ON THE USAGE OF THE PARTICLE VELOCITY FIELD FOR BOTTOM CHARACTERIZATION

P. Felisberto[a], O. Rodriguez[a], P. Santos[a], S.M. Jesus[a]

[a]Institute for Systems and Robotics, University of Algarve, Campus de Gambelas, 8005-139, Faro, Portugal

Paulo Felisberto, Instituto Superior de Engenharia, Universidade do Algarve, Campus da Penha, 8005-139 Faro, Portugal, Fax. Nº +351 289 888 405, pfelis@ualg.pt

Abstract: *Vector sensors (VS) are devices that measure the vectorial particle velocity field. Compared with traditional hydrophone arrays that measure the acoustic pressure, systems based on VS present enhanced spatial filtering capabilities. The feasibility of bottom characterization with a 4-element 40cm length vector sensor array (VSA) in a frequency band of 8-14 kHz was recently demonstrated by Santos et al. The study suggests that systems based on VS outperform traditional hydrophone arrays, when considered in geoacoustic parameter estimation. Vector sensor data can improve the resolution of the estimators, moreover the highest resolution of the estimates were achieved with the vertical particle velocity measurements alone. Bearing in mind that actually VS are not widely available, the present work shows through simulations that using a narrow band signal and a vertical array which elements are pairs of hydrophones one can estimate the vertical particle field and attain a resolution for the bottom parameters similar to that obtained by a VSA. Based on a normal mode description of the pressure and particle velocity field, the resolution gain achieved by a linear estimator based on the vertical component only, is compared with similar estimators based on the pressure or on the horizontal component. Using simulations for different shallow water typical scenarios, we point out sensible values for the number of sensors, inter sensor spacing for system design as well as preferred equipment location for best results.*

This work is a contribution to the design of a compact array of hydrophones that takes advantage of the higher sensitivity of the vertical particle velocity field for geoacoustic parameter estimation.

Keywords: *particle velocity, vector sensors, geoacoustic estimation.*

INTRODUCTION

The particle velocity is the gradient of the pressure, thus it is a vectorial field. A device that measures the particle velocity exhibits intrinsic spatial filtering properties that have been explored to improve direction of arrival estimates or sea bottom characterization, among other applications [1]. Such device, which output is 3 streams with the orthogonal components of the particle velocity and very often includes also the pressure is known a vector sensor (VS). State-of-the-art VS devices are low size, operate over wide frequency bands of few Hz to several kHz and have large dynamic ranges. Santos et al. [1] used data acquired during the MAKAI'05 experiment by a vertical array of 4 such vector sensors (VSA), spanning 40cm of the water column to perform geoacoustic parameter estimation with signals in the ten of kilohertz band. Although, the high frequency of the signals used, the few elements and the small aperture of the VSA, it was possible to estimate the sediment velocity, density and attenuation in line with the ground truth for the area. The estimates were obtained using an extension of the Bartlett processor to include particle velocity measurements. It was shown that the VSA measurements remarkably improve the resolution of the estimates, when compared with pressure only data of an array of similar characteristics (number of sensors, array aperture). Moreover, the highest resolution of the bottom parameters was achieved when the vertical component of the particle velocity was considered alone. Since, state-of-the-art VS are defence sensitive devices that are not commercially available, one can consider the usage of a vertical array, which elements are pairs of closely located hydrophones to explore the vertical particle velocity for geoacoustic parameter estimation. This work presents a normal mode representation of the particle velocity field, which is used to discuss the potential gain provided by particle velocity measurements and settle rules to design a measurement system (frequency, source depth, sensor separation) for geoacoustic parameter estimation based on VS or alternatively in pairs of closely located hydrophones. The MAKAI'05 geometry was used for the simulations, where a bottom mounted source was transmitting to a surface suspended short aperture vertical array. It is shown for the noise free case the performance achieved by vertical particle velocity sensors or pair of hydrophones are similar once hydrophone separation obeys the sampling rules applied to high order modal functions. In the presence of noise, herein simulated using the noise model proposed by Kuperman [2] extended to include the particle velocity field, the performance of estimates based on the hydrophone pairs slightly degraded, however in the analyzed cases they perform generally better than those obtained using hydrophone arrays directly (i.e. without estimating the vertical particle velocity field).

NORMAL MODE REPRESENTATION OF THE PARTICLE VELOCITY FIELD

Consider an ocean waveguide with cylindrical symmetry characterized by sound speed profile $c(z)$ and density $\rho(z)$, then the acoustic pressure from a narrow band point source at depth z_s, emitting a signal of frequency ω at a faraway point of depth z and range r can be written as sum of normal modes given by [3]

$$p(r,z) = S(\omega)\frac{e^{i\frac{\pi}{4}}}{\rho(z_s)\sqrt{8\pi r}}\sum_{m=1}^{M} u_m(z_s)u_m(z)\frac{e^{ik_{rm}r}}{\sqrt{k_{rm}}} \qquad (1)$$

where $S(\omega)$ is the source strength, M is the number of modal functions u_m and k_{rm} is its respective horizontal wavenumbers. The horizontal wavenumbers k_{rm} are ordered as $k_{r1}^2 > k_{r2}^2 > \cdots > k_{rM}^2$. The m-th modal function has m zeros and is characterized by the depth varying vertical wavenumber $k_{zm}(z)$, being $k^2(z) = k_{rm}^2 + k_{zm}^2(z)$ where $k(z) = \omega/c(z)$. Given a depth z the vertical wavenumber increases with mode number m, i.e $k_{z1}^2 < k_{z2}^2 < \cdots < k_{zM}^2$.

The particle velocity v and the pressure are related by, $-\nabla p = \rho \frac{\partial \mathrm{v}}{\partial t}$, thus the horizontal ($v_r$) and the vertical ($v_z$) components of the particle velocity can be written as

$$v_r(r,z) = -\frac{1}{i\rho\omega}\frac{\partial p(r,z)}{\partial r},\ v_z(r,z) = -\frac{1}{i\rho\omega}\frac{\partial p(r,z)}{\partial z} \quad . \tag{2}$$

The horizontal component of the particle velocity becomes

$$v_r(r,z) = -S(\omega)\frac{e^{i\frac{\pi}{4}}}{\omega\rho^2\sqrt{8\pi r}}\sum_{m=1}^{M} u_m(z_s)u_m(z)\sqrt{k_{rm}}e^{ik_{rm}r}, \tag{3}$$

where a term proportional to $(r\sqrt{r})^{-1}$ is neglected. The m-th modal function in the horizontal particle velocity is weighted by $\sqrt{k_{rm}}$, whereas in pressure is weighted by $1/\sqrt{k_{rm}}$. Since k_{rm} decreases with increasing mode number, the contribution of lower modes is enhanced in horizontal particle velocity.

The vertical component of the particle velocity is given by

$$v_z(r,z) = -S(\omega)\frac{e^{i\frac{\pi}{4}}}{i\omega\rho^2\sqrt{8\pi r}}\sum_{m=1}^{M} u_m(z_s)\frac{d}{dz}u_m(z)\frac{e^{ik_{rm}r}}{\sqrt{k_{rm}}}. \tag{4}$$

It is well known that the derivative of a function acts as a high pass filter, with a linear increasing frequency response. Since, the vertical wavenumber k_{zm} increases with mode number, the derivative of mode functions emphasizes the contribution of higher order modes to the vertical particle velocity.

SIMULATIONS

In this section is considered a simulation scenario based on MAKAI'05 experimental setup [1], which geometry is depicted in Fig. 1 left. The environment is modelled as range independent 104m water column over a sediment half-space. The sound speed profile (MAKAI ssp) is represented by the dashed line in Fig. 1 right, showing a relatively deep thermocline starting at depth 60m giving rise to a narrow acoustic channel bounded by the sea bottom. The source deployed at depth 98m and the 30cm aperture VSA at 79m (deepest sensor) are in this part of the water column. The receiver is 1830m distant from the source. In the forthcoming simulations is also considered an isovelocity (ISO ssp), 1530m/s (Fig. 1 left solid line), equal to the water sound speed at water-bottom interface of the MAKAI ssp. The bottom is modelled has a half-space.

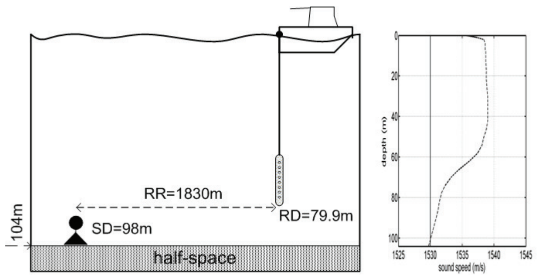

Fig. 1 Baseline environment considered for simulations: geometry (left) and sound speed profiles – ISO solid and MAKAI dashed line - (right).

The simulations presented here were computed using the KRAKENC normal modes code to obtain the modal functions and the equations (1), (3), (4) to synthesize the pressure, horizontal and vertical particle velocity fields. Fig. 2 shows the normalized pressure, radial and vertical particle velocity fields for a frequency of 13kHz, the MAKAI ssp, a bottom speed of 1575m/s, density of 1.5 and an attenuation of 0.6dB/λ .

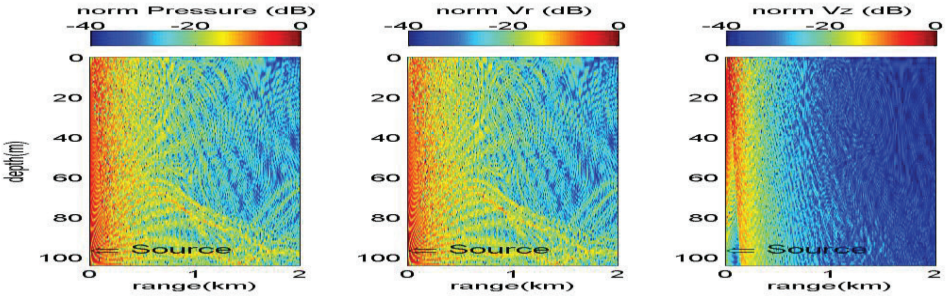

Fig. 2 Pressure, horizontal (Vr) and vertical (Vz) particle velocity fields for the MAKAI sound speed profile

One can observe that pressure and the horizontal particle velocity field (Fig. 1 left and middle) show similar interference patterns, which are related to lower order modes (energy with low propagation angles and remarkable influence of the shape of the sound speed profile). In the vertical particle velocity field (Fig 1. right), one can see that the contribution of higher order modes is highlighted (energy with high propagation angles). The number of modes and their propagation parameters are strongly influenced by the bottom characteristics, mainly bottom sound speed, thus one can expect that estimates of bottom parameters based on the vertical particle velocity will show higher resolution than similar estimates based on the pressure (or horizontal) particle velocity field. This behaviour is presented in Fig. 3, that shows the correlation between replicas computed by the propagation model considering a frequency of 13kHz for varying bottom compressional speed between 1535m/s and 1800m/s, assuming a fixed bottom speed of 1750m/s. The sound speed considered is the MAKAI – left column and ISO right. The array spans 30cm of the water column, but different equidistant type of sensors were considered: 16 hydrophones (black curve), 4 hydrophones (dotted curve), 4 horizontal velocity sensors (blue curve), 4 vertical velocity sensor (red line) and 4 pairs of 2-cm vertically separated hydrophones. For this last configuration the correlation is on the pressure difference in hydrophone pairs in order to explore the vertical particle velocity field using pressure measurements. The 2-cm separation between hydrophones in a pair was considered in order to adequately sample the high order modes.

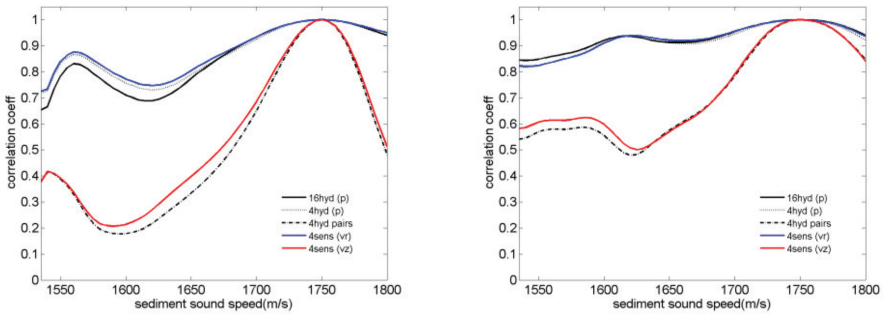

Fig. 3 Replica correlation for varying bottom sound speed (fixed value 1750m/s): MAKAI ssp (right), ISO ssp (left)

The results show that in all considered situations the highest resolution is obtained using the vertical particle velocity field, either through vertical velocity sensors or hydrophone pairs. The curves based on pressure sensors and radial velocity sensors are similar, as expected from equations (1) and (3). Since in this noiseless cases, the high order modes are adequately sampled (Nyquist theorem) by the 4 hydrophone configuration, the oversampling obtained by the 16 hydrophone configuration does not improves the resolution. The curves also suggest that sound speed profile has influence in the resolution of the estimators; the worst case is observed for the isovelocity sound speed profile since the energy spreads over the whole water column. Conversely, the source depth also influences the resolution and side lobe level, what is illustrated in Fig. 4 left for the MAKAI ssp, where one notices an increased side lobe height when the source is in the thermocline layer or above (red curves refer to vertical particle velocity, black curves to pressure difference). In Fig. 4 the “true” value of bottom sound speed is 1750m/s.

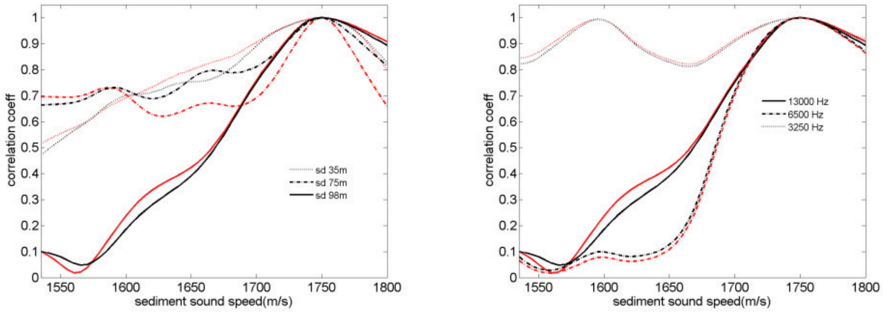

Fig.4 Replica correlation dependence on source depth (left) and signal frequency (right): red lines refer to vertical particle velocity, black lines refer to pressure difference.

The frequency of the source has influence on the resolution and side lobe height, as can be seen in Fig. 4 right (red curves refer to vertical particle measurements, black curves to pressure difference) for the baseline scenario presented in Fig. 1. The number of modes decreases with frequency, thus one notices a significant increasing of side lobe level for the lower frequency. For the higher and middle frequency the shape of the curves are close, what suggests that there is a frequency range where enhanced bottom parameters estimates based on vertical particle velocity are attainable. This was also noticed for the other considered environmental scenarios (not shown). The curves presented for the noiseless cases showed that results obtained from directly measurements of the vertical particle velocity or by the pressure difference from pair of hydrophones are similar.

At the considered frequencies the surface generated ambient noise is a concern. Using the ambient noise model proposed by Kuperman et al. [2] adapted for particle velocity it was noticed that the estimator based in pressure difference is more sensitive to noise (increased sidelobe/mainlobe height) than that based on direct measurements of the particle velocity. Anyway, at a lower SNR as 0dB the estimates based in pressure difference is much better than those obtained using pressure directly. Moreover, an higher SNR can be easily accomplished with a controlled signal source. The sensitivity on bottom density and attenuation parameters is in general greater for the vertical particle velocity field than for pressure (not shown). As mentioned above the results shown herein were obtained using a normal mode model, however those simulations were replicated using the ray tracing model TRACEO [1] with similar results.

CONCLUSIONS

This paper considered a representation of the vertical and horizontal particle velocity using a normal mode formulation. Based on this model it was discussed the improvements in resolution of bottom parameters that are achieved when vertical particle velocity is used.
The qualitative analysis and simulations presented herein suggest that the advantage of the vertical particle velocity for bottom characterization shown in [1], for real data acquired during the MAKAI'05 can be verified in other environments. This advantage is related to high frequency modes, thus depends on factors that cannot be controlled by the user (sound speed profile), but also remarkably on the setup of the measurement system (frequency band of the source, sensor spacing, source/receiver depth). Moreover, it was shown that estimates based on vertical particle velocity field obtained by the difference of pressure from close located hydrophones improve the estimates of the bottom parameters. This work is a contribution for the development of a short vertical array of pairs of hydrophones to characterize the sea bottom.

ACKNOWLEDGEMENTS

This work was funded by National Funds through FCT- Foundation for Science and Technology under project SENSOCEAN (PTDC/EEA_ELC/104561/2008).

REFERENCES

[1] **P. Santos, O.C. Rodríguez, P. Felisberto and S.M. Jesus**, Seabed geoacoustic characterization with a vector sensor array, *Journal of Acoustical Society of America*, vol. 128 (5), pp. 2652-2663, 2010.

[2] **W.A. Kuperman and F. Ingenito**, Spatial correlation of surface generated noise in a stratified ocean, *Journal of Acoustical Society of America*, vol. 67 (6), pp. 1988-1996, 1980.

[3] **F.B. Jensen, W.A. Kuperman, M.B. Porter and H. Schmidt**, Computational Ocean Acoustics, AIP Press, 1994.