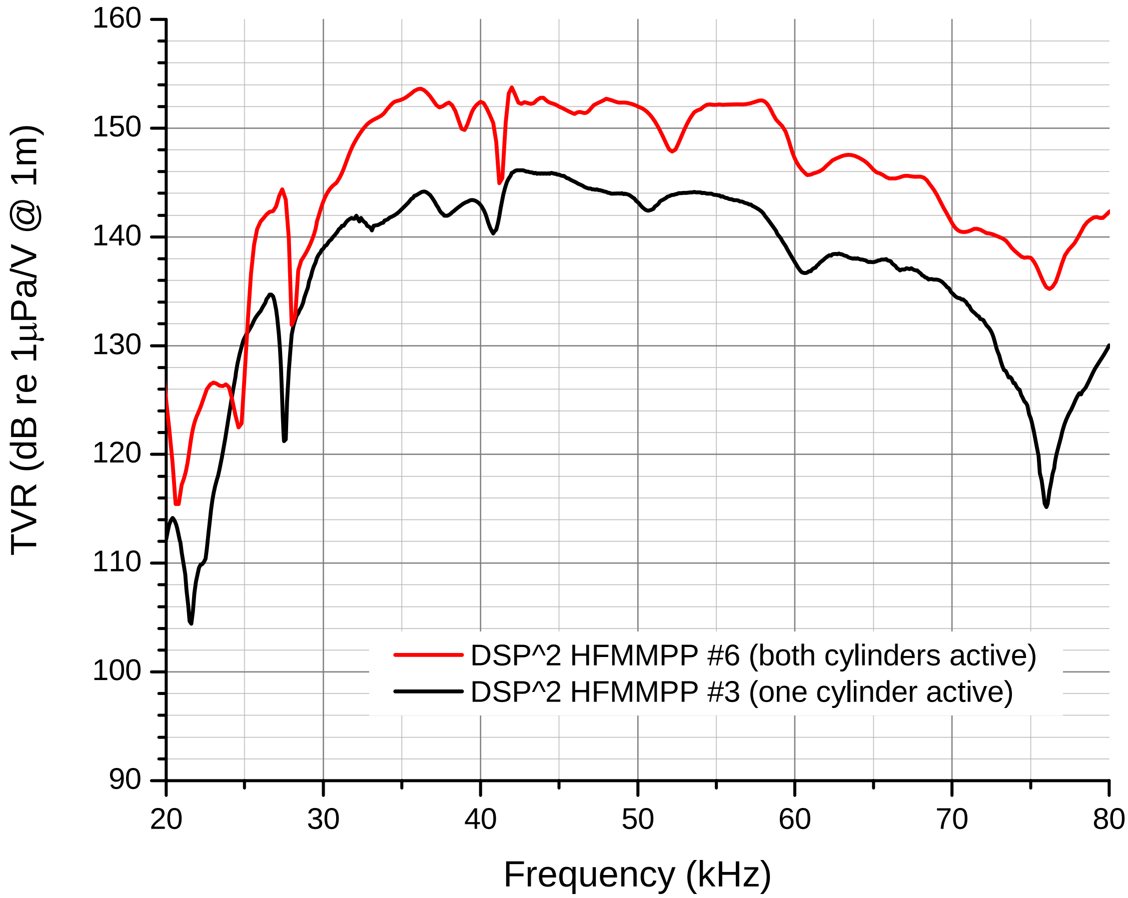

Figure 15 Broadside TVR comparison between DSP^2 HF MMPP units 3 and 6.

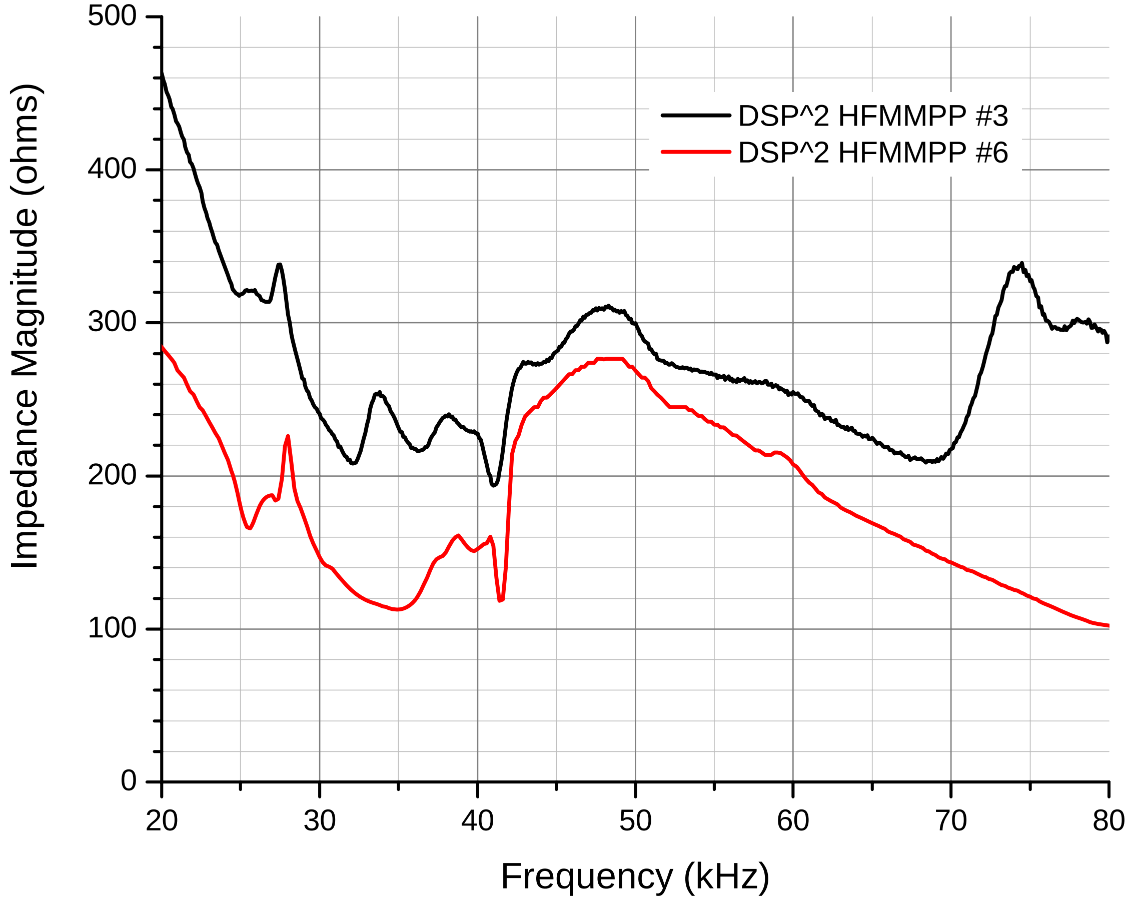

Figure 16 Un-tuned impedance magnitude comparison between DSP² HF MMPP#3 (only one cylinder driven) and DSP² HF MMPP#6 (both cylinders driven).

4 Conclusions

The hypothesis of changing the fundamental drive motor motion of the HF MMPP has resulted in greater acoustic output in the broadside aspect over the 30-55 kHz band. This new design meets the initial requirements for the DSP^2 acoustic source. Using a radially-poled drive motor arrangement, substantially greater output of the 30-55 kHz band is achieved. With a single active PZT-5 element, a DSP^2 achieved no less than 140 dB re 1μPa/V @ 1m in the broadside aspect and an endfire TVR on the order of 143 dB re 1μPa/V @ 1m of the same band. With both cylinders active, this output increased by approximately 6 dB with a decrease in impedance magnitude. The power factor of the single active cylinder version of the DSP^2 HF MMPP is greater than 0.9 from 30 to 60 kHz making it a well-behaved load in terms of limited reflected power.

Follow-on work to characterize the beampattern of these devices as a function of frequency is planned. As well, maximum depth of operation and maximum drive voltage limits will be explored.

References

[1] Fleming R. and Purcell C., Multi-Mode Pipe Projector, US Patent 6,584,039, 24 June 2003 (2003).

[2] Fleming R., High Frequency Multi-Mode Pipe Projector, DRDC Atlantic Technical Memorandum, TM 2003-218 (Limited Distribution), (2003).

[3] Fleming R., Endfire Acoustic Radiation Reduction Technique for the HF MMPP, DRDC Atlantic Technical Memorandum, TM 2006-261, (2006).

List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
R&D	Research & Development
DSP^2	digital spread spectrum with digital signal processing
MMPP	multi-mode pipe projector
HF MMPP	high frequency multi-mode pipe projector
MAVART	model to analyze the vibration and acoustic radiation of transducers
TVR	transmitting voltage response
Pa	Pascal
ACT	acoustic calibration tank
kHz	kilohertz
rms	root mean square
mH	millihenry

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Breathing-Mode DSP^2 High Frequency MMPP:

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Fleming R.

5. DATE OF PUBLICATION (Month and year of publication of document.) November 2008	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.) 28	6b. NO. OF REFS (Total cited in document.) 3

7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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The high frequency multi-mode pipe projector (HF MMPP) transducer has been employed in many applications since its inception. With its wide bandwidth, one of its uses has been as an acoustic source for underwater communications. The digital spread-spectrum with digital signal processing (DSP^2) project identified the need for a more efficient underwater communications acoustic projector in the 35 kHz to 60 kHz band. Two versions of a new breathing-mode DSP^2 HF MMPP were developed using finite element design techniques and initial testing has demonstrated design objective conformance.

Le transducteur du projecteur à tube multimodes haute fréquence (MMPP HF) a servi à de nombreuses applications depuis sa conception. Grâce à sa grande largeur de bande, il a servi de source acoustique de communications sous-marines. Le projet d'étalement numérique du spectre avec traitement numérique des signaux (DSP^2) a fait ressortir le besoin d'un projecteur acoustique de communications sous-marines plus efficient dans la bande de 35 kHz à 60 kHz. Deux versions d'un nouveau MMPP HF DSP^2 en mode hermétique ont été mises au point à l'aide de techniques de conception par éléments finis, et l'essai initial en a démontré la conformité à l'objectif de conception.

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high frequency; mmpp; breathing mode; dsp^2

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