Introduction

General Dynamics Applied Physical Sciences Corporation (APS) has developed, patented, and fabricated marine vibrator technology to meet the specifications established by the Marine Vibrator Joint Industry Project (Feltham et al. 2017). Presented here is an overview of the APS Marine Vibrator Integrated Projector Node, recent in-water shakedown testing results, and 3D deep water marine vibrator seismic array concepts. Detailed performance measurement results acquired in January 2018 at the Seneca Lake Sonar Test Facility will also be presented at the 2018 EAGE Annual Conference.

The Applied Physical Sciences Marine Vibrator Integrated Projector Node

The fundamental building block of the APS marine vibrator system is the Integrated Projector Node (MV-IPN) pictured in Figure 1. The MV-IPN consists of three primary subsystems secured within a towable free-flooding frame. These subsystems include the Power Amplifier (MV-PA), Full-Scale Projector (MV-FSP), and Control & Monitoring System (MV-C&M).

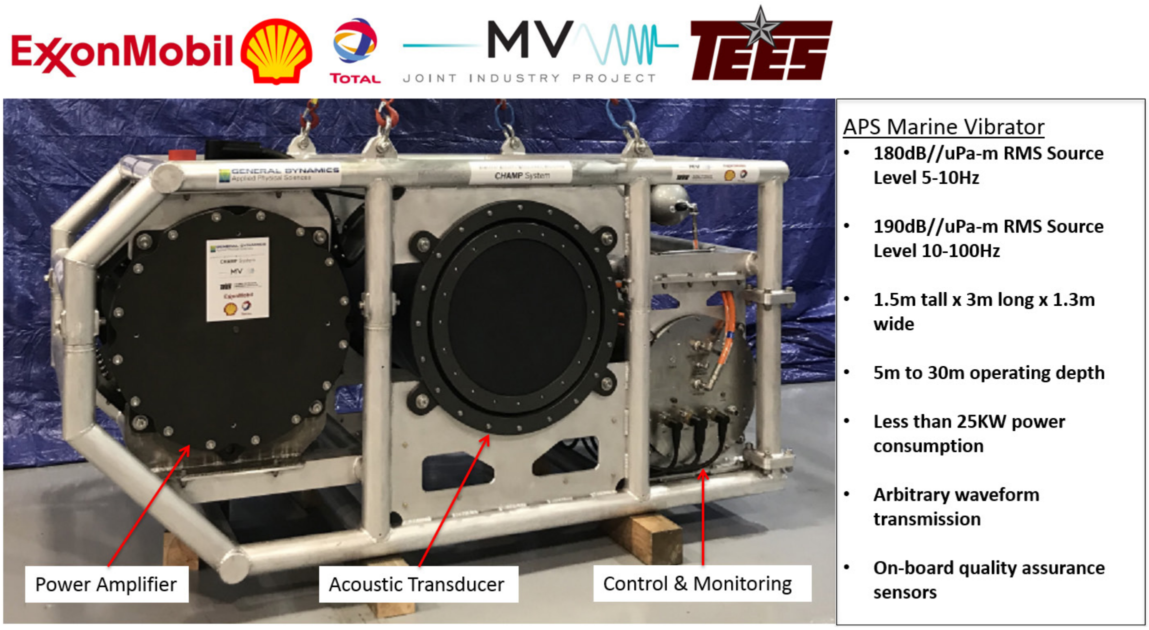

Figure 1 *The APS Marine Vibrator Integrated Projector Node consists of the power amplifier (left), full scale projector (center), control & monitoring system (right), and free-flooding frame.*

The Full-Scale Projector produces controlled, coherent, modulatable acoustic energy from 5Hz to 100Hz in accordance with the Marine Vibrator Joint Industry Project (MV-JIP) specification (Schostak et al. 2015). The MV-FSP implements moving armature, electromagnetic transduction which causes the radiating pistons to oscillate, as depicted in Figure 2. Magnetic flux from permanent magnets located within the transducer couple to, and magnetically bias, the specially-shaped armature assembly. Currents carried via electrical coils produce an additional magnetic field, which is also coupled to the armature assembly. The sum of the magnetic fluxes creates a net force proportional to the drive current which is transferred from the armatures to the pistons via linear shafts. The resulting out-of-phase piston oscillation causes radiated sound in accordance with well-understood, classical, underwater acoustics in the low frequency regime (Kinsler et al. 2000). Unlike moving coil electrodynamic transducers that use Lorentz forcing, the moving armature electromagnetic transducer uses magnetic forcing and stationary coils providing a high degree of system reliability. Armature shaping, the control system, and other design features are used to reduce harmonic signal content. In addition, although the pistons each produce 17,800 N (4000 lbs) of peak dynamic force, they move in controlled opposition to one another such that the stator and integrated node experience negligible vibration. This provides a stable platform for towing and further enhances system reliability.

Importantly, the transducer can produce arbitrary pressure waveforms including, but not limited to, up-swept or down-swept linear chirps, logarithmic chirps, phase or frequency shift keyed encoded waveforms, and pseudorandom noise. An on-board digital controller ensures high signal to noise ratio, low harmonic distortion, flat frequency response, and highly repeatable outputs. This technology offers a wealth of source waveforms to enable enhanced seismic survey and analysis capabilities.

The MV-FSP drive currents are produced using a two channel, state-of-the-art, transconductance amplifier adapted from the medical Magnetic Resonance Imaging industry. Positioning the amplifiers within the free-flooding frame and adjacent to the MV-FSP permits passive cooling and the use of DC power to energize the amplifier. This power is supplied via umbilical from high-efficiency power supplies residing on-board the survey vessel. This arrangement is safer and much more efficient than sending the high-current AC drive signal down the umbilical, which may be up to 1km long.

The MV-C&M subsystem performs several functions, including monitoring all MV-IPN engineering and quality assurance sensors; housing biasing, signal conditioning, & analog to digital conversion electronics; hosting a high-speed field programmable gate array (FPGA) based digital controller with Ethernet connectivity; and hosting a pneumatic-based hydrostatic pressure compensation system. The primary engineering and quality assurance sensors used by the MV-IPN are low noise, high dynamic range accelerometers mounted on the MV-FSP pistons. The measured piston acceleration is used to estimate the radiated acoustic pressure. Furthermore, by regulating piston acceleration, the digital control system ensures that the MV-IPN produces the output pressure commanded by the pilot or reference waveform. It also ensures that the resulting pressure has a high signal to noise ratio and low harmonic distortion.

The pressure compensation system uses a network of valves and dry, compressed air supplied from the survey vessel (via the umbilical) to regulate the internal gas pressure of the MV-FSP. By matching the internal gas pressure to the external hydrostatic pressure, the system minimizes the net hydrostatic forces on the pistons. These hydrostatic forces would otherwise cause the pistons to displace with changes in depth, gas temperature, or wave action, thereby reducing the dynamic range of the MV-IPN. The pressure compensation system has been designed to sufficiently regulate the pressure and resulting hydrostatic forces in operational conditions up to and including sea state 4.

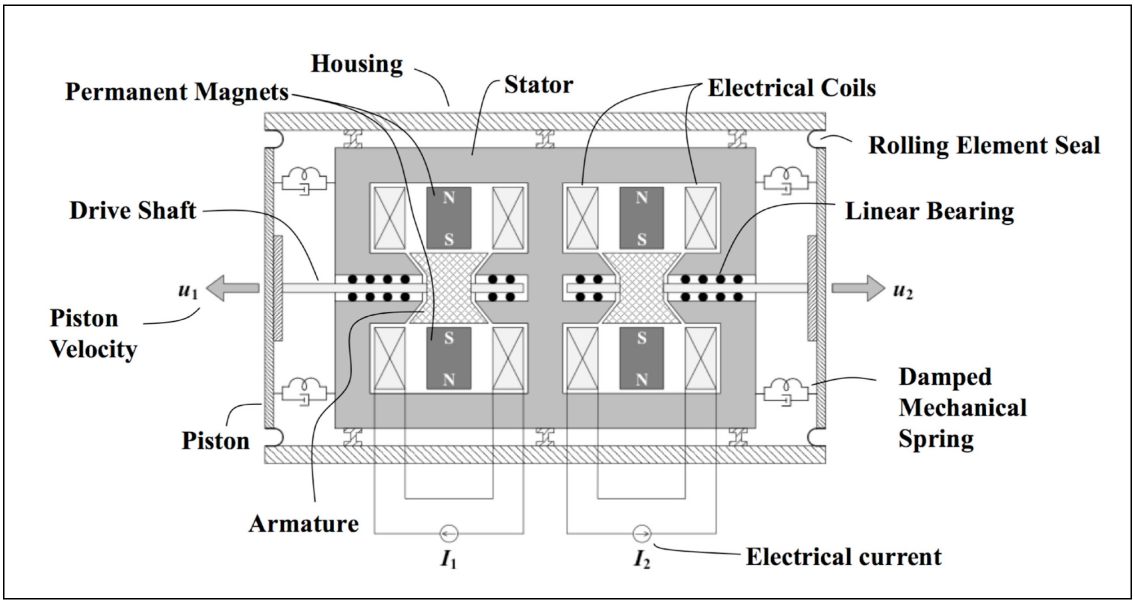

Figure 2 *The APS Marine Vibrator Full-Scale Projector (MV-FSP) functional schematic from the APS patent (McConnell et al.). The radiated acoustic pressure is proportional to the drive currents I_1 and I_2 respectively*

Shakedown Testing and Results

The APS MV-IPN underwent extensive laboratory and subsequent shakedown testing in December of 2017. While submerged in a quarry in Arvonia Virginia, U.S.A., the unit operated for over 72 sweep hours without any maintenance or modification. Specifically, the unit transmitted a 5 second long, linear chirp from 5 to 100Hz with 53% duty cycle for over 135 hours. Throughout the test both engineering and quality assurance sensors were monitored and recorded to detect any signs of premature wear, malfunction, or degradation of signal fidelity. Following the test, the MV-IPN was returned to Applied Physical Sciences for extensive examination and inspection. After complete disassembly of the IPN to the subsystem level, it was determined that the unit showed no signs of premature wear. APS personnel determined that the unit could have stayed in service, thereby exceeding the 72 sweep-hour minimum line-change endurance specified by the MV-JIP requirements. Furthermore, APS plans to conduct an extended reliability test in the spring of 2018 where the submerged unit will operate for 720 sweep hours (over 56 days at 53% duty) with only line-change-type maintenance occurring not more than every 72 sweep hours.

Deep Water Stationary Performance Testing and Predictions

In January of 2018, the MV-IPN will undergo deep-water stationary performance testing at the Naval Underwater Warfare Center Seneca Lake Sonar Test Facility in Dresden, New York. The extensive testing is designed to characterize the MV-IPN's source level, bandwidth, acoustic output variation, linearity, dynamic range, and harmonic content. Ahead of the scheduled in-water testing, laboratory testing indicates that the MV-IPN is expected to meet or exceed requirements, including but not limited to source level and bandwidth. An example of measured hydrophone data from the shakedown test is shown in Figure 4.

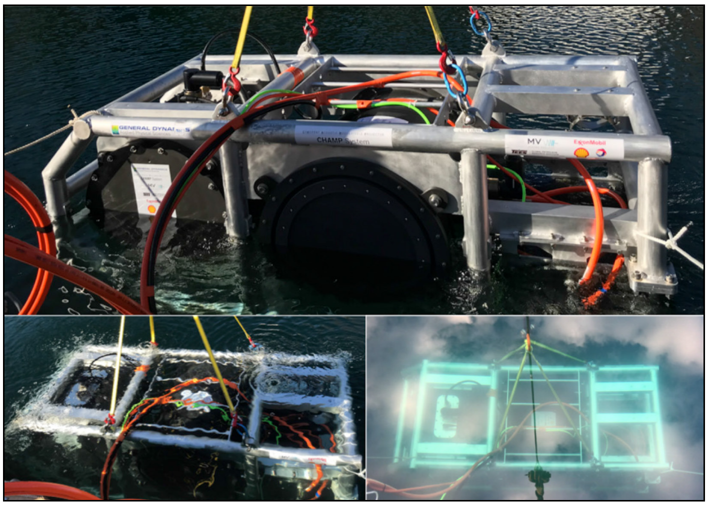

Figure 3 *The APS Marine Vibrator Integrated Projector Node is photographed while being submerged into a testing pond in Arvonia Virginia, U.S.A. for extended in-water shakedown testing (top). Air escaping from the free flooding frame causing bubbles (bottom left). The MV-IPN after operating for over 135 hours (bottom right).*

Full 3D Seismic Marine Vibrator Arrays for Deep Water Surveys

Ultimately, the APS Marine Vibrator system will consist of multiple, time-synchronised & geospatially located MV-IPNs configured in arrays of up to 18 nodes and having array apertures up to 18 by 18 meters. The nodes can be suspended from surface floats or via a series of shuttle floats that control deployment depth. The MV-IPN arrays may be towed via umbilical cables with lengths of up to 1 kilometer. Applied Physical Sciences has executed preliminary engineering analyses, trade studies, and market research to inform pending detailed engineering design. APS has also engaged geophysical and marine seismic industry partners and plans to execute detailed design and prototyping of MV-IPN arrays, requisite hardware, and software beginning in 2018.

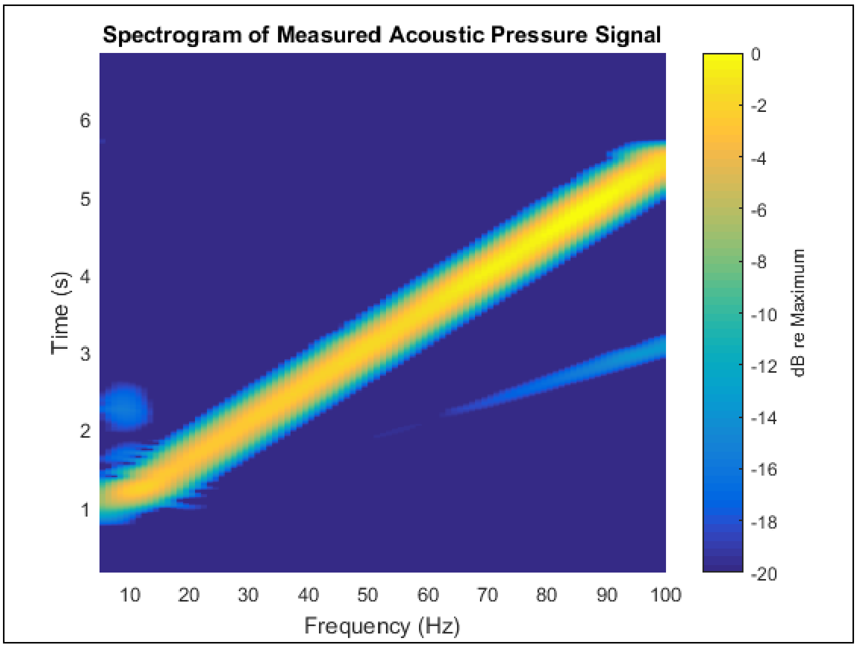

Figure 4 *Measured hydrophone spectra from the MV-IPN collected during in-water shakedown testing at Arvonia VA – recent improvements to the control system further reduce signal distortion levels.*

Conclusions

APS has designed, fabricated, and tested a commercial Marine Vibrator for use in deep water 3D and transition zone marine seismic exploration. Deep water testing conducted in January 2018 will accurately characterise system performance and will be presented. In addition, upcoming array and requisite hardware design efforts will focus on integrating MV-IPNs into arrays and aim to reduce the size and weight of the MV-IPN, primarily by eliminating or reducing the control electronics housing.

Acknowledgements

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