A Marine Vibrator to Meet the Joint Industry Project Specification

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Summary

The performance requirements outlined in the Marine Vibrator Joint Industry Project (MVJIP) specification were extremely challenging to achieve. The approach taken by General Dynamics Applied Physical Sciences Corp. (GD APS) has been physics based and utilized multiple engineering disciplines to design a system to meet the required output levels, distortion, and reliability. A discussion of governing physics, design trades, and measured acoustic and reliability performance is presented.

Introduction

In 2011 the Marine Vibrator Joint Industry Project (MVJIP) released an advertisement requesting information on commercially available low frequency acoustic source technologies that could be adapted to meet their seismic specifications. The technology is required to operate over an *octave and decade of bandwidth* with acoustic wavelengths varying from 300m to 15m. In addition, the out of band harmonic distortion specification is 40dB down which is particularly challenging at the required source level. Furthermore, the units are required to operate for 720 sweep hours between overhaul cycles with *no more than* two hours of maintenance performed during line changes conducted at 72 sweep hour intervals.

As indicated by Shostak and Jenkerson (2015), the motivation for the development of marine vibrator technology includes, among other things, "geophysical and operational benefits such as shallow water operations, improved bandwidth control, and signal encoding capabilities." In addition, marine vibrator array outputs have substantially lower peak intensities compared to conventional air gun arrays, which is an environmental advantage.

To meet the MVJIP specification and realize the benefits of marine vibrator arrays over conventional air gun arrays, GD APS designed, fabricated, tested, and validated the Marine Vibrator Integrated Projector Node (MVIPN). Key MVIPN design features & trades as well as in-water performance data are discussed. Finally, endurance tests scheduled for this spring are described.

Transduction Method and Trades

The MVJIP specification is for an array of vibrators and must be scaled by the number of transducers in the array to derive the individual node source level requirements. In order to meet the source level specified by the MVJIP, the GDAPS array will consist of 18 MVIPNs. Therefore each IPN has the following output requirements:

- 165dB//uPa-m/Hz from 5Hz to 10Hz
- 175dB//uPa-m/Hz from 10Hz to 100Hz

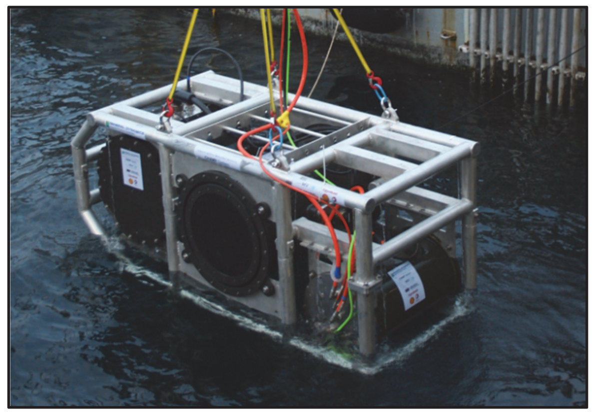

Figure 1: The GDAPS Marine Vibrator Integrated Projector Node (MVIPN) undergoing performance verification testing at NUWC Seneca Lake Sonar Test Facility in Dresden NY

The nominal seismic source pilot specified by the MVJIP is a 5 second long linear swept sine from 5Hz to 100Hz. To achieve the node output specification, the node source level requirements are as follows:

- 180dB//uPa-m between 5Hz and 10Hz
- 190dB//uPa-m between 10Hz and 100Hz

Regardless of the transduction technology employed, to achieve a given source level at a particular frequency, a transducer with characteristic dimensions much smaller than a wavelength must produce a given volume velocity, Q. This is essentially the product of the radiating surface area, A_n, and the average surface normal velocity, u_n. The transducer designer is free to choose the radiating surface area and the average normal velocity, but their product is determined by the specification of source level. For a time harmonic signal the average normal displacement of the radiating surface, x_n, is simply $\frac{u_n}{j*2\pi f}$. This means that a transducer design must satisfy the equation:

$$|Q| = |A_n * x_n * j2\pi f| \qquad \text{Eq. 1}$$

For a given source level, it's evident from Equation 1 that the product of the radiating surface area and average normal displacement is greatest at the lowest operating frequency. The tradeoff between radiating surface area and displacement to achieve a given source level must also consider the high frequency end of the specified band. In particular, if the transducer designer implements a large surface area to minimize the displacement requirement, the designer must ensure that the radiating surface is sufficiently stiff, such that it does not have any structural modes within the operating band. Additionally, the transducer designer must take care that, in an attempt to stiffen the radiating surface, the mass is not excessively increased, thereby requiring more force to displace it. Alternatively, if the designer chooses to use a small radiating surface area and a large displacement, the transduction mechanism must remain linear over that distance. The extreme bandwidth requirement of the MVJIP requires both large displacements *and* large radiating area. The design challenge is complicated by a need to operate the transducer over a shallow range of depths from 2-30m without the onset of cavitation.

The GDAPS transducer is specifically designed to remain highly linear over the required displacements and to keep the radiating surfaces stiff within the operating band thereby permitting the use of a single transducer to cover the entire band. Dividing the overall band into sub-bands and using one transducer per sub-band was also considered. This alleviates the stiffness requirement on the low band transducer's radiating surface and allows the high band transducer to have a lower displacement capability, dramatically reducing the transducer design difficulty. However, having a single transducer covering the entire band can be advantageous. If multiple sub-band transducers are used to transmit the up-swept chirp, in band harmonic distortion from the low band transducer may contaminate the signal from the high band transducer and correlate positively in time during wavelet compression. For a single transducer, in band harmonics correlate in negative time for the upswept signal, mitigating this concern.

The transducer force requirement is dominated by the total moving mass, m_{total}, at the high frequency limit. The total moving mass includes the moving parts of the transducer m_{mech} and the entrained water mass displaced by the transducer $m_{water} \approx \rho 8a^3/3$ for a circular piston of radius a. For the time harmonic case, the force is then:

$$Force = (m_{mech} + m_{water}) * \frac{u_n}{j2\pi f} \qquad \text{Eq. 2}$$

To reduce the transducer force requirement (and resulting size and current, and thus power dissipation), the total moving mechanical mass must be minimized while simultaneously keeping the radiating surface stiff.

From these simplified physics based expressions, the transducer design is constrained and assured to meet the source level requirements.

The MVIPN Transducer Design

To meet the MVJIP source level requirements with 18 MVIPN transducers, each transducer was designed with a total radiating surface area of approximately 0.8m^2, 23mm of displacement, and 18kN of force generation capability.

As described by McConnell *et al.* (2017), the radiating surface area is separated into two circular pistons, each coupled by a shaft to a magnetically soft armature. Within the transducer, powerful permanent magnets induce a bias flux that couples the armature, stator, and electrical coils, as seen in Figure 2. When electric current is forced through the coils, the resulting flux is also coupled to the armature and stator. By superposition, the coil flux reinforces the magnet flux on one side of the armature, and subtracts from the magnet flux on the opposing side of the armature. Consequently, the magnetic attraction force between the stator and the armature is greater on one side of the armature than the other, resulting in a net force that is linearly proportional to the drive current. Note that the armature and stator poles are shaped to keep the permanent magnet and coil induced flux constant over displacement, thereby keeping the force produced per amp of drive current constant over the entire stroke. The transduction method implemented by GDAPS is known as a biased moving armature, and has many notable advantages over electrodynamic voice-coil transducers.

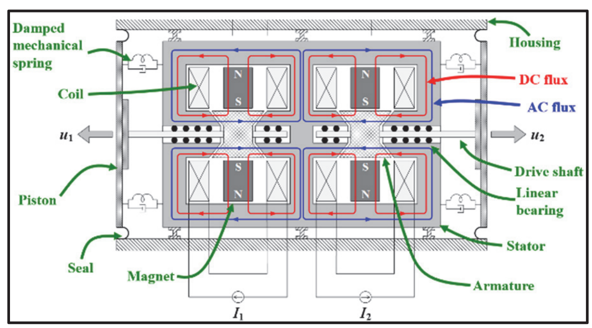

Figure 2: GDAPS marine vibrator transducer schematic

In a moving armature transducer both the electrical coils and bias magnets are stationary, which is a principal advantage over typical voice coil transducers. In the latter, the coils are commonly attached to the radiating surfaces and are subjected to high vibration and fatiguing of the lead wires, a common failure point. Furthermore, because the coils constitute a portion of the moving mass, their cross sectional area is minimized to reduce their mass and the resulting transducer force requirement. This yields a higher coil resistance, more power dissipation, and potentially higher operating temperatures. The moving armature coils do not contribute to the moving mass, and can be sized to accommodate the current with minimized power dissipation and no fatiguing.

In addition to shaping the armature and stator poles to keep the transducer highly linear over the entire stroke, special care was taken to keep the radiating pistons as light as possible and sufficiently stiff to prevent them from becoming modal within the specified operating band. If the pistons become modal and vibrate without uniform normal velocity, their radiation efficiency is dramatically reduced. Outside of the operating band where the harmonic distortion is specified at 40dB down, a modal piston can be beneficial since it does not radiate well. However, if the modes are high Q, meaning they are not well damped, they may radiate well over a narrow bandwidth causing peaks in harmonic distortion at discrete frequencies. To guarantee sufficient damping of the system, the GDAPS transducer employs damping treatments on select structures.

Design for Reliability

The MVIPN, designed to meet the source level and harmonic distortion requirements in the MVJIP specification, must also meet the reliability requirements. Periodic maintenance can only be performed during line changes, occurring not more often than every 72 sweep hours, or 144 operational hours at 50% duty cycle. Maintenance occurring during a line change cannot exceed two hours, limiting which operations and procedures can be considered maintenance. Any process or operation that cannot be completed in the two hour window may be executed during overhaul cycles occurring at 720 sweep hour, or longer, intervals. Given the limited maintenance and overhaul period, the MVIPN must be extremely reliable.

One key reliability design feature is configuration of the rolling element rubber seals that connect the piston edges to the transducer enclosure, preventing water from entering the transducer. The seals were custom designed to operate over wide operating temperatures, have extreme fatigue life, be petrochemical resistant, and have good UV light tolerance. Finite element modeling was also used to ensure that the rolling element seals are not subjected to localized cavitation that can damage the seals. To validate the ruggedness and reliability of the seal design, multiple seals were subjected to extensive cycling, exceeding the required operational life of a seal by a substantial margin. If a rolling element seal needs to be replaced in the field, it can be accomplished within the two hour window during a line change.

A second key reliability design element is the longevity of the coil springs within the transducer. If a spring were to prematurely fail, the transducer would require an overhaul to replace the spring. Therefore, the springs were designed to operate for the life of the transducer without failure. In particular, the springs were manufactured to exacting tolerances and surface defects (points in the spring where stress concentrations could initiate cracking) where removed by an electro-polishing process. Residual stress concentrations resulting from the manufacturing process are removed by double shot peening to plastically deform the surface material into a relaxed state. The springs are then coated in a protective epoxy paint to prevent corrosion. To validate the spring reliability, a representative sample of springs was subjected to more than 10 million cycles with no change in performance.

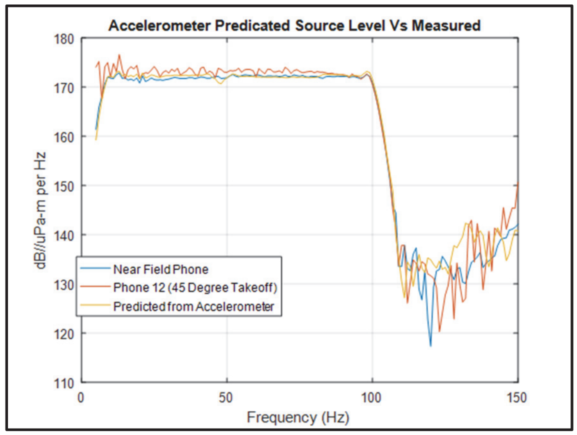

Figure 3: Comparison of the accelerometer prediction of source level and measured source level using calibrated hydrophones.

Besides designing and testing key components specifically for reliability, the entire MVIPN was tested at a 72 sweep-hour in water shakedown test, after which no unexpected wear was observed. Furthermore, the MVIPN is scheduled to undergo 720 sweep-hours of in water endurance testing in the spring of 2018. The endurance testing is designed to ensure all aspects of the MVIPN are vetted for reliability, and to gain some statistically relevant wear information on maintenance items within the IPN.

MVIPN Performance Measurements

Following the in-water shakedown test, the MVIPN was characterized with calibrated instrumentation at the NUWC Seneca Lake Sonar Test Facility in Dresden, NY. Because the transducer pistons are stiff in band, an accelerometer is used both to compute the system source level, and as part of a feedback control system. In a simplified example, the feedback controller compares the measured acceleration against the user-provided pilot sweep, and corrects the drive current in real time to force the acceleration to match the pilot. This reduces harmonic distortion and enables the transducer to transmit arbitrary pilot waveforms.

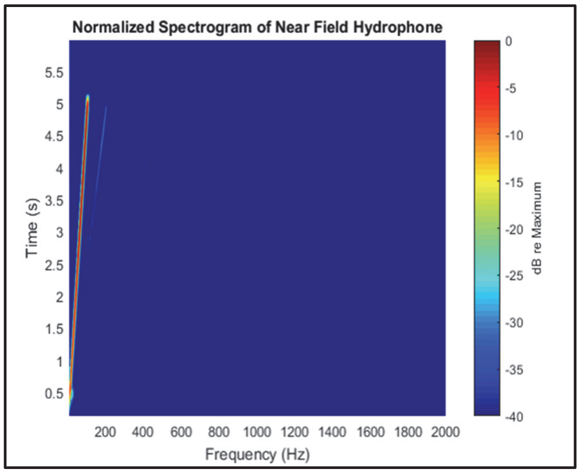

Figure 4: Hydrophone data spectrogram of a 5 second long, linearly swept 5Hz-100Hz seismic sweep on 40dB scale

The MVIPN source level, harmonic distortion, operational depth range, operational frequency range, and waveform diversity capabilities were characterized and validated. Figure 3 shows excellent matching between the accelerometer based predictions of source level and calibrated hydrophone measurements. Figure 4 shows excellent harmonic distortion performance while transmitting the 5Hz-100Hz linearly swept sine seismic source signal.

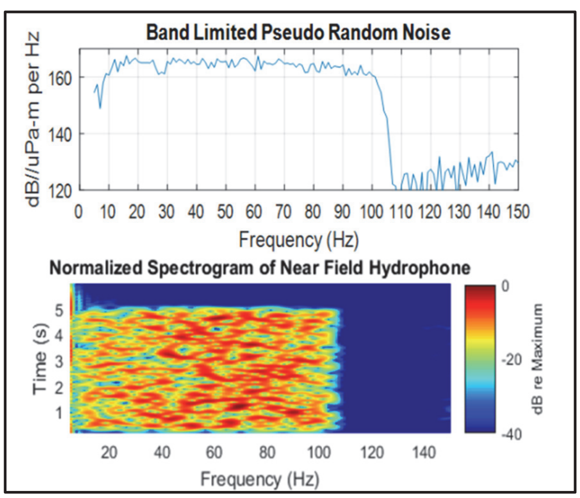

Figure 5: Measured spectrum and spectrogram of a 5 second long pseudo random noise transmission

Figure 5 depicts a band-limited pseudo random noise signal as captured on the piston accelerometer. The plots in Figure 6 show the times series hydrophone recordings of the linearly swept 5Hz to 100Hz pilot with 0 and 90 degrees phase shifts. This capability allows for the sources to be "flip flopped" with alternate arrays transmitting sequentially.

In addition to testing the IPN with the specified linearly swept sine, pseudo random noise (PRN), quadrature phase shift keyed signals, tones, and, to the surprise of the Seneca Lake staff, even music were transmitted in high fidelity through the transducer.

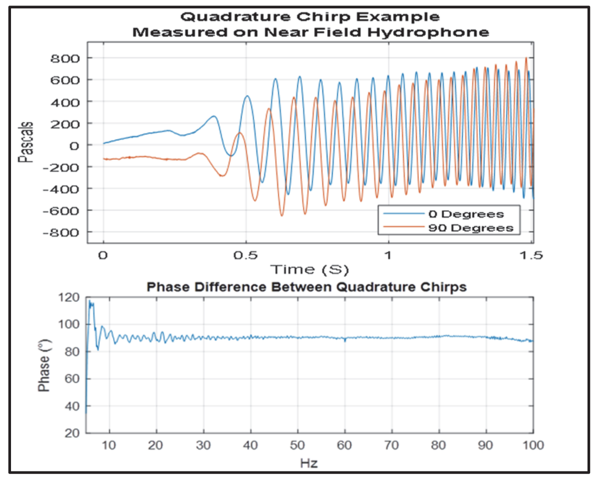

Figure 6: The 5Hz-100Hz linearly swept sine waveform is transmitted with 0 and 90 degree phase shifts

The testing at Seneca Lake has proven that the GDAPS marine vibrator will realize the advantages over air gun arrays that first motivated the development of marine vibrators. The achieved source level, harmonic distortion, and diverse set of waveforms offers survey designers a whole new set of capabilities in 3D, 4D, and shallow water explorations, production monitoring & surveying, and in environmentally sensitive operational areas. Reliability testing confirms that the design features enable future seismic survey deployment.

Acknowledgements

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