Environmental Impact of Underwater Noise: sound pressure and particle velocity

Angelo Farina
Department of Engineering and Architecture
University of Parma, ITALY
farina@unipr.it

Abstract
This paper focuses on the importance of employing also measurements of sound particle velocity, and not just sound pressure, when assessing the environmental impact of underwater noise. This is due to the fact that most marine species are equipped with water movement sensors, not sound pressure sensors, which instead are typical of mammals and birds.

INTRODUCTION

In the last few years, the importance of assessing the environmental impact caused by underwater noise generated by human activities has grown significantly, mainly due to the effect that has been found on the fishery industry and on the depauperation of marine protected areas.

A large number of surveys have been conducted, on one side, and laboratory and field tests for evaluating the effect of noise on marine species have been performed.

However, in most cases, the only physical quantity being measured is a scalar quantity, the sound pressure in Pa, and the vectorial and kinematic nature of the sound field is substantially neglected. This despite there is strong experimental evidence that most marine species do not have sound-pressure sensors, and instead are equipped with sensorial systems capable of detecting mostly kinematic quantities such as water particle velocity or water particle acceleration.

This paper begins with a recall from the fundamentals of acoustics, and the relationship between sound pressure and particle velocity. Unfortunately most acousticians, working either in air or underwater, seem to have forgotten these basic concepts, and assume that particle velocity is just proportional to sound pressure, which in general is absolutely false.

The paper continues with the description of methods for recording the sound pressure and particle velocity signals, on one side, and on methods of reproducing an artificial sound field inside an enclosure, where sound pressure and particle velocity can be controlled independently, on the other side.

Applications are shown in the case of noise pollution surveys (using special hydrophone arrays) and for laboratory tests on marine species (using underwater loudspeaker systems), employing in both cases the old (and almost completely forgotten) theory known as Ambisonics, developed in the seventies in UK for completely different applications (music recording and playback).

The conclusion is that, when assessing the level and the potential environmental impact of underwater noise, it is wrong to specify values and limits just as SPL (Sound Pressure Level): it is also necessary to evaluate the PVL (Particle Velocity Level) values, which in general must be subjected to limits different than the SPL limits.

Finally, the problem of the frequency weighting is also explored: in fact the sensitivity of different species to underwater noise changes dramatically with frequency, but, even for the same species, the sensitivity curve can be different for sound pressure and for particle velocity.

PRESSURE AND VELOCITY: BACK TO THEORY

At the beginning of every Acoustics course, one lesson is devoted to explaining the physical quantities involved in sound generation, propagation and perception.

Here the dual nature of sound is first encountered, and the dualism between sound pressure and particle velocity is usually presented as a cause-effect relationship: a body is vibrating with a given velocity, and this causes pressure fluctuations in the fluid in contact with it, which propagate in the whole medium as acoustical waves. At the receiver, the relevant quantity is the sound pressure, as humans are equipped with eardrums, which are basically pressure transducers.

The most simple case is a plane, progressive wave originated inside an infinitely-long duct by a vibrating piston, and typically this is presented as in fig. 1.

Such a scheme depicts a very unusual case, as the motion of air particle obeys to the same law imposed by the moving piston everywhere along the duct. Furthermore, in such a very simple scheme, the sound does not attenuate during the propagation, and sound pressure fluctuations are always in-phase with particle velocity fluctuations.

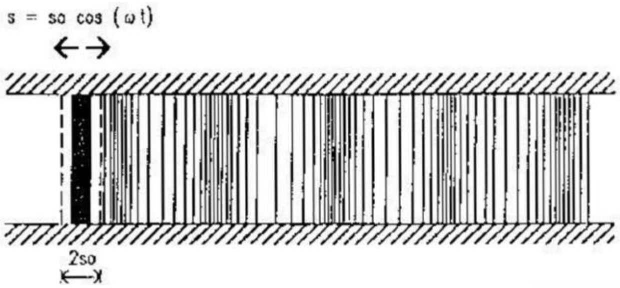

FIGURE 1. PLANE PROGRESSIVE WAVE INSIDE A DUCT

Such a simple case is analogue to an electric circuit made just of a resistor, where an AC current source is applied. In such analogy, current can be thought as analogue to particle velocity (the cause of the phenomenon) and voltage is the analogue of sound pressure (the effect).

The resistor is a very simple circuit, which maintains voltage and current in phase and linearly proportional.

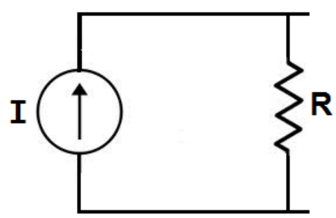

FIGURE 2. A VERY SIMPLE PURELY RESISTIVE AC CIRCUIT

For the acoustical case, the linear proportionality between particle velocity and sound pressure of a plane progressive wave is given by:

$$\frac{p}{v} = z = const \qquad (1)$$

Where z is the characteristic acoustic impedance of the fluid, given by the product of its density ρ and the speed of sound c:

$$z = \rho \cdot c \qquad (2)$$

In the case of the electric circuit of fig. 2, the proportionality between voltage V and current I is given by:

$$\frac{V}{I} = R = const \qquad (3)$$

However, it is obvious that in general an electric circuit is much more complex than a simple resistor, hence in general the above relationship is not valid anymore, and the ration between Voltage V and current I applied to a load is all but constant, and often becomes a complex quantity, meaning that the voltage and current are not anymore in phase. The V/I ratio is called electrical impedance Z, and big effort is employed for analyzing how it varies depending on space, time and frequency.

The same occurs obviously also in acoustics, hence generally speaking the acoustic impedance z is a complex quantity, changing with space, time and frequency.

Despite this obvious fact, most acousticians seem to forget this, and compute particle velocity always according to eq. (1) and (2), as if the sound field was a plane progressive wave inside a duct. In most real cases, and in particular in the underwater sound field occurring close the coast line, the sound field is very far from this theoretical model, hence the value of particle velocity becomes a quantity which is substantially independent from sound pressure. The value of acoustical impedance becomes very high against large, hard surfaces, and oppositely it becomes very small at entrance of small caverns, which act as a Venturi, significantly boosting the particle velocity amplitude.

Another fact which must be taken into account, and is not properly exploited by the “plane wave in a duct” example, is the vectorial nature of the particle velocity. Sound pressure is a scalar quantity, hence it does not carry any directional information. A pressure microphone, or a pressure hydrophone, is “omnidirectional” by definition.

Instead a particle velocity sensor is generally sensitivity also to direction-of-arrival of the sound wave, and for detecting the complete particle velocity vector one needs to employ three orthogonal velocity sensors. Each velocity sensor has a “figure of 8” polar pattern of sensitivity, and one of the two lobes has negative (reversed) polarity compared with the polarity of a pressure sensor (which typically is assumed positive when the instantaneous sound pressure is above the average pressure of the fluid).

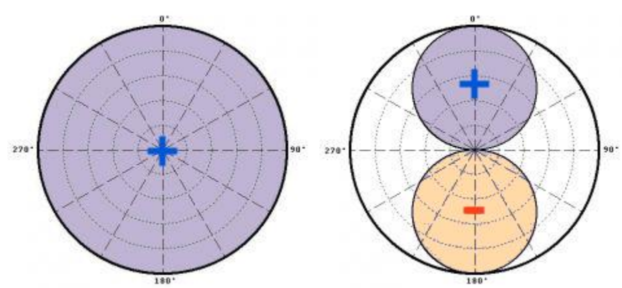

FIGURE 3. POLAR PATTERN OF A PRESSURE SENSOR (LEFT) AND OF A PARTICLE VELOCITY SENSOR (RIGHT)

This change of polarity allows for understanding also the versus of propagation of the sound wave, by comparing the polarity of the velocity component with the polarity of the pressure component.

In conclusion, the complete knowledge of the physical quantities necessary to fully describe the sound field in a point in space requires to detect 4 independent signals: the sound pressure p and the three Cartesian components of the particle velocity vector, v_x, v_y and v_z.

As in a generic electrical circuit, in any point, the knowledge of voltage does not mean knowing also the current, similarly in a generic sound field knowing the sound pressure does not means knowing also the particle velocity. Hence a 4-sensors (4 channels) pressure-velocity probe is required for capturing what's happening in a point of a sound field.

It must be remembered, however, that physics imposes some constraints between the spatial variation of sound pressure and the temporal variation of particle velocity, expressed by the well known Euler's equation:

$$grad(p) = \rho \cdot \frac{\partial v}{\partial \tau} \tag{4}$$

This opens the possibility to employ an array of pressure sensors, sampling the spatial variation of sound pressure, for computing the particle velocity signals, as explained in the following chapter. Coming back with comparison with electric circuits, this is the same as employing a small shunt resistor and measuring voltage difference at its two terminals for inferring the value of current flowing through it.

AMBISONICS AND THE SOUNDFIELD MICROPHONE

Back in the seventies, an almost-unknown British scientist, named Michael Gerzon, developed a complex theory for describing, recording and reproducing a three-dimensional sound field, known as Ambisonics [1,2].

It was the first successful attempt allowing for recording and reproducing a realistic three-dimensional sound field. The method was based on decomposing the sound field in a number of signals, employing a spherical harmonic decomposition of the spatial information. A detailed spatial analysis is possible using high order expansions, as required for creating detailed spatial maps of sound distribution, employed for example in modern "acoustic camera" systems or passive sonar systems.

Of course in the seventies this was not possible yet, hence the spherical harmonics expansion was limited to order 0 and 1. Michel Gerzon developed (and patented, together with Peter Craven) a compact microphone array capable of producing the 4 signals corresponding to this spherical harmonics expansion, called Soundfield Microphone [3].

The raw signals coming from the sensors (A-format) are processed for getting the required spherical harmonics signals (B-format).

The following figures show the polar patterns of the 4 "virtual microphones", a.k.a. B-format signals, obtained processing the A-format signals coming from a Soundfield microphone, and a photo of Michael Gerzon with the very first prototype of the Soundfield microphone array.

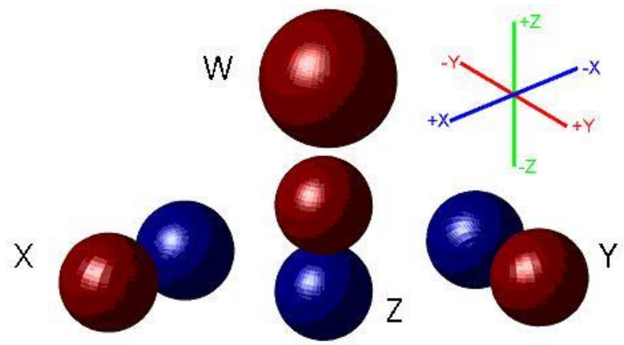

FIGURE 4. POLAR PATTERNS OF B-FORMAT SIGNALS

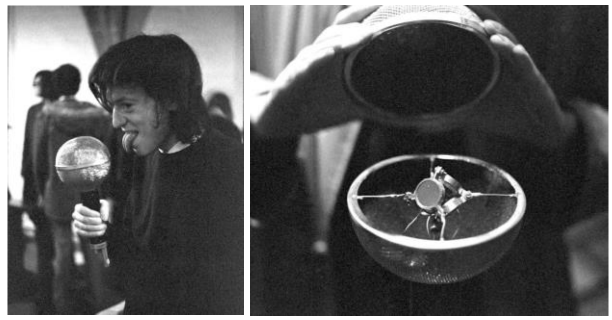

FIGURE 5. MICHAEL GERZON AND THE FIRST SOUNDFIELD

Looking at the polar patterns in fig. 4, it is clear that the signal called W is in reality the sound pressure signal, and the signals called X,Y,Z are the three Cartesian components of the particle velocity signal. Hence the Soundfield was the first pressure-velocity 3D probe.

The tricky job is, of course, to process in real time the signals coming from the 4 transducers for deriving the 4 output signals, avoiding a number of problems related to signal-to-noise ratio at low frequency and distortion of the polar patterns at high frequency.

The analog circuitry developed in the seventies by Gerzon and Craven was performing quite badly, and this was one the main causes of the commercial failure of Ambisonics. Which in turn caused also the fact that this approach, which in reality is very promising, never migrated to fields such as acoustic intensity measurements (in air) or underwater noise assessment (which is the application presented in this paper).

Of course Ambisonics and the Soundfield microphone were not the only attempt to record the particle velocity signals. Other attempted to use geophones [4], hot wire differential anemometers [5] and Laser Doppler velocimeters [6]. But none of these approaches resulted to be robust and reliable enough for being used outside scientific laboratories.

Nowadays Ambisonics is seeing a new wave of success, thanks to better A-format to B-format conversion made possible employing a matrix of long digital FIR filters instead of analog circuitry [7], and to the availability of massive spherical microphone arrays, such as the Eigenmike-32™, which allows for higher-order spherical harmonics expansion, providing much sharper spatial information.

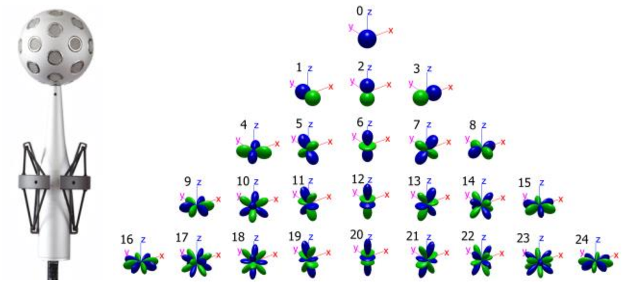

FIGURE 6. EIGENMIKE AND SPHERICAL HARMONICS UP TO 4^{TH} ORDER

The last point to be remembered about Ambisonics is that it is not just a technique for recording (sampling) the sound field in a point: it also allows for reproducing the recorded spatial sound field employing either a three-dimensional array of loudspeakers or a pair of headphones.

Whilst headphones reproduction is of little usefulness for studies on the impact of noise on marine species, the capabilities of employing proper transducer arrays for controlling independently the sound pressure field and the particle velocity field inside a volume of fluid are of paramount importance for analyzing the behavioral response of marine animals both in captivity and in the field.

AMBISONICS UNDERWATER

The first attempts of employing the Ambisonics technology underwater date back to 2009 [8]. An underwater Soundfield-like tetrahedral hydrophone array was built, calibrated and tested for evaluating noise pollution inside a Marine Protected Area [9].

Fig. 7 shows the hydrophone array.

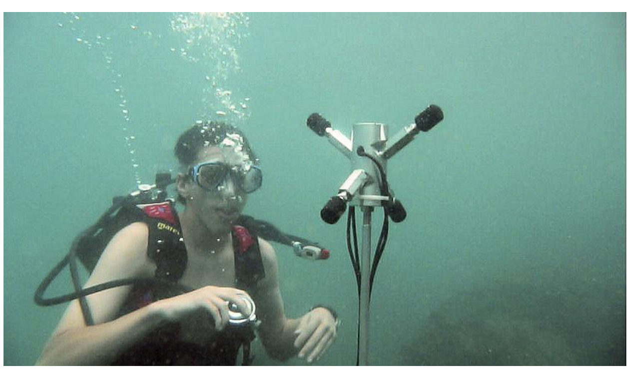

FIGURE 7. TETRAHEDRICAL HYDROPHONE ARRAY

The conversion from A-format (the 4 raw signals coming from the hydrophones and recorded on a waterproof-encased compact digital Zoom H2N sound recorder) and B-format (the 4 signals expressing sound pressure and Cartesian components of particle velocity) was performed employing a matrix of 4x4 FIR filters (4096-points long at 48 kHz sampling frequency):

$$\begin{aligned} W &= p_1 * f_{1w} + p_2 * f_{2w} + p_3 * f_{3w} + p_4 * f_{4w} \\ X &= p_1 * f_{1x} + p_2 * f_{2x} + p_3 * f_{3x} + p_4 * f_{4x} \\ Y &= p_1 * f_{1y} + p_2 * f_{2y} + p_3 * f_{3y} + p_4 * f_{4y} \\ Z &= p_1 * f_{1z} + p_2 * f_{2z} + p_3 * f_{3z} + p_4 * f_{4z} \end{aligned} \qquad (5)$$

The filter matrix F (in frequency domain) is computed employing the "virtual microphone" approach described in [10], based on a number of anechoic impulse response measurements C obtained with different direction-of-arrival of the sound over the hydrophone array:

$$F = \frac{C^* \cdot T \cdot e^{-j\pi k}}{C^* \cdot C + \beta \cdot I} \qquad (6)$$

Where T is the target directivity pattern (a positive or negative gain depending just on direction-of-arrival and not on frequency, and describing the polar patterns of fig. 4), k is the wave number (ω/c) and β is a small positive number (regularization parameter), which can be made frequency dependent [11] for better performances in the frequency range where the hydrophone spacing is optimal.

This measurement-based, theory-less approach has a number of advantages, for example it automatically compensates for the phase-magnitude difference between transducers, for the acoustical reflection-diffraction-shielding of the mechanical system supporting the transducers, and by adjusting β it allows to keep under control the low frequency noise boost which inherently comes from the integration operation required for solving Euler's equation (4).

After the 4 components of the spherical harmonics expansion are found, they can be used mainly for two purposes:

1) Evaluating the instantaneous or averaged spectrum of Sound Pressure Level and Particle Velocity Level
2) Based on the vectorial information, tracing the position of the noise source over time (typically the trajectory of a boat passing nearby)

Fig. 8 shows an example of the 1/3 octave-bands averaged spectrum of SPL and PVL measured inside a marine protected area during the passage of a boat at less than one mile:

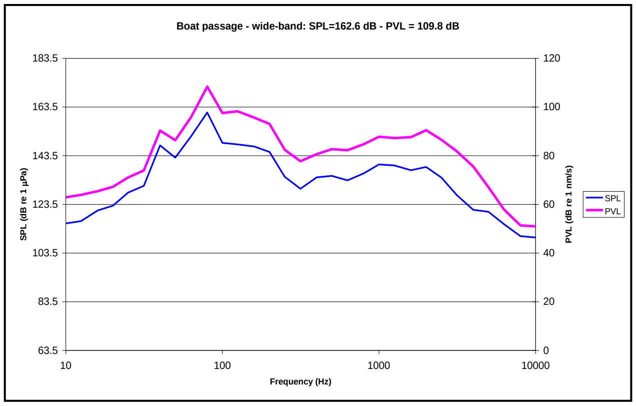

FIGURE 8. SPL AND PVL SPECTRA OF A BOAT PASSAGE

It must be noticed that in underwater acoustics SPL and PVL numbers are very different. Whilst in air the reference quantities for constructing the dB scale are chosen so that, in normal conditions, for a plane, progressive wave we get SPL = PVL, instead in underwater acoustics the reference values are respectively 1 μPa for sound pressure and 1nm/s for particle velocity. These values are not fully standardized yet, but are commonly employed [12].

With this choice of reference values, assuming a typical value of water impedance of 1.500.000 Rayls, the SPL of a plane, progressive wave is 63.5 dB larger than the PVL. Hence the dB scales of fig.8 are offset by this amount. If the sound field had been a plane, progressive wave, the two spectra should be superposed. Instead fig. 8 shows that, at the measurement position (shallow water close to the coast line) the Venturi effect is boosting significantly the PVL.

An environmental assessment based on "traditional" conversion of SPL into PVL, employing the plane-wave assumption, had resulted in a systematic underestimation of the underwater noise velocity signal.

For tracing the instantaneous position of the sound source, the pressure and velocity signals are combined, computing short-term time averages of the Sound Intensity vector:

$$\vec{I} = p \cdot \vec{v} \tag{7}$$

And of the Energy Density (scalar quantity):

$$E_d = \frac{1}{2 \cdot c} \cdot \left[\frac{p^2}{z} + z \cdot |v|^2 \right] \tag{8}$$

The ratio $I/(E_d \cdot c)$ provides a number (called r_E by Michael Gerzon), bounded between 0 and 1, which expresses how much the sound field is close to the plane-progressive wave (r_E=1) or is fully reactive (standing waves, r_E=0). A reliable estimation of the position of the sound source is possible only when this number is above 0.5, meaning that there is a dominant sound source. When r_E is less than 0.5, it means that the sound field is mostly diffuse, and no dominant sound source can be located.

In the following figure, a number of source-position estimates obtained with the Sound Intensity vector method is charted, in comparison with the GPS track of the real trajectory of the boat, which was passing close to the underwater tetrahedral hydrophone array.

The diameter of each circle is proportional to r_E.

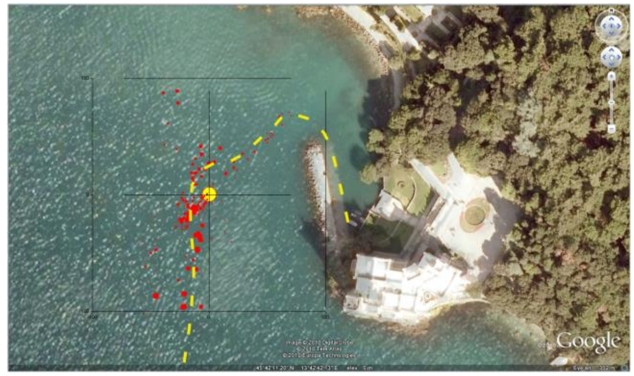

FIGURE 9. ESTIMATION OF BOAT TRAJECTORY

Of course, being an Ambisonics detector limited to first-order spherical harmonics, the capability of locating accurately the source position is still quite coarse. Better results are possibly obtainable with higher-order Ambisonics hydrophone arrays, employing a larger number of sensors and output channels.

HIGH ORDER AMBISONICS UNDERWATER

As it has been done successfully in air with the Eigenmike™, also in underwater acoustics it is possible to extend the spatial analysis employing an expansion of the sound field in spherical harmonics up to higher orders.

This of course is possible only increasing the spatial sampling, employing a larger number of hydrophones.

Albeit in theory nothing prevents to build an "underwater Eigenmike" with 32 hydrophones, currently we have built just an array equipped with 12 hydrophones, which allows to extract 9 spherical harmonics signals (orders 0, 1 and 2), as shown in fig. 10.

The step from 1st to 2nd order Ambisonics, indeed, provides a significant improvement in the capability of source localization, and allows for much less noise and more stable polar patterns for the particle velocity signals, resulting in smaller measurement errors of the first-order components.

The problem with this 12-hydrophones array comes from the fact that currently on the market a compact, battery-operated digital sound recorder equipped with 12 microphone inputs is not yet available.

Hence this hydrophone array must be operated with long cables going on the boat, where a professional multichannel digital sound recorder can be employed.

FIGURE 10. A SPHERICAL HYDROPHONE ARRAY WITH 12 SENSORS ON THE SURFACE OF A SPHERE

Also in this case the conversion from the 12 hydrophone raw signals to the 9 spherical harmonics signals is done employing a 12x9 FIR filter matrix, computed with the same approach described for the first-order array in previous chapter.

Due to the much larger number of computations required, the filtering can be performed in realtime only employing a very special software, called X-volver [13].

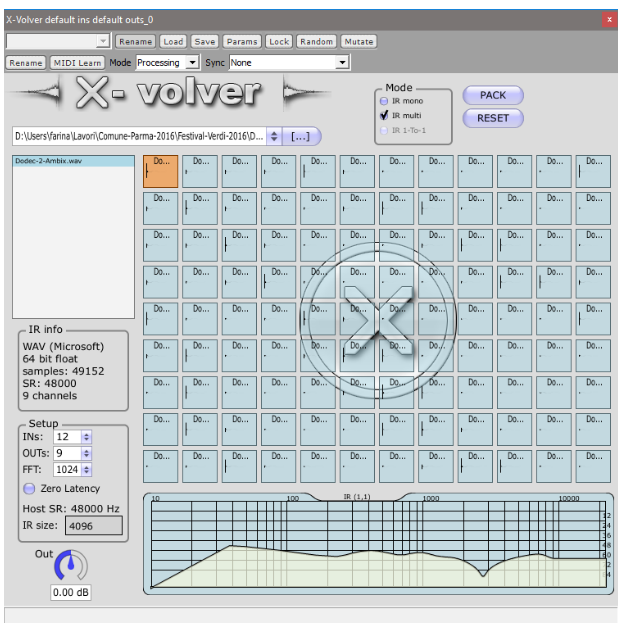

FIGURE 11. X-VOLVER (MATRIX CONVOLUTION PLUGIN)

The second-order hydrophone probe has just been built and has not yet be tested underwater at time of writing, but its debut is planned for March 2008 at MaRHE (the Marine Research and High Education center of University Milano Bicocca, located at Magoodhoo, Maldives), where both calibration measurements and experiments of noise pollution assessment are planned.

A panoramic camera system will be mounted on top of the array, as shown in fig. 12. This will make it possible to get a complete visual display of what happens around the probe, and also to use the recordings in immersive audio-video rendering systems, such as "cave" projection rooms equipped with Ambisonics loudspeaker arrays [14] or personal Head Mounted Display devices equipped with headphones (Oculus Rift, HTC Vive, Samsung Gear VR, Samsung Odyssey, etc.), as shown in fig. 13.

FIGURE 12. UNDERWATER PANORAMIC CAMERA AND RESULTING EQUIRECTANGULAR VIDEO

FIGURE 13. USING AN HMD FOR AUDIO-VISUAL RENDERING OF UNDERWATER RECORDINGS

SENSITIVITY OF MARINE SPECIES TO PRESSURE AND VELOCITY

Only very recently the need of recording particle velocity (or particle acceleration) for assessing the effect of noise on marine species has been recognized by the scientific community.

Here we reproduce a short passage coming from the recent paper of Sophie L. Nedelec and others [12]:

"Audiometric studies have long recognized the significance of particle-motion detection in fishes and invertebrates (e.g. Chapman & Hawkins 1973; Fay 1984; Popper, Salmon & Horch 2001), yet investigations of

acoustic phenomena in the ecology of aquatic systems have previously focused on only one component of the sound field: sound pressure (see for exception Banner 1968; Sigray & Andersson 2011).

From an ecological perspective, there are several key reasons why we need to better understand the particle-motion component of underwater sound. First, while aquatic mammals use sound pressure, all fish and many invertebrates (i.e. most acoustically receptive aquatic organisms) detect and use the particle-motion component of sound (Popper, Salmon & Horch 2001; Bleckmann 2004; Kaifu, Akamatsu & Segawa 2008)."

As we did already find that the values of PVL can be significantly larger than the corresponding values of SPL, we can argue that in most studies of environmental noise pollution the usage of measurements limited to sound pressure caused a systematic underestimation of the potential impact of noise.

Another case where the evaluation of the particle velocity field could have been provided deeper understanding is the analysis of the acoustic effects of shelters and other nests employed by fishes. It had been suggested that some species of fishes choose shelters due to their acoustical amplification capabilities [15, 16]. But these amplification capabilities were assessed only in terms of sound pressure, not in terms of particle velocity, which probably is boosted much more at the entrance of a cavity, which acts as an Helmoltz resonator.

Finally, also the evaluation of the sensitivity of marine species to noise could have been strongly biased by ignoring their sensitivity to particle velocity.

In facts, experiments for determining the sensitivity of fish and invertebrates to noise have often been performed in captivity, using water tanks equipped with a single underwater loudspeaker for generating the test sound, and then evaluating the behavioral response of the species under study.

A single sound source inside a small tank drives the acoustic pressure quite linearly, but does not excite properly the particle velocity field, as the cavity is smaller than the wavelength, and hence reacts as a "pressure driven" cavity. This means that, when defining the threshold of sound level causing reactions from the marine species, the annotated value is that of sound pressure, and the particle velocity level is instead probably much smaller, and definitely unknown.

This sheds a deep shadow on most studies performed under such badly-controlled conditions.

A comprehensive analysis of known literature regarding fish sensitivity to noise is found in a report of the U.S. Department of the Interior, published in 2014 [17]. The following figure, duplicated from this public report, summarizes the known information coming from such "controlled" experiments:

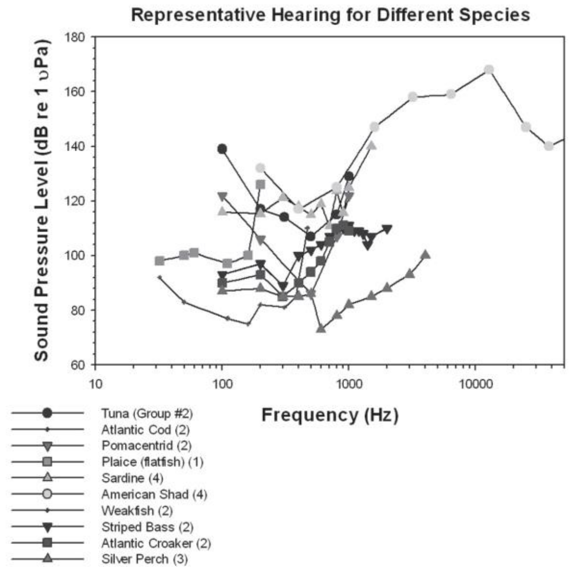

FIGURE 14. HEARING THRESHOLD FOR A NUMBER OF MARINE SPECIES

It must be noted that, invariantly, the hearing threshold of marine species is expressed in terms of Sound Pressure Level, instead of Particle Velocity Level, which was generally unknown during the experiments, as no velocity transducer was employed.

Only in very few studies in tanks and in situ, such as for example in [18,19], the problem that fish are generally sensitive to fluid motion and not to sound pressure is recognized, albeit the methods employed for addressing this issue in the second paper are slightly questionable, as the values of particle velocity or particle acceleration were estimated theoretically, instead of being properly measured, as advocated in this paper.

In conclusion, it appears that when performing underwater acoustical surveys for evaluating potential noise pollution it is should be mandatory to employ a set of transducers capable of recording both sound pressure and the three Cartesian components of particle velocity, such as the Ambisonics hydrophone arrays presented in previous chapters.

And when performing studies on the reaction of marine species to noise, the test sound should be generated controlling both its pressure and its particle velocity, something which is only possible employing Ambisonics loudspeaker arrays, as explained in the following chapter.

GENERATING A SOUND FIELD WITH CONTROLLED SOUND PRESSURE AND PARTICLE VELOCITY

The Ambisonics methodology is a comprehensive approach which starts from an analysis of all the components of a three-dimensional sound field, produces a number of signals representing a spatial expansion in spherical harmonics, and concludes with a method for recreating the original sound field inside a controlled volume of fluid, driving it with a peripheral array of loudspeakers, as shown in fig. 15.

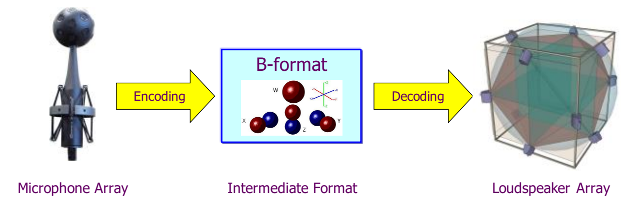

FIGURE 15. AMBISONICS FRAMEWORK

For controlling independently sound pressure and particle velocity, an Ambisonics loudspeaker array makes use of several "opposite loudspeaker pairs".

Let's consider just one pair, along the x-axis, which means it will be capable of controlling just p and v_x.

FIGURE 16. OPPOSITE LOUDSPEAKER PAIR

If the two loudspeakers are fed with the very same signal, at the center of array the two sound pressure waves will sum algebraically, whilst the two opposite particle velocity vectors will cancel each other, resulting in a sound field with a lot of sound pressure and substantially no particle velocity.

If instead the loudspeaker on the right is fed with a signal having reversed polarity (or, simply, if the two wires driving the loudspeaker are swapped), then at the center of the array the sound pressure waves will cancel each other, whilst the two velocity vectors, having opposite direction but also opposite polarity, will sum. This will result in a soundfield with a lot of particle velocity and almost zero sound pressure.

Employing more than one loudspeaker pair it is possible to control the velocity vector in the three-dimensional space, carefuly reconstructing the original spatial sound distribution.

The reconstruction area is quite small around the center of the array if the order of spherical harmonics is limited to 1. High Order Ambisonics, on the other hand, had been demonstrated capable of controlling the three-dimensional sound field in an enlarged "sweet spot area".

As high order Ambisonics signals for testing the sensitivity to noise of marine species can be generated artificially at the computer, nothing forbids to employ a very high order, for example 7^{th} order (64 channels), for controlling both sound pressure and particle velocity inside a huge volume of fluid.

This means that all the experiments conducted in past decades aimed to establish the hearing thresholds of marine species should be repeated by scratch, employing an Ambisonics playback system, either installed inside a water tank or to be positioned around the fish shelter for "in situ" evaluations. Luckily enough, software for synthesizing and decoding High Order Ambisonics signals is available for free [20].

CONCLUSIONS

This paper presented various scenarios where the recording or playback of particle velocity signals provides relevant advantages regarding the assessment of the effect of underwater noise on marine life.

Traditional studies focused on just one physical quantity, sound pressure, which is relevant only for marine mammals and birds. Most vertebrates and invertebrates, such as fishes, crustaceans and molluscs, are typically sensitive more to particle velocity than to sound pressure.

In most cases, the relationship between sound pressure and particle velocity is very far from theoretical assumptions: so it becomes necessary to be able to record the particle velocity signals independently.

This goal can be accomplished with various types of transducers, such as geophones and accelerometers. Till now the latter were the favourite ones, as deriving velocity signals from pressure transducers (hydrophones) had always being considered difficult and delicate.

This papers shows that instead such a derivation is simple and easy, thanks to the very old methodology known as Ambisonics. Which also comes handy when dealing with sound reproduction, allowing to recreate faithfully a previously recorded sound field, or to synthesize artificial sound fields with perfect and independent control of both sound pressure and particle velocity.

The scientific community is starting just now to understand the relevance of the particle velocity information for evaluating the effect of noise on aquatic life.

Under the light of such understanding, it appears that most of the work done in previous decades is fundamentally wrong, as the wrong physical quantity was observed both when analyzing the noise pollution in the sea and when studying the sensitivity to noise of marine species.

The approach described in this paper, based on the Ambisonics method, provides the required tools for recording pressure and velocity signals, and for recreating an artificial sound field with complete control of both physical quantities.

What is required now is to start collecting data on environmental noise pollution employing pressure-velocity probes, and to repeat experiments aimed to establish the hearing threshold of fishes and other animals when stimulated by sound pressure waves, particle velocity waves, or combinations of the two.

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REFERENCES

[1] Peter Fellgett, “Ambisonics. Part one: general system description”, *Studio Sound, Vol. 17 no. 8*, August 1975 pp. 20-22.

[2] Michael Gerzon, “Ambisonics. Part two: Studio techniques”, *Studio Sound, Vol. 17 no. 10*, October 1975, p. 60.

[3] Michael A. Gerzon, "The Design of Precisely Coincident Microphone Arrays for Stereo and Surround Sound". *50th Convention of the Audio Engineering Society, Preprint L–20*, 1975.

[4] Thomas B. Gabrielson, “A simple neutrally buoyant sensor for direct measurement of particle velocity and intensity in water”, *The Journal of the Acoustical Society of America 97*, 1995, pp. 2227; https://doi.org/10.1121/1.411948

[5] H-E. de Bree, Peter Leussink, Twan Korthorst, Henri Jansen, Theo S.J. Lammerink, Miko Elwenspoek , “The Miroflown - a novel device for measuring acoustic flowns”, *Sensors and Actuators,* 1996.

[6] K. J. Taylor, “Absolute measurement of acoustic particle velocity”, *The Journal of the Acoustical Society of America 59*, 1976, pp. 691; https://doi.org/10.1121/1.380896

[7] Fons Adraensen, “A Tetrahedral Microphone Processor for Ambisonic Recording”, *proc. of Linux Audio Conference*, Berlin, 2007.

[8] Angelo Farina, Enrico Armelloni, Lorenzo Chiesi, “Experimental Evaluation Of The Performances Of A New Pressure-Velocity 3D Probe Based On The Ambisonics Theory”, *4th international conference and exhibition on Underwater Acoustic Measurements: Technologies and Results* - Kos (Greece), 20-24 June 2011.

[9] Angelo Farina, Adriano Farina, Enrico Armelloni, Linda Sebastianutto, Carlo Franzosini, Marta Picciulin, “First description of the sound pressure and particle velocity components of the ambient noise and boat noise recorded at the WWF- Miramare Natural Marine Reserve (Trieste, Italy)”, *The Effects of Noise on Aquatic Life - Series: Advances in Experimental Medicine and Biology, Vol. 730*, Springer 2012 - pp. 485-488

[10] Angelo Farina, Andrea Capra, Lorenzo Chiesi, Leonardo Scopece, “A Spherical Microphone Array For Synthesizing Virtual Directive Microphones In Live Broadcasting And In Post Production”, *40th AES Conference "Spatial Audio - Sense the Sound of Space"*, Tokyo, Japan, 8-10 October 2010.

[11] O.Kirkeby, P.A. Nelson, P. Rubak, A. Farina, “Design of Cross-talk Cancellation Networks by using Fast Deconvolution”, *106th AES Convention*, Munich, 8-11 May 1999.

[12] Sophie L. Nedelec, James Campbell, Andrew N. Radford, Stephen D. Simpson and Nathan D. Merchant, “Particle motion: the missing link in underwater acoustic ecology”, *Methods in Ecology and Evolution 7*, 2016, pp. 836–842; doi: 10.1111/2041-210X.12544

[13] http://www.angelofarina.it/X-volver.htm

[14] Regis Rossi Alves Faria, Marcelo Knorich Zuffo, J.A. Zuffo “Improving spatial perception through sound field simulation in VR”. *Proceedings of the 2005 IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurement Systems*, August 2005 DOI10.1109/VECIMS.2005.1567573

[15] Marco Lugli, “Acoustics of fish shelters: Frequency response and gain properties*”, J. Acoust. Soc. Am. 132 (5), November 2012*, pp. 3512-3524.

[16] Marco Lugli, “Acoustics of fish shelters: Background noise and signal-to-noise ratio”, *J. Acoust. Soc. Am. 136 (6), December 2014*, pp. 3382-3388.

[17] “Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry”. *Sound-Generating Activities - Workshop Report.* Prepared under BOEM Contract M11PC00031 by Normandeau Associates, Inc. 25 Nashua Rd. Bedford, NH 03110. Published by. U.S. Department of the Interior. https://www.cbd.int/doc/meetings/mar/mcbem-2014-01/other/mcbem-2014-01-submission-boem-01-en.pdf

[18] Wysocki, L.E., Codarin, A., Ladich, F., Picciulin, M., “Sound pressure and particle acceleration audiograms in three marine fish species from the Adriatic Sea” *J. Acoust. Soc. Am. 126*, 2009, pp. 2100–2107

[19] Marta Picciulin, Linda Sebastianutto, Antonio Codarin, Angelo Farina, Enrico A.Ferrero, “In-situ behavioral responses to boat noise exposure of Gobius cruentatus and Chromis chromis living in a Marine Protected Area”, *Journal of Experimental Marine Biology and Ecology, Vol. 386 (2010)*, pp. 125–132.

[20] Matthias Kronlachner, “Plug-in Suite for Mastering the Production and Playback in Surround Sound and Ambisonics”, *Proc. of 136th AES Convention Berlin*, April 2014, http://www.matthiaskronlachner.com/?p=2015