Simulation and Testing of Tunable Organ Pipe for Ocean Acoustic Tomography

Andrey K Morozov[1]

[1] Advanced Technology Group, Teledyne Marine Systems, 49 Edgerton Drive North Falmouth, MA
02556 USA, Tel: +1 508 299 6284, Fax: +1 508 563 5352, email amorozov@teledyne.com

Abstract— **Long-range, ocean acoustic tomography, require low frequency signals covering a broad frequency band. To meet this requirement, Teledyne Webb Research has developed a system which uses a tunable, narrow-band, high-efficiency sound resonator. The high-Q resonator tunes to match the frequency and phase of a reference frequency-modulated signal. The projector transmits a digitally synthesized frequency sweep signal and mechanically tunes an organ pipe to match the frequency and phase of a reference signal. The computer timing system uses high precision Cesium atomic clock. The resonator tube projector consists of a volume source in a form of pressure balanced symmetric Tonpilz driver and aluminum free flooded pipe. The actuator smoothly tunes the frequency of the resonator tube over the large frequency band. The transmission duration can vary from five seconds to a few minutes. The first sound source was built for the Naval Postgraduate School (Monterey, CA) for studying temperature variability in the California Current over the bandwidth 200-300 Hz. Since 2001, all ocean acoustic tomography experiments have used this type of TWR sound source. Modification with 140-205 Hz frequency sweep has been built. The transmission duration can vary from one second to a few minutes. This type of sound sources has been used in many experiments: Pacific Ocean, Pioneer Seamount (2001); MOVE Experiment (2004 - 2005); Pacific Ocean ,Hoke Seamount (2002- 2004); NPAL04, SPICE04, Pacific Ocean (2004 -2005); Fram Strait 2008-2012; Philippine Sea (2009,2010-2011); Newfoundland, Canada (2014-2015). In 2013 the TWR specially designed a sound source for a sea floor deployment. The bottom-deployed swept frequency array can be used for high-resolution seismic imaging of deep geological formations. During its 15 years of operating history the Teledyne underwater tunable resonant sound source demonstrated exceptional performance. It is coherent, efficient, powerful, and had unlimited operational depth, as well as a minimum level of high frequency harmonic content. The analysis of a new high-Q resonant organ pipe with an octal band 500-1000 Hz is analyzed by the COMSOL multi-physics simulation. The finite analysis computer simulation gives the affectionate picture of tunable resonator acoustics. For clear interpretation of sound pressure levels (SPL) the analysis was done for the standard spherical piezo-ceramic driver. The finite element simulation shows the structural acoustics of the tunable resonator. The results are compared with the experimental test. Application of COMSOL finite element analysis predicted optimal parameters of the resonator and avoided a long series of water tests with parameters adjustment. The parameters of the sound source were close to the COMSOL simulations.**

I. INTRODUCTION

DEEPWATER low-frequency sound sources are used in sonar systems, ocean acoustic tomography, seismic sub-bottom imaging, long-range navigation and communications [1-10]. These applications require a high-power source of sound covering a wide range of frequencies [11-13]. Many of these applications operate autonomously for a few years and need high efficiency. Different frequencies transmitted in sequence, or swept signals, are appropriate when the investigated medium does not change appreciably over the duration of the transmission. Such signals are commonly used for ocean acoustic tomography, long-range navigation, geophysical seismic bottom imaging, continuous active sonar (CAS) and long-range communications. Continuous phase modulation, continuous-phase frequency-shift keying or minimum-shift keying (MSK) are methods for modulation of data commonly used in a frequency band limited channels [14]. The continuity of phase not only increases noise immunity of communications, but can make the transmission of signals very efficient because it saves energy that is accumulated in the resonator from previous transmissions, for a currently transmitted oscillation. Saving energy in the resonator makes the transducer very efficient, when its dimension is smaller than a wavelength. In that case, a large portion of the acoustic energy is oscillating in the near-field zone and only a small fraction of that energy is radiating. Without saving energy on each wave period only a small fraction of driver energy propagates. By saving energy and keeping near-field oscillations, the acoustic driver will add only the fraction of energy radiating on each cycle. High-Q resonators are very efficient transducers. The resonant tube is a simple, efficient, narrow-band projector that operates at any ocean depth. To cover a large frequency band, we propose to tune a high-Q, narrow-band resonator to keep the system in resonance with the changing instantaneous frequency of the transmitted signal [15-18]. This projector combines the efficiency and simplicity of resonant tube projectors with the possibility of using wide frequency ranges demanded for a high resolution remote sensing systems. The system is similar to a low-frequency spectrum analyzer sweeping over a frequency band for a time less than the time constant of measured parameters. Such approach yields:

- very high efficiency;
- large frequency band;
- simple reliable engineering;
- medium to high power output;
- low-level high-frequency harmonics;
- reasonably small weight, can use carbon fiber pipe.

In additional the free flooded tunable tube or organ pipe offers unlimited operating depth. Automatic tuning of the projector resonant frequency stabilizes the system against variations of water properties. This is important because the organ-pipe is storing energy from sea water compression and inertia and its resonance depends on water temperature and pressure.

The tuning mechanism should change the resonance frequency without losing efficiency. It is easy to do this by mechanically changing parameters of the resonator. Rather than change the length of pipe we proposed to change the inertia of water in a small gap under the sleeve covering an orifice in the organ pipe. When the gap is small the inertia of water in it can be large enough to shift the resonance frequency of the main pipe. A low power electro-mechanical actuator can tune the organ pipe in a large frequency range by shifting sleeve only a few inches. The typical design of such a mechanical tuner will be shown in the next section. The shifted frequency can be twice as large as the initial frequency and projector can cover an octave of bandwidth. The advantage of this approach is a high rate of frequency change and a constant Q-factor over the working frequency band. The maximum rate of frequency sweep can be a fraction of a second.

The key component of the system is a phase locked loop (PLL) feedback. The projector transmits a frequency sweep while mechanically tuning the resonator tube to match the frequency and phase of a reference signal. A computer-controlled electromechanical actuator moves the cylindrical sleeves along the tubes, covering the tuning slots and keeping the projector in resonance at the instantaneous frequency of a swept frequency signal. The duration of the signal can vary from a fraction of a second to a few hundred seconds. Two different approaches can be used to design an acoustic projector on the basis of a tunable resonator. It can be a self-generating system, tracking the reference signal, or it can be the resonator driven by the digitally synthesized signal with feedback, which tunes it to maintain the resonator at peak output and in phase with the signal. A comparison of both approaches was conducted in [16] and has shown that the second method is preferred. A computer synthesizes the linear frequency-modulated signal; compares the phase between transmitted and reference signals; and using a phase-lock loop (PLL) system, keeps the resonator tube frequency in resonance with the driver frequency.

The estimated PLL precision is a few degrees of phase error. Mathematical analysis and numerical simulation show that the tunable resonator has the ability to quickly adjust its resonant frequency to the instantaneous frequency signal. Walter Munk proposed this method in 1980 as a “state-switched” sound source concept when he was analyzing different approaches for the design of high-efficiency sound sources for an ocean-acoustic tomography experiment. A high-Q narrow-band resonant system with single fundamental resonant frequency can generate a broadband signal if it at any time it maintains a resonance with the signal. The system must be tuned to the instantaneous signal frequency and always be maintained in a resonance state. When transition from one frequency to another without change of energy there is no time response or group delay. Reference [16] describes this concept of fast frequency adjustment in detail. The frequency change rate is limited only by the inertia in a mechanical system. The Sleeve can be made out of a light composite carbon-fiber material (US patent) and the frequency chirp can be done for a fraction of a second. The same projector can be used for the radiation of different narrow-band or continuous-waves (CW) signals in a wide range of frequencies. This projector combines the efficiency and simplicity of resonant tube projectors with the possibility of using wide frequency ranges.

The material including 15 years of operating history of tunable sound sources will be partly presented at OCEANS-16 Conference, Monterey CA [19].

The organization of the paper is as follows. In section II, the general design of tunable resonator is described. An example of computer finite element analysis is considered in section III. In section IV, the operating history of high-Q tunable organ pipes is discussed. A summary and conclusions are given in section V.

II TUNABLE RESONANT ORGAN-PIPE

The organ-pipe design is a configuration of slotted resonator tubes driven by a coaxially mounted, symmetrical piezo-ceramic Tonpilz transducer. The piezo-ceramic stacks of the Tonpilz driver moves pistons symmetrically from the center of the pipe resonator and they vary the volume. The general diagram of tunable resonator is shown in Fig. 1. Two symmetrical pipes are coupled through the Tonpilz and operate as a one half-wave resonator with a volume velocity source driver. A spherical oil-filled transducer is another variant of the volume velocity acoustic driver. However the symmetrical Tonpilz driver is more preferable because it can better adjust the tension on the piston, the stiffness of the driver and the voltage on the ceramics. The Tonpilz ceramic is pre-stressed to the necessary level. The Tonpilz driver can be filled with oil with the compensator outside the main resonator pipe.

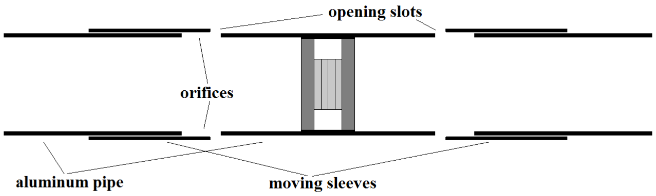


Fig. 1. Tunable resonant sound source with a piezo-ceramic symmetrical Tonpilz driver.

To change the resonant frequency of the projector, the resonator tubes are fitted with slots or vents at a distance of one-third the resonator tube length measured from the acoustical driver. Two stiff coaxial tubular sleeves of larger diameter move axially along the resonator tubes. To achieve smooth control of resonance frequency the sleeves slide along the main pipes with a small gap. The inertia of the water layer in the gap between the two coaxial tubes depends on the position of the sleeves relative to the tube slots. The position of the sleeves relative to the slots causes a change in the equivalent acoustic impedance of the slots, thus changing the resonant frequency of the whole resonator. In the next section, a computer simulation of that design will be conducted. A computer-controlled actuator moves the sleeves and keeps the projector in resonance with a swept-frequency signal. A simple model based on the similarity of mechanical differential equations and equations for ordinary electrical elements, such as capacitors, inductors, resistors, and transformers was developed in [15,16]. The model truly reflects organ-pipe sound physics, but for engineering solutions a 3D finite element computer simulation is necessary. The simulation helps to design some of the important details of the resonator and tuning mechanism, such as the optimal profile of the opening slots. The finite element model is presented in the next section.

III FINITE-ELEMENT ANALYSIS OF A TUNABLE RESONANT ORGAN-PIPE

The analysis of a high-Q resonant organ pipe for ocean acoustic tomography with a frequency range 200-300Hz was done in previous publications [15-16]. In this section, a new high frequency variant of the Teledyne Webb research (TWR) sound source with an octave band 500-1000 Hz is considered.

The finite analysis, computer simulation gives a demonstrative picture of organ pipe acoustics. For a clear interpretation of sound pressure levels (SPL) the analysis was done for a standard spherical driver (ITC1007), see Fig. 2. The SPL is shown for a voltage on the piezo-ceramic equal to 1000 V rms.

The dimensions of the sound source model are:

- the diameter of the main resonator pipe - 8 inches;
- the length of the main pipe - 50 inches;
- the tuning sleeve length - 9.25 inch;
- the wall thickness for pipe and sleeve - 0.25 inch;
- the gap between main pipe and sleeve - 0.1 inch;
- the sleeve displacement for each curve is 1 cm.

The small dimensions of the sound source make it very attractive for application in shallow water experiments, where a whole system with electronics and batteries can be handled without a crane. The material of the pipe resonator and tuning sleeves is aluminum 6061-T6. That aluminum does not need to be anodized for long term experiments in sea water. To make resonator lighter the thickness of the walls was reduced to a quarter of an inch. The thin walls are vibrating and storing a significant amount of acoustical energy. To avoid acoustical coupling of the main resonator with the mechanical part of another part of the system the main resonator pipe was attached to the strong backbone rail with the shock mounts. However, it was not enough to avoid unexpected resonance effects in the tuning mechanics. The finite-element computer simulation shows how to improve the tuning mechanism.

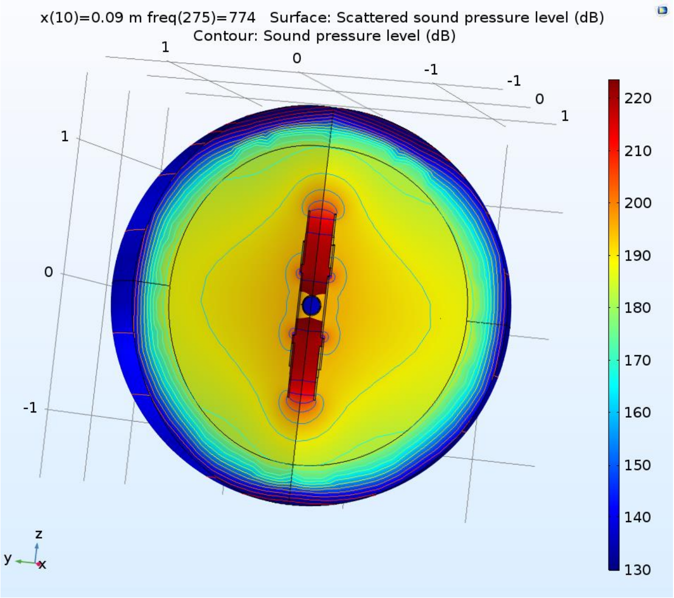


Fig. 2 The FEA simulation of the tunable organ pipe.

The source was designed and built as a scaled version of low-frequency 200-300 Hz Ocean Acoustic Tomography sound sources [15,16]. However direct scaling exposed a problem with the frequency response near frequencies of 700-800 Hz. The simulation and the test were pointing to the same problem.

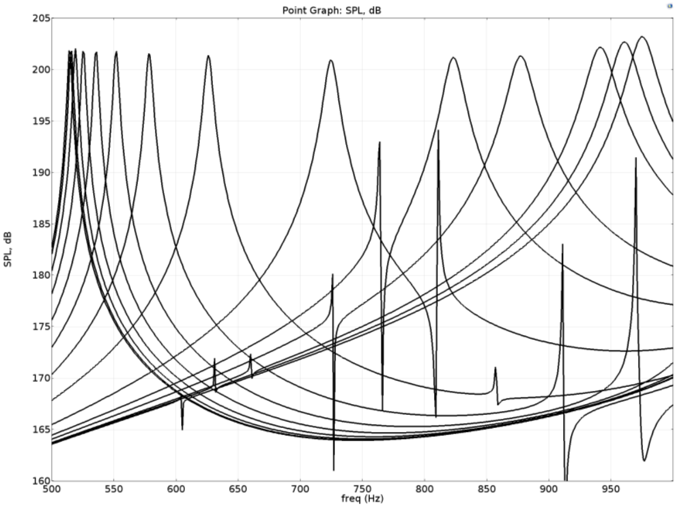


Fig. 3 Frequency response for different sleeve positions.

The general picture of the computer simulation is shown in Fig. 2. The 3D contour picture shows the absolute value of the sound pressure in Pa for the middle resonance frequency 774 Hz. At that position of the sleeve, the vents in the main resonator pipe just start opening and sound energy starts penetrating through the gap to the outside of the organ pipe. To avoid dual resonances at that position, when the vents start opening, in a low frequency design the sharp edges of the sleeve cylinder were rounded. In high frequency variant of resonator case it did not completely solve the problem. The resonance curves for different sleeve positions are shown in the Fig. 3. Each sleeve position is shifted one centimeter. At a 8 cm shift the resonant curve splits into two parts. The same deformation was seen in the experiment. The main pipe vibrations and the water under the sleeve were resonating and disturbing the main resonant curve. Experiment has shown that if the thickness of wall is increased twice that effect disappears, but the pipe becomes too heavy. The simulation is in good agreement with experiment and shows the same problem. After trying different variants of the design a solution was found: the gap between sleeve and main pipe must be only from one side of the orifice.

The improved design of the tunable mechanism is shown in the Fig. 4 and Fig. 5.

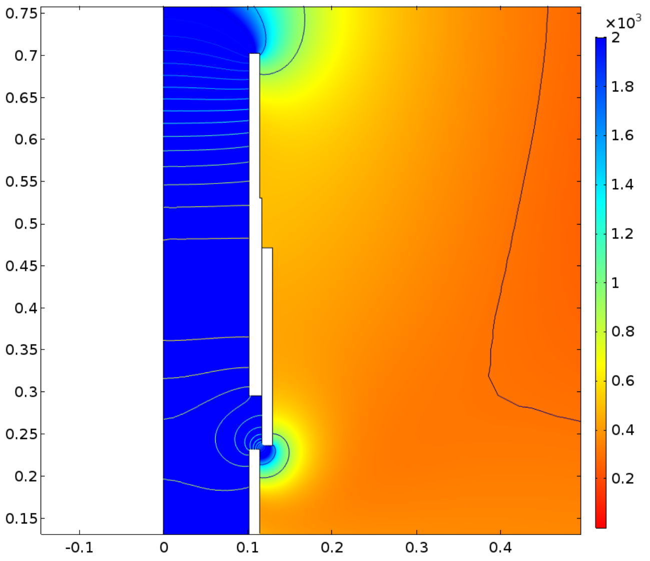


Fig. 4 Optimal frequency tuning mechanism

The sound pressure levels in dB for the improved design with are shown in the Fig. 5. The resonance curves are calculated for different positions of sleeve, shifted by an equal step of 1 cm. The frequency resonances are continually shifting from low frequencies to high frequencies. The resonance frequency curve became smooth over the band. The bandwidth increases with the resonance frequency and reaches its maximum at the end of the band. The amplitude of resonances is increasing by 3 dB at the end of the frequency band. The sound source tunes frequency in a range from 500 to 1000 Hz. The octave frequency band is the maximum that can be achieved by a tunable organ pipe, without interfering with the second mode of pipe.

The sound pressure level in dB for the starting frequency 500 Hz when the slots are completed closed and for the final frequency when the slots are opened is shown in a Fig. 6 and Fig. 7.

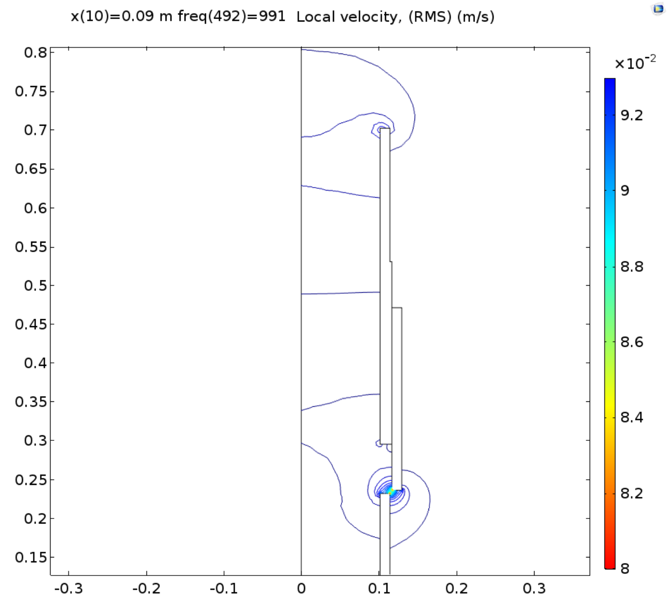


Fig. 5 Particle velocity in the opening frequency tuning mechanism.

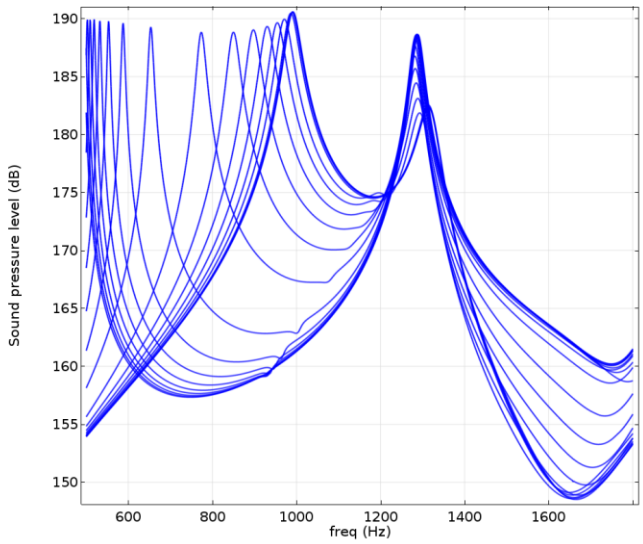


Fig. 5 Frequency response for different sleeve positions.

At the beginning of the frequency range at 500 Hz with completely closed tuning vents the pipe works as a half wavelength resonator and radiates though its main orifices. When the tuning vents start opening the sound source works like four element array and radiates from the main pipe orifices and through the opening vents. At the end of the frequency band at the maximum resonance frequency 1000 Hz the sound source radiates mostly through completely opened tuning vents. This explains why the frequency bandwidth increases with increasing resonance frequency. These transitions from one state to another are going smoothly without a sudden change of its frequency response. The directivity pattern remains approximately 90 degrees in the horizontal direction in all frequency ranges.

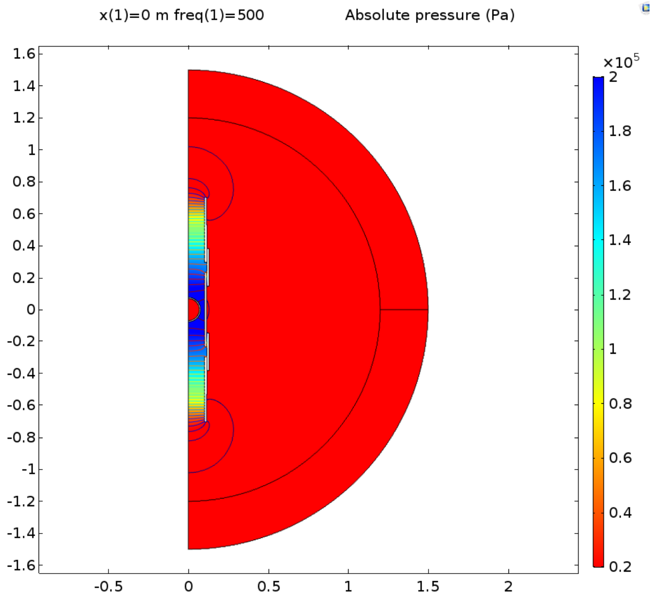


Fig. 6 Absolute sound pressure at 500 Hz.

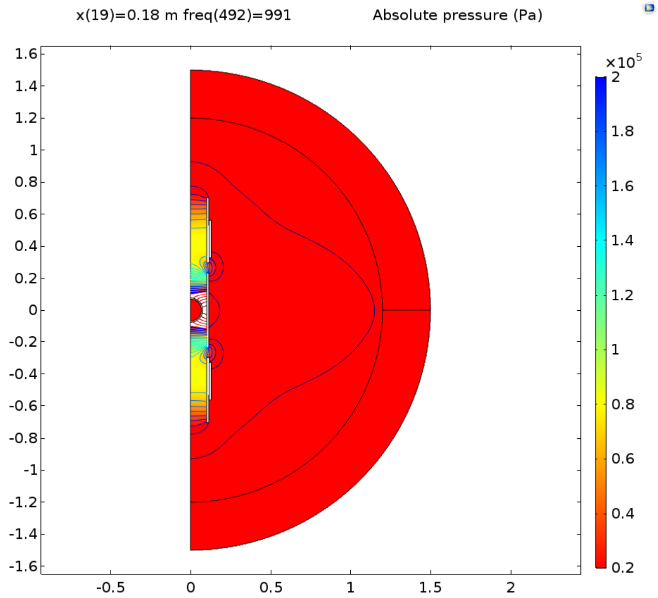


Fig. 7 Absolute sound pressure at 1000 Hz.

The high frequency variant of tunable sound source with the small sleeve and the proper driver will be able to sweep over a frequency range in a fraction of a second.

VI TESTS IN TELEDYNE SONAR TEST POOL AND WOODS HOLE OCEANOGRAPHIC INSTITUTION DOCK

The results of the simulation were used for experimental testing. The aluminum pipes were cut in exact accordance with the model and the sound source was tested in the Teledyne Benthos acoustic test pool. The results were similar to the simulation. The expected octave frequency range has been achieved. The resonant impedance has sharp high-Q shape continuously shifting from low frequency to maximum frequency in accordance with the position of the tuning sleeve. However the resonance frequencies was shifted to the lower frequencies. That effect can be explained by not perfectly round shape of the resonator pipe. The eleptical shape of the pipe makes it more compliant and decrease the resonant frequency. The limited dimention of the pool was another reason of the frequency shift. To get the precise sound source parameters the test was conducted in the Woods Hole Oceanographic Institution dock. The final adjustment was done by cutting the pipes. The final version of the sound source with complete set of control electronics is shown in the Fig 7. The sound source at Woods Hole test site is shown in the Figure 8.

Fig. 7 Sound source system.

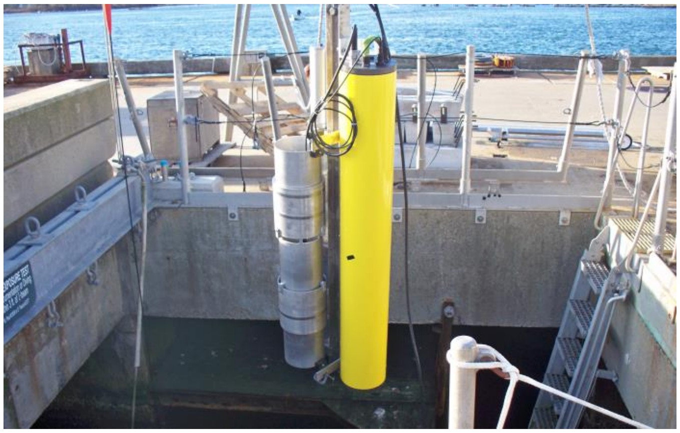
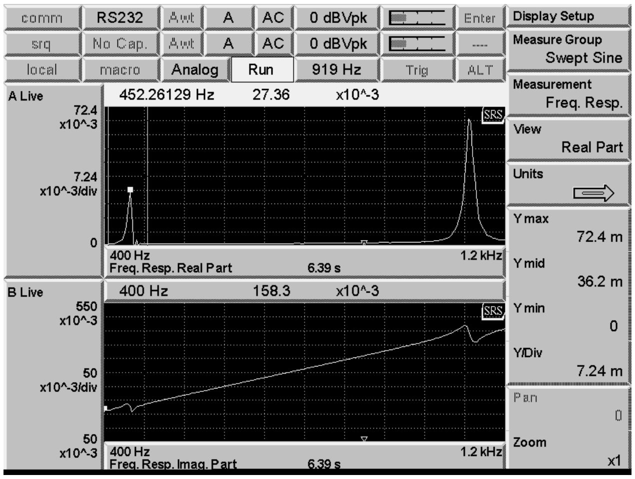


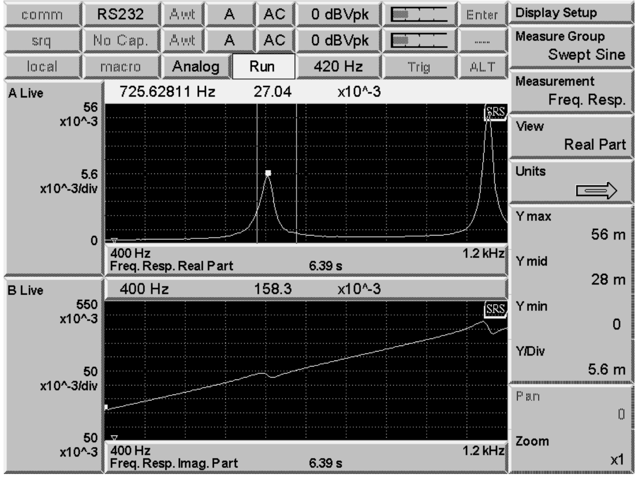
Fig. 8 Woods Hole Oceanographic Institution.

The experimental real and imaginary part of the admittance is presented in the Figure 9. Note that although the simulation is very efficient at predicting the resonance frequencies, the real Q-factor is smaller than in the model. Such a difference was expected at the beginning because real losses are hard to predict and real design varied slightly in detail from the model. A tunable resonant system usually needs a precise, complicated adjustment of its parameters to get the necessary frequency range. The octave frequence range was reached in that design for the first time only because of the COMSOL simulation. Application of the COMSOL finite element analysis allowed prediction of necessary parameters and avoid a long series of water tests with parameter adjustment. The parameters of the sound source prototype were reasonably close to the simulation.



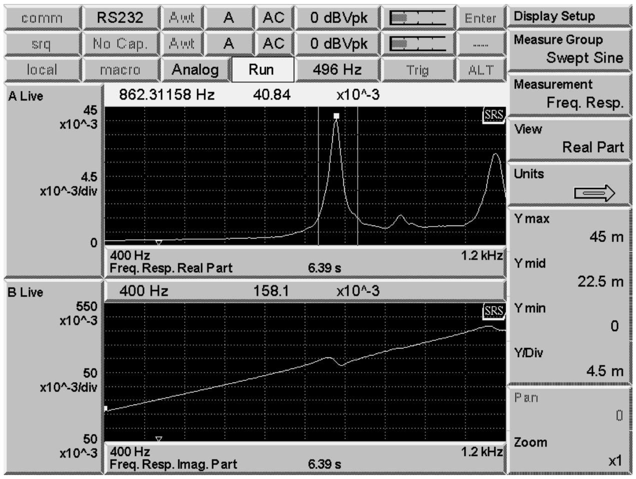
A Live 452.26129 Hz 27.36 x10^-3
Freq. Resp. Real Part 6.39 s
B Live 400 Hz 158.3 x10^-3
Freq. Resp. Imag. Part 6.39 s
Display Setup
Measure Group Swept Sine
Measurement Freq. Resp.
View Real Part
Units
Y max 72.4 m
Y mid 36.2 m
Y min 0
Y/Div 7.24 m
Pan 0
Zoom x1

a. Slots are closed completely.



A Live 725.62811 Hz 27.04 x10^-3
Freq. Resp. Real Part 6.39 s
B Live 400 Hz 158.3 x10^-3
Freq. Resp. Imag. Part 6.39 s
Display Setup
Measure Group Swept Sine
Measurement Freq. Resp.
View Real Part
Units
Y max 56 m
Y mid 28 m
Y min 0
Y/Div 5.6 m
Pan 0
Zoom x1

b. Slots are in the middle.



A Live 862.31158 Hz 40.84 x10^-3
Freq. Resp. Real Part 6.39 s
B Live 400 Hz 158.1 x10^-3
Freq. Resp. Imag. Part 6.39 s
Display Setup
Measure Group Swept Sine
Measurement Freq. Resp.
View Real Part
Units
Y max 45 m
Y mid 22.5 m
Y min 0
Y/Div 4.5 m
Pan 0
Zoom x1

c. Slots are opened

Fig. 9. The impedance of tested sound source prototype for different positions of the tuning sleeve (a,b,c).

CONCLUSIONS

Application of COMSOL finite element analysis helped design innovative tunable sound source for long-range sound propagation. Due to COMSOL simulation an octave frequency band has been reached. The parameters of the sound source prototype were reasonably close to the COMSOL simulations.

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