Low-frequency source for very long-range underwater communication

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***Abstract* - Long range underwater acoustic communication achievement is a decisive milestone for very long cruising AUVs deployment (>1,000 km). This paper describes a new kind of acoustic source designed and manufactured by iXBlue, the Janus-Hammer Bell (JHB) as shown in Figure 1, which was recently used in the at-sea experiments for long-range communication. The modem center frequency is 500 Hz, and its bandwidth 100 Hz. It provides a 200 dB (ref. 1 µPa @ 1 m) flat signal level spectrum with full immersion capability and is designed to be battery operated. This patented underwater acoustic source was exploited in a "passive time reversal" process. This method newly achieved long range communication at a rate of 100 bit/s at 1,000 km.**

***Keywords* - Janus-Hammer Bell; JHB ; long range communication; horizontal wave-guide propagation; time-reversal communication; piezoelectric ceramic stack; ring resonator; SOFAR**

I. INTRODUCTION

With increased processing capabilities and battery life, the use of unmanned or autonomous underwater vehicles and their cruise distances have grown significantly over the past decade. Areas of use include the oil and gas industry, mine countermeasure and geosciences.

The goal of the research performed was to design and realize a communication system for use over 1,000 km for future application with such a long cruising range type of AUV.

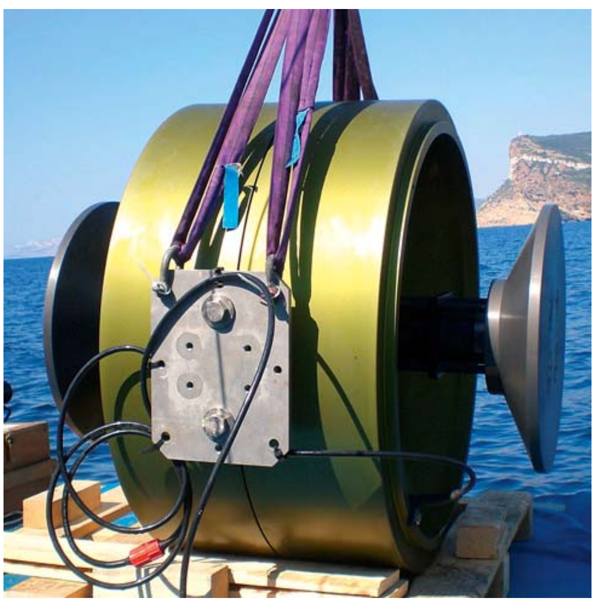

Figure 1: iXBlue SEABELL 500

Underwater acoustic communication is classified according to range as very long, long, medium, short and very short [2]. Table 1 summarizes the different communication classes.

	Range [km]	Bandwidth [kHz]
Very Long	>100	<1
Long	10-100	1-5
Medium	1-10	5-20
Short	0.1-1	20-50
Very Short	<0.1	>100

Table 1: Underwater acoustic communication classification

Very long-range underwater communication deals with low frequency horizontal wave-guide propagation in a highly dispersive medium, yielding high inter symbol interference (ISI) [3]. This difficulty is increased for very long-range communication with an AUV system because of the physical dimension of a low frequency source and the limited battery power available. It is even worse when cruising under the ice, which was one point of interest, as shown in Figure 2.

To overcome these difficulties, a single-input multiple-output (SIMO) communication method based on the passive time-reversal process [4] and [5] has been developed. In passive time-reversal, a probe signal and data signal are transmitted continuously from a source and received using a vertical array. These signals are cross-correlated and summed over the channels.

At-sea experiments have been carried out [6], [7] and [8] demonstrating communication performance up to 300 km. In addition, using data obtained by ocean acoustic tomography (OAT), the performance of time-reversal communication at ranges over 1,000 km has been predicted using a continuous source at 500 Hz [9].

To achieve such a range, a new kind of transducer, named Janus-Hammer Bell (JHB), has been designed for this specific need. The entire transmission chain has been developed by the Acoustics R&T group of iXBlue, based in La Ciotat, France, using an AUV transmission chain previously designed for a sub-bottom profiler (SBP). The modem center frequency is 500 Hz, and its bandwidth is 100 Hz. It provides a continuous 200

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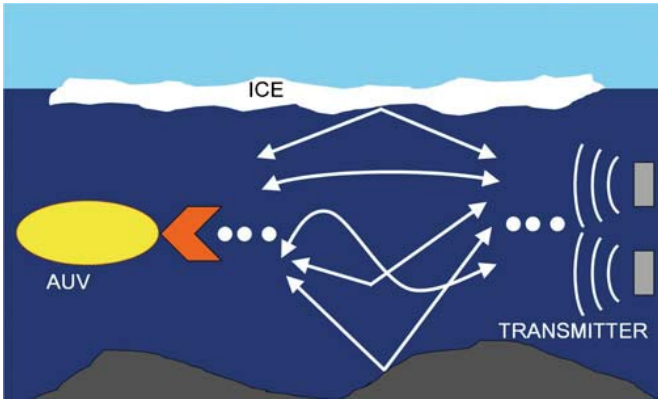

Figure 2: U/W long distance acoustic communication complexity

dB (ref.1µPa@1m) flat signal level spectrum with full immersion capability and was designed to operate by battery.

In this paper we first describe the JHB transducer analytic and finite element modeling. Then we present results from lake tests of the transducer alone and of the overall transmission chain. Finally, very long range passive time-reversal communication experiment and results are discussed, showing performance of 100 bit/s at 1,000 km.

II. JANUS-HAMMER BELL TRANSDUCER

In a previous project, in collaboration with IFREMER, France, iXBlue manufactured a sub-bottom profiler (ECHOES 5000) which was placed on an AUV by IFREMER [10], based on the principle of the Janus-Helmholtz (JH) transducer [11]. JH transducers are based on the coupling between a Janus ceramic stack and the Helmholtz resonance of fluid cavity (seawater or perfluorocarbon). These transducers have the advantage of broadband (100% of central frequency) and not being depth-limited. However, for the long-range AUV communication application, the Janus-Helmholtz transducer shows two main limitations. First, a 500 Hz Helmholtz resonance in a seawater cavity has large dimensions. Secondly, a ceramic stack resonating at 500 Hz exhibits a very low resistance at resonance, requiring an impedance matching with high self and resistance values. Such an adaptation generates losses in the transmission chain which is very problematic in the context of an AUV.

The Janus-Hammer Bell transducer principle is based on the coupling of the ring mode of two aluminum bells with the longitudinal mode of a Janus type piezoelectric ceramic stack. The ring modes are excited through seawater. This architecture benefits from the relative compactness of the 500Hz resonant aluminum ring. Indeed, according to [12], the radial resonance frequency of a ring of radius a, length L, thickness t, in a material with a speed of sound c and a density ρ and in a fluid with a density ρ0 is given by:

$$f_r = \frac{c}{2\pi a}\left(1+\frac{\rho_0\sqrt{\frac{aL}{2}}}{\rho t}\right)^{-1/2}$$

With a = 500 mm, L = 290 mm, t = 20 mm, ρ = 2700 kg/m^3, $\rho 0$ = 1020 kg/m^3 and c =5090m/s; the radial resonance frequency is 660 Hz.

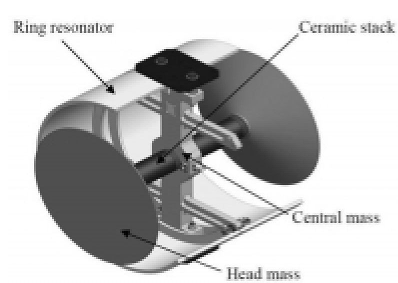

Figure 3: Schematic view of the JHB transducer

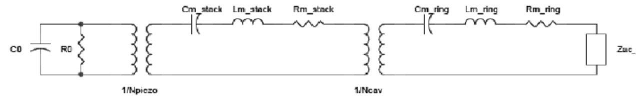

Figure 4: Lumped equivalent circuit of the JHB transducer

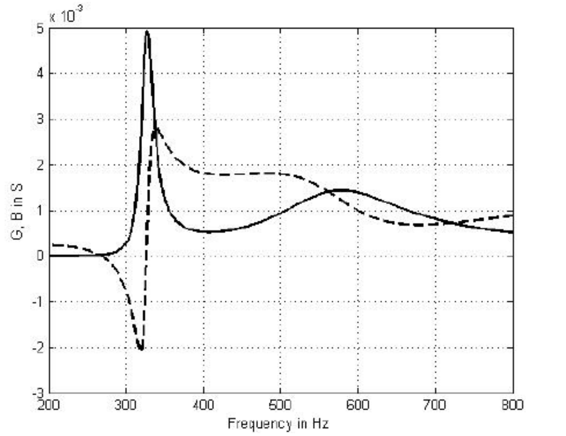

Figure 5: Typical simulated admittance in water (real part, fu line; imaginary part, dashed line)

This means that by exciting the ring mode through seawater with a Janus type ceramic stack of a resonance frequency close to 500 Hz, one can establish a coupling between the stack mode and the ring mode. Figure 3 shows the overall structure of the transducer.

Using the electromechanical analogy, a reasonably good approximation of the behavior of the JHB transducer is given by the lumped equivalent circuit shown in Figure 4. This analogy allows a first dimensioning of the transducer. In this circuit, C0 stands for the transducer clamped capacitance. R0 is the dielectric loss resistance. N_{piezo} is the electromechanical turn ratio. The two RLC motional branches describe Janus and ring resonances. N_{cav} is the coupling ratio between the two resonances. Finally, Z_{ac_rad} is the radial acoustical impedance of the rings. Response of the circuit has been implemented and typical real and imaginary parts of the admittance of the transducer are given in Figure 5, illustration the coupling between ceramic stack and ring resonances.

In order to finely model the transducer, finite element modeling was conducted using ATILA coupled with GID mesher (Figure 6). Once manufactured, the SEABELL 500 has a diameter of 1.1m, a height of 1.1m, a weight in air of 400kg and a weight in water of 250kg. Then, due to the very low frequency spectrum of the transducer, measurements were performed in the French Navy installation in the Castillon Lake, France. Figure 7 shows the measurements results for admittance and transmitting voltage response (TVR).

Those results show a good agreement between finite element modeling and measured results and an efficient coupling

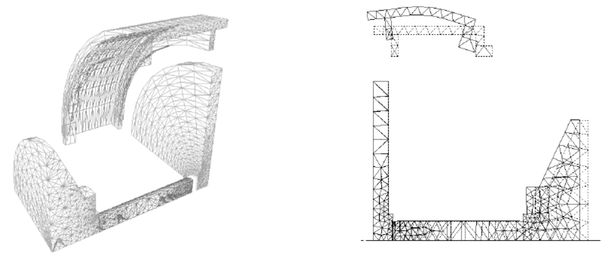

Figure 6: Meshing view of the Finite Element Model (right) and displaced structure (full lines) & rest structure (dashed lines), at 500 Hz (left)

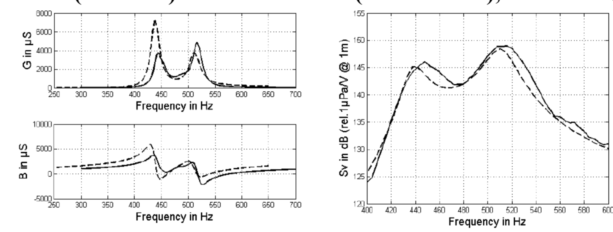

Figure 7: Admittance real part (top left), imaginary part (bottom left) and TVR (measured, full line; simulated, dashed line) (right)

between the Janus ceramic stack and the two aluminum rings through seawater cavity. The first resonance peak, showing the highest conductance value is less than 450 Hz, as required. The overall bandwidth of the transducer above 140 dB (ref. 1µPa/V @ 1m) is more than 20%.

Transducer overall dimension are: 1.1m diameter, 1.1m height, weight in air and water are 400 kg and 250 kg respectively.

III. LONG RANGE COMMUNICATION SYSTEM & EXPERIMENT

The overall communication system chain is designed in order to achieve a source level higher than 197 dB (ref. 1µPa/V @ 1 m) on the useful bandwidth of 450-550 Hz at full power. Coupled with the impedance matching stage, a stage of compensation has been designed specifically in order to achieve minimum source level variation on the useful bandwidth.

For communication purposes, the acoustic source has to be omni-directional in the horizontal plane, which is fulfilled through the construction of the transducer. More important is the elevation aperture of the acoustic beam. On the assumption that the exact position of the AUV is unknown, a wide aperture in elevation is preferred (Figure 8). This was achieved successfully.

The acoustic source is designed to be integrated in an AUV later on and powered by a battery (fuel cell). Thus the overall system design has been devoted to obtaining a 65% electro-acoustic efficiency (Figure 9).

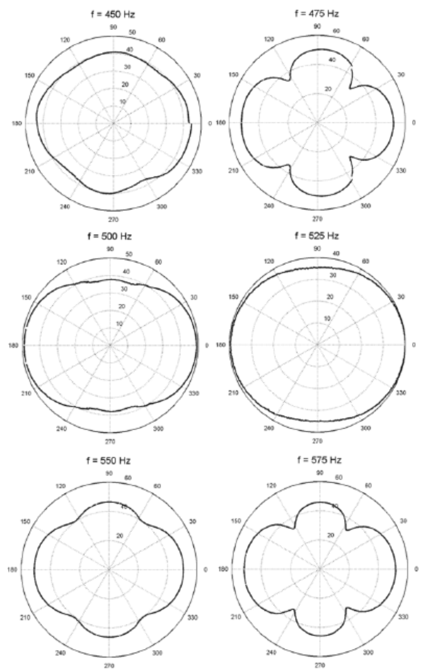

Figure 8: Acoustic source directivity at different frequencies

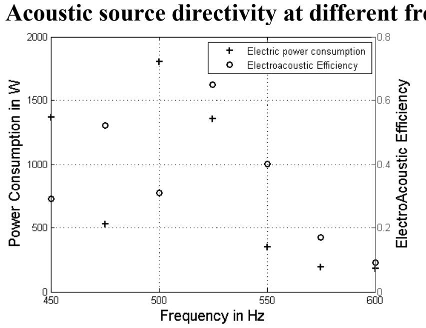

Figure 9: Electric power consumption of the system (cross dot) and Electro-acoustic efficiency (circle dot)

The experiment site had depths of approximately 4,000 m to 5,000 m. The measurement of communication was executed on the line between two points (A & B) at a range of 1,000 km. The sound velocity profiles were measured at both locations.

In this experiment, a 20-channel receiver array was moored at point A and the SEABELL 500 source was moored at point B. Both of them were at a depth of 1,000 m, around the axis of the SOFAR channel.

The signals after chirp correlation received at the array and show that many multipath signals were received. Two methods were tested: ‘TR' - when only time reversal is used and ‘TR+AE' in which time reversal and adaptive equalization were combined. From experiment results, it has been proved that the proposed method, TR+AE, makes communication possible at a range of 1,000 km with no bit errors.

IV. CONCLUSION

We have introduced an original type of transducer, the Janus-Hammer Bell, also known as the SEABELL 500, which has remarkable properties in terms of electro-acoustic efficiency and compactness, with regard to the low transmitted frequency. It is therefore an excellent solution for very long-range acoustic communication with a long cruise distance AUV. Results of modeling and in-lake tests were presented and a very-long range communication was reported. A data rate of 100 bit/s over 1000 km range has been achieved.

After this successful test, a second system has been manufactured by iXBlue and is under operation for further long distance communication experimentation, opening new horizons for long cruise distance AUV development. This new type of transducer could also be used for acoustic tomography and as a seismic source for sub-bottom profiling.

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