Modeling and Testing of Carbon-Fiber Doubly-Resonant Underwater Acoustic Transducer

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Abstract: This paper describes the design, the COMSOL simulation and the sea test of a deep-water, low-frequency (500Hz) sound source for long-range acoustic communications, navigation and ocean tomography. This design uses innovative carbon-fiber composite materials and a depth independent, oil-filled acoustic transducer. It makes the transducer very light, and it is operational to all ocean depths. To meet the demand for the frequency range the doubly resonant organ pipe resonator was suggested. A multi resonant system usually needs a precise, complicated adjustment of its parameters to get the necessary bandwidth, with limited variability of frequency response inside the frequency range. It can be even more complicated, when the design includes new, never tested, materials. 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 COMSOL simulations.

Keywords: Underwater sound source, resonator, doubly-resonant systems, low frequency transducer, long-range acoustic communications.

1. Introduction

Deepwater, low-frequency, broad-band sound projectors are used in sonar systems, ocean acoustic tomography, long-range communications, acoustic navigation, deep-towed seismic profiling and underwater acoustics research [8-11]. These applications require a moderate power source of sound covering a wide range of frequencies [1]–[6]. Some of these applications operate autonomously at great depths for a long period of time and need a highly efficient sound source. High-power, low-frequency sound can be transmitted by different means (pneumatic, electric spark, electromagnetic devices, etc. [3]). Free-flooding organ pipes are often employed as underwater sound projectors because their characteristics are practically depth independent.

Doubly resonant short tubes, or rings, in which the fundamental cavity mode is closely coupled to the ceramic ring mode, can deliver high acoustic power over a wide frequency band. Such sound sources are unacceptably large, heavy and expensive at frequencies below 1 kHz. Long tubes, or pipes, exhibit high-efficient sound radiation in a very narrow frequency band close to its resonant frequencies, but the output is usually negligible between these resonances. Shifting two resonances of organ pipe close to each other can potentially increase the response between resonances and enable a piezoelectric ceramic tube to be used over a much wider band of frequencies, while retaining the advantages of a high electrical-to-acoustical efficiency, a medium power output, and a small dependence from ocean depth. This method was proposed and published in [6]. The doubly resonant tubular system can be created by another approach by placing one pipe with a smaller diameter inside another pipe with a larger diameter and adjusting the coupling of two close resonance systems by shifting pipes along the axis relative to each other to meet demand for the frequency range [7]. The resonance system comprises an inner resonator tube with thin walls tuned to a certain frequency surrounded by a shorter, larger-diameter, lower frequency tuned outer resonator tube. The sound pressure emits by a standard, oil-filled, spherical piezo-ceramic depth independent transducer placed inside the inner pipe with a smaller diameter. The system includes only tubular parts and a standard spherical sound source, which are combined together by a rubber shock mounts. Application of composite carbon-fiber tubes makes the system very light and suitable for underwater communications with small unmanned underwater vehicles (UAV). This projector combines the efficiency and simplicity of resonant tube projectors with the possibility of using wide frequency ranges. The theoretical research of the doubly resonant tube projector, based on COMSOL numerical parameter simulation, and the results of the experimental testing of the prototype design are presented in this paper.

2. Doubly-Resonant Underwater Acoustic Transducer

This work focuses on the COMSOL finite element modeling of a new underwater sound source [7]. and the comparison of its results with an experimental test. The sound source was specially designed for long-range acoustic communications and potentially can be used for navigation of underwater gliders in the Arctic [8-11]. As was mentioned above, when the single-resonance organ-pipes do not provide sufficient bandwidth, a doubly resonant organ pipe provides transmission of arbitrary waveforms over a much wider frequency band. As with the single-resonance pipes, the sources can be used at all depths and are efficient and very light if built from composites. The doubly-resonant organ pipes comprise an inner resonator tube with thin walls tuned to a certain frequency surrounded by a larger-diameter tube. The projector is driven by a monopole acoustic source attached by shock-mounts inside the inner resonator. These resonating tubes are open on both ends and typically made of aluminium or carbon-fiber. The inner tube typically has much thinner walls to allow the sound pressure to spread into the outer tube. The tubes are asymmetrically shifted along the main axis and sound pressure can penetrate from the internal pipe though the area under the shifted external pipe into the external pipe and back. By changing the length of the shifted area, the coupling coefficient of the two resonators can be regulated to achieve the desired bandwidth. The resulting resonant frequency is proportional to the pipe length. The radiated power from the resonators is proportional to the area of the orifices and the square of the propagated frequencies. To achieve a symmetrical frequency response, the radiated power from both resonators should be approximately equal. The system can be expanded to the multi-resonance, multi-frequency case with multiple coaxial pipes coupled through the shifted areas. The preliminary experiments with a doubly-resonant sound source at the Woods Hole Oceanographic Institution have shown that it exhibits a high electro-acoustical efficiency and a high power output over a large operating band. The US patent is pending. The frequency response is very sensitive to the resonator parameters and the resonator needs to be tested in water and adjusted according to the testing results. It is time consuming, especially for a new design. The numerical simulation helps to predict the required parameters of the resonator and save time necessary for fine-tuning in the water. The sound source was designed and then simulated with finite element analysis. We used the COMSOL Multiphysics Acoustic-Structural Interaction module and made the simulation for an aluminum variant of the resonator. The prototype of an aluminum variant sound source was built and tested in an acoustic pool. The test results were very close to the simulation. Finally, we built the carbon fiber prototype with the stiffness of pipes close to the aluminum variant. The doubly-resonant sound source was tested in water at the Woods Hole Oceanographic Institution dock and it exhibited a high electro-acoustical efficiency and a high power output over a large operating band. The parameters of the sound source, after a little fine-tuning, were reasonably close to the COMSOL simulations.

3. Use of COMSOL Multiphysics

This section should contain a mathematical description of how COMSOL was used for sound source simulation. We used the COMSOL Multiphysics Acoustic-Piezoelectric Interaction module, Frequency Domain.

The geometry and model used a 2D axisymmetric (cylindrical) approach. The geometry of model is shown in Fig. 1.

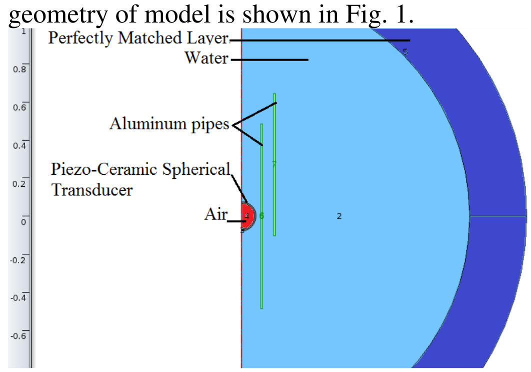

Figure 1. System geometry.

Here, we describe the design of first, aluminum variant of resonator. Aluminum pipes are shown in green, water in blue, piezo-ceramic spherical transducer in the center in grey, and air inside the sphere in light grey. The sound source was surrounded by a Perfectly Matched Layer sphere with a spherical wave propagation condition. The Acoustic Structure Boundaries are the surfaces of the spherical transducer and the aluminum pipes. The Electric Potential boundary condition, 100 V, was initiated on the external surface of the pieze-ceramic sphere. Simulated admittance of the transducer is shown in Figure 2. Sound pressure 1 meter from sound source (z = 0) is presented in Figure 3. The 2D sound pressure field is shown in Figure 4.

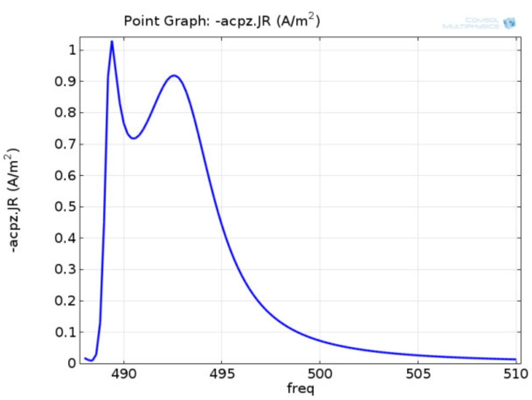

Figure 2. Admittance of the transducer.

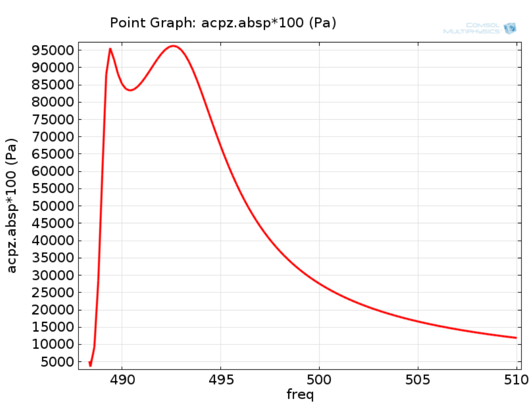

Figure 3. Sound pressure at the distance 1 meter from sound source axis.

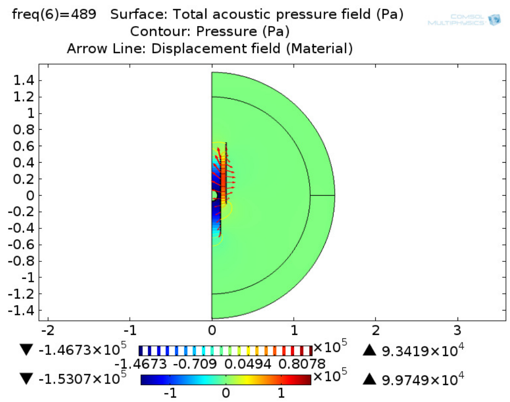

Figure 4. The 2D sound pressure field.

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. Two close resonances were found without any adjustment, and only a slight adjustment of shifting pipes along the axis relative to each other was necessary to obtain a good frequency response. The carbon fiber pipes were ordered with the radial stiffness similar to the aluminum prototype. Note that stiffness of the composite pipes in radial and axial directions can be modified by changing the angle of fiber winding relative to the pipes axis. Additionally, the hollow spherical transducer was replaced by an oil-filled pressure compensated transducer. The final variant of the fiber carbon sound source was tested in the Teledyne Benthos pool and then in the Woods Hole Oceanographic Institution dock. The final adjustment was done by cutting the pipes, which resulted in a small increase of the frequency band. Such an adjustment was necessary because of different pipe material and acoustical driver, which were similar to the initial simulation.

The final version of the sound source is shown in the Figure 5, 6 and 8.

The experimental real and imaginary part of the admittance is presented in the Figure 7. 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. As a result, the bandwidth of the real transducer is a larger than the simulated bandwidth.

Figure 5. The carbon-fiber variant of doubly resonant sound source.

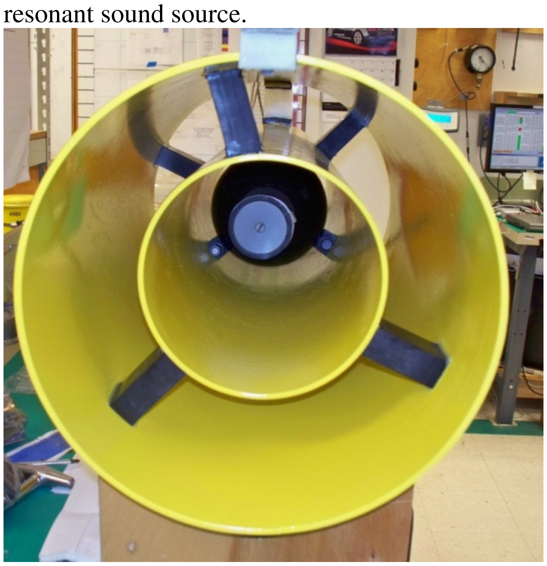

Figure 6. The internal view of the resonator.

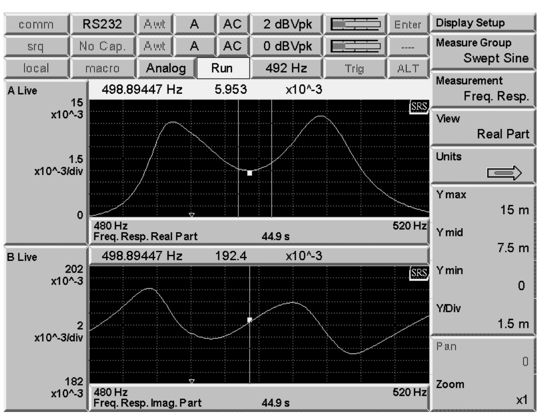

Figure 7. Real and imaginary part of the experimental admittance. (scale 0.019 = 1/32000 1/ohm).

Figure 8. The sound source at the WHOI dock.

The final version parameters of the low frequency sound source are shown in the Specification.

6. Conclusions

Central frequency	- 500 Hz,
Frequency bandwidth	- 30 Hz
SPL	- 185 dB
Weight in water	- 10 kg
Weight in air	- 21 kg
Dimensions:	
Central pipe i.d..	-203.2 mm
Length	- 951 mm
Wall thickness	-5.18 mm
External pipe i.d.	-355.6 mm
Length	-650.5 mm
Wall thickness	-6.05 mm
Shift between pipes	-98.425 mm

Maximum amplitude of driving signal 1500 rms.

7. Conclusions

Application of COMSOL finite element analysis helped design innovative carbon-fiber sound source for long-range sound propagation. The parameters of the sound source prototype were reasonably close to the COMSOL simulations.

8. References

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9. Acknowledgement

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