Bubble sweep-down occurrence characterization on Research Vessels

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ABSTRACT

Bubble sweep-down on oceanographic vessels generates acoustic perturbations. We propose in this work to characterize the sub-surface bubbles occurrence conditions from acoustic data analysis acquired during surveys in relatively shallow water with the IFREMER research vessels Thalassa and Pourquoi Pas?. The methodology of data analysis used in this work allows us to characterize the sailing conditions influence on bubble sweep-down occurrence. The correlation between sailing conditions and acoustic perturbations tends to demonstrate that the presence of bubbles under the hull is clearly related to the wind speed and natural aeration, and that surface bubbles are advected differently in the water column by the two vessels.

Keywords:
Bubble sweep-down
Acoustic perturbation
Ship motion

1. Introduction

The generation of bubbles in the open ocean has been the topic of several works, most often motivated by a better understanding of gas exchanges with the atmosphere. Thorpe (2005) describes the fact that small bubbles, of radius less than about 1 mm, are stabilized by surface tension while those of larger radius are fragmented by shear stresses in the turbulent motion induced by the breaking event. The smaller bubbles rise very slowly and are consequently more persistent in the water column and often advected at a greater depth.

Movement of the surface ship bow is a source of air bubbles generation. While the ship is moving, these bubbles may be entrained under the hull where the transducers are mounted. This phenomenon of bubble sweep-down is an issue of major importance for oceanographic vessels designers. Air bubbles passing under sounders location may absorb or reflect the acoustic wave and be a source of inconvenient noise affecting sonar's data. Such disturbances strongly affect the productivity of some vessels dedicated to acoustic survey, as we can see in Fig. 1. In this figure we can see the perturbation induced on one ping for sea bottom detection by a multibeam sounder Reson Seatbat 7150 used at 24 kHz on the IFREMER research vessel Pourquoi Pas ?. The horizontal red line is the seabed detection at 2180 m depth: the detection is well marked without acoustic perturbation (Fig. 1 bottom) while it can be undetected for the perturbed ping (Fig. 1 top). In this extreme case, the acoustic wave is completely absorbed in the bubble layer and the transmitted pulse does not reach the seafloor, thus no echo can be observed. During the receiving time, the high noise level is attributed to the broadband noise of the bubbles collapsing in front of the transducer. This kind of perturbation is not only due to ship motions but by a combination of factors from which wave/bow interactions play an important part.

Many studies have therefore been dedicated to this topic since Dalen and Lovik (1981) who investigated bubble effects on biomass estimation of aquatic targets using echo-integration technique, first described by Dragesund and Olsen (1965) and now widely adopted in fishery research. The purpose of their work was to find an empirical formula that would enable the prediction of acoustic signal attenuation depending on weather conditions. Novarini and Bruno (1982) also studied the effect of bubbles layer on sound propagation. Later, New (1992) exposed the progress performed in oceanography thanks to the wider use of Acoustic Doppler Current Profilers on research vessels. However, New pointed out that problems remained under more or less bad weather conditions because of interferences generated by the near surface bubbles layer that can be overcome by lowering the transducer below the bubbles layer. Trevorrow (2003) developed in 2003 an analytical model to determine the influence of bubbles on high-frequency sonar performances. Finally, Shabangu et al. (2014) compared the attenuation of acoustic signals caused by bubbles for different sorts of transducer installations. Conclusions of these works are to recommend the installation of the transducers as deep as possible to avoid the under hull bubble layer and

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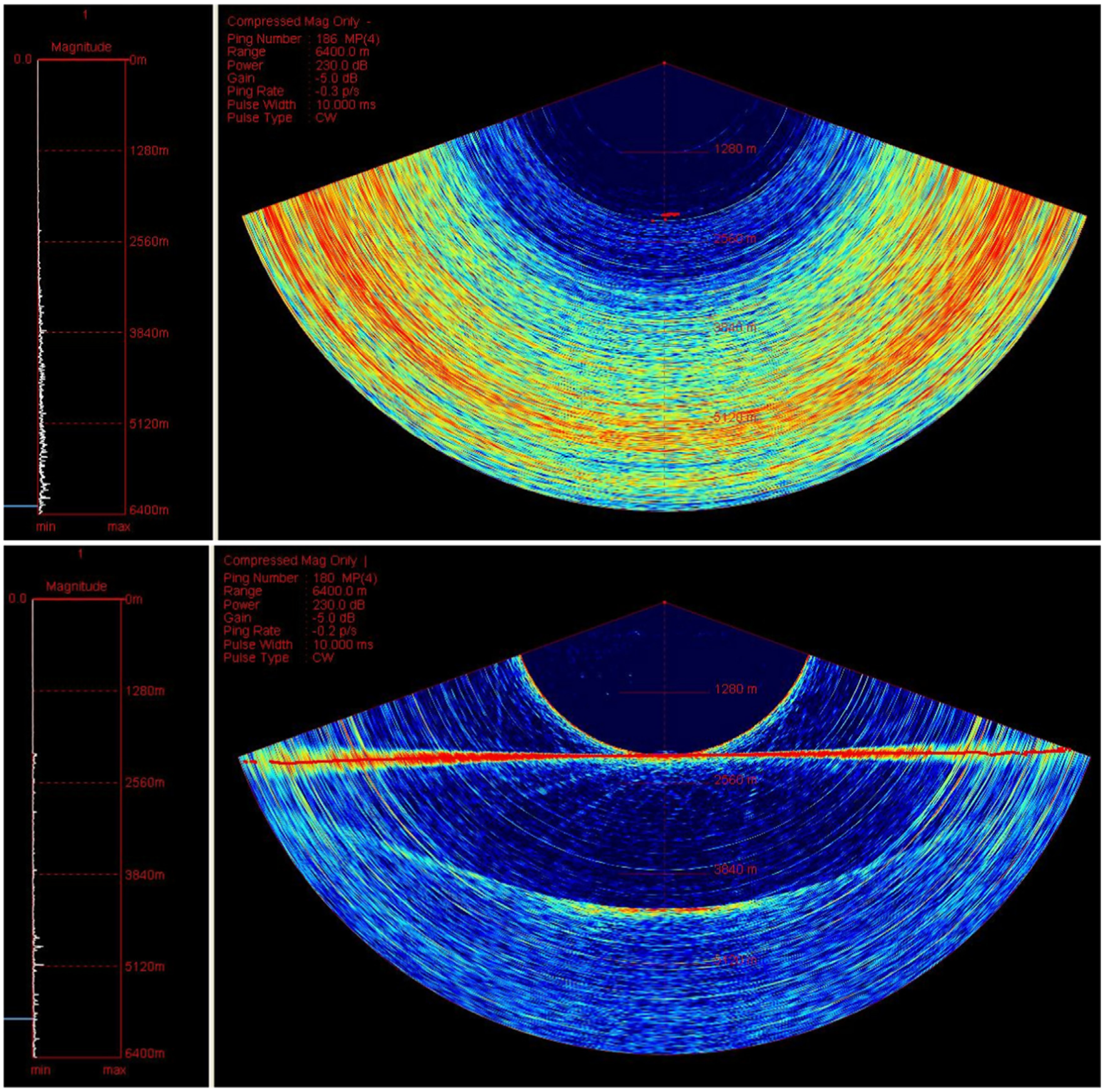

Fig. 1. Comparison between a "bubbled" ping (on top) and a non perturbed ping (bottom) from a multibeam sounder acquired in the same conditions on the Pourquoi Pas ? (dt < 1 min). The horizontal red line is the seabed detection. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

significant acoustic signal attenuation for wind speed above 10 m/s. This solution is not always possible or efficient and solutions to minimize this phenomenon are still being sought (Rolland and Clark, 2010).

For that purpose comparison of bubbles generation should be undertaken for several oceanographic vessels. Nonetheless there are many parameters controlling this issue (hull characteristics, wind and sea state, heading, ship's velocity and motions, depth, etc.) and the conditions of occurrence of this phenomenon are consequently still poorly known. The objective of this study is to find a methodology for the analysis of acoustic data allowing the prediction of bubble generation under the hull of research vessels. Here we propose a first study to characterize the bubbles occurrence conditions.

The data used for this work come from the French survey series International Bottom Trawl Survey (IBTS) 2010–2013 undertaken in winter (January/February) in the Channel and the North Sea with the research vessel Thalassa. After the presentation in the second section of the equipments and the methodology of data analysis used in this work, the main results in term of sailing conditions influence on bubble sweep-down occurrence are exposed. The main advantage of direct measurement of bubble backscatter, over the method proposed by Shabangu et al. (2014) to measure the attenuation on the seafloor echo, is to avoid the influence of the variation of the seafloor backscatter for characterizing the attenuation and hence the bubbling. Once the bubbling is detected, prediction of attenuation can be done based on models of bubble size distribution and individual bubble backscattering cross-section (Weber, 2008). A correlation between wind speed, sailing conditions and acoustic perturbations is attempted and a comparison between the Ifremer research vessels, Thalassa and Pourquoi Pas ?, is given to prove the consistency of the methodology of acoustic data analysis for bubble sweep-down detection.

2. Material and methods

2.1. Eastern channel and north sea case study

The research vessel Thalassa is one of the main fisheries research vessel of Ifremer fleet. The primarily assignments of this vessel deal with fisheries-based missions such as population ecology and assessment of fish stocks. For this purpose, in addition

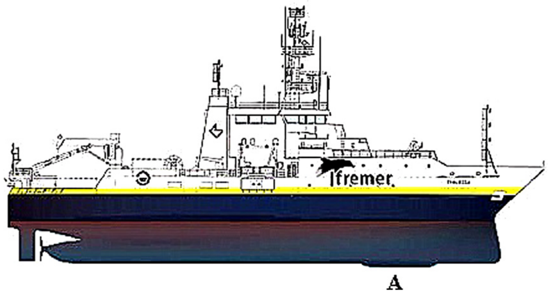

Fig. 2. The Thalassa with Echosounders position noted A.

Fig. 3. Route of the Thalassa during the first week of IBTS 2013 cruise in the eastern Channel, North of France.

to traditional fishing equipment, Thalassa is equipped with six Simrad ER60 echosounders (18, 38, 70, 120, 200 and 333 kHz) and a Simrad ME70 multibeam echosounder in the range 70–120 kHz (Trenkel et al., 2008). All equipments are calibrated regularly in order to provide absolute acoustic backscatter measurements of the water column and the seafloor. These transducers are installed close to each other, as shown in Fig. 2, to ensure that the different echosounders observe as much as possible the same scenes (Korneliussen et al., 2008). Ship's motions are recorded from an inertial measurement unit with a frequency of 10 Hz. Remaining information related to this study, like ship velocity and heading, wind speed and direction, are recorded from all sensors every 30 s and synchronized by the mean of a custom acquisition system.

As part of the International Bottom Trawl Survey, the Fishery Resources Laboratory of the IFREMER North Sea-Channel Center is conducting a one-month annual IBTS cruise in the eastern English Channel and in the North Sea. Carried out in collaboration with six European partners and coordinated by the International Council for Exploration of the Sea (ICES), this research cruise on the research vessel Thalassa is undertaken to calculate abundance indices for the main commercial species caught in this area.

Acoustic samples collected during three IBTS cruises, between 2010 and 2013, are considered in this work. During these periods, the Thalassa activities are concentrated in the east Channel (see the route of the Thalassa during the first week of IBTS 2013 in Fig. 3) and a part of the North Sea. This working area is characterized by shallow water, for a mean depth close to 50 m and always lower than 150 m. The maximal value of the true wind encountered is 72 knots (36 m/s). The significant wave height, defined as the mean of the highest third of the waves, is between 0.5 and 3.5 m, with a maximal wave period of 9 s.

The first step of the data analysis consists in a selection of measurement periods which can be analyzed. Such periods are automatically defined by stable sailing conditions (velocity and heading) for a duration of 20 min. Then ship's motions, especially pitch and heave, are analyzed on these periods and finally acoustic disturbances are quantified. By this way all these stable periods form a database allowing a statistical research of the factors of bubble generations.

2.2. Methodology of acoustic data analysis

Quantifying the disturbances on acoustic signals due to the presence of air bubble clouds under the hull is a complex problem. Different phenomena possibly happen: bubbles may reflect partially or completely the acoustic waves, but also absorb it. Reflection and absorption occur along the propagation path of the acoustic wave and masking can occur for the transmitted and/or the reflected wave, depending on the spatial extent of bubble clouds. Disturbances range from insignificant attenuation to complete loss of data. Bubble bursting can be as well a source of additional noise.

This study is limited to the quantification of the backscatter signal on clouds of bubbles images by the echosounder (absorption and bubble bursting are not considered here). The variations of backscatter, in a layer just under the hull ("layer 1", between 2 m and 4 m under the sonar, with ship's movements compensation), are considered to be only due to the quantity of air bubbles in this layer. Considering a volume V, the volume backscattering strength (S_v) is defined as (MacLennan et al., 2002):

$$S_v = 10 \log \left(\frac{\sum \sigma_{bs}}{V} \right) \tag{1}$$

with σ_{bs} being the backscattering cross-section:

$$\sigma_{bs} = \frac{r^2 \, I_{bs}(r) 10^{\alpha r/10}}{I_{inc}} \tag{2}$$

where r is the distance of the measurement position from a small target, $I_{bs}(r)$ is the intensity of the backscattered wave, I_{inc} is the intensity of the incident wave at the target, and α is the acoustic absorption coefficient depending on the temperature and salinity of seawater but principally of the wave frequency.

The mean of the volume backscattering strength S_v is calculated in the layer 1 for each impulse (ping) of the echosounder by the software Movies 3D, developed by Ifremer (Trenkel et al., 2009), with minimum and maximum thresholds respectively -100 and 0 dB. For each measurement period of the database previously defined, the presence of bubbles can be quantified by the fluctuations of S_v by the following method based on the work of Trevorrow (2003).

According to Medwin and Clay (1998), the backscattering cross-section per unit volume of a bubbles cloud (s_v), with $S_v = 10 \log(s_v)$, ignoring multiple reflections, can be calculated by:

$$s_v(f, z) = \int_0^\infty \sigma_{bs}(a, f) \cdot n(a, z) \, da \tag{3}$$

where $n(a, z)$ is the bubble size distribution in the cloud, a the bubble radius, z the depth and f the signal frequency. σ_{bs} is the acoustic scattering cross section of a single bubble:

$$\sigma_{bs}(a, f) = \frac{a^2}{((f_R/f)^2 - 1)^2 + \delta^2} \tag{4}$$

with δ being the damping constant, taken equal to ka, by ignoring the damping due to shear viscosity and the damping due to thermal conductivity. The resonant frequency f_R for a given bubble radius a is:

$$f_R = \frac{\sqrt{3\gamma P_0/\rho}}{2\pi a} \tag{5}$$

with γ being the heat capacity ratio ($=1.4$ for air), P_0 the static pressure on the bubble ($= P_{atm} + \rho g z$) and ρ the density of seawater.

An expression for the bubble size distribution must be used. It is currently admitted that breaking waves create clouds of bubbles whose void fraction can reach a value of 10% very close to the surface (Lamarre and Melville, 1994). Deane and Stokes (1999, 2002) developed an optical system capable of recording bubbles of radii $>200\ \mu m$. Two mechanisms controlling the bubbles size are identified. For bubbles larger than about 1 mm the density is proportional to the bubble radius to the power of $-10/3$ and smaller bubbles follow a density with a $-3/2$ power-law scaling. Thorpe et al. (2003), Thorpe (2005) described the fact that small bubbles (radius <1 mm) are stabilized by surface tension while those of larger radius are fragmented by shear stresses. On the opposite, very small bubbles, with a radius smaller than about 30 μm, are also unstable. Many of the gaseous content pass rapidly into solution and bubbles eventually dissolving completely. In this case, the bubbles size distribution usually decreases with decreasing bubble radius. However small bubbles with a very low rise velocity are more persistent in the water column, at a greater depth. It is therefore appropriate to use a bubbles size distribution that includes radii between around 30 μm and 1 mm. Vagle and Farmer (1998) found by acoustic measurements that the density of bubbles of radii greater than 20 μm can be described, for a depth of 0.5 m, by the relation:

$$n(a) = n_0 \cdot \exp(-a/34) \tag{6}$$

with n_0 being the characteristic density. Trevorrow (2003) used this spectra with an exponential decay with depth:

$$n(a,z) = n_0(z) \cdot \exp(-a/34), \quad \text{with } n_0(z) = n_0 \cdot \exp(-z/d) \tag{7}$$

with d being the critical depth. With such distribution, the backscattering equation becomes:

$$s_v(f,z) = n_0(z) \int_{20}^{1000} \sigma_{bs}(a,f) \cdot \exp(-a/34)\, da \tag{8}$$

Consequently measurements of S_v enable an estimation of $n_0(z)$ and the determination of the Void Fraction:

$$VF = \int_{20}^{1000} \frac{4}{3} \pi a^3 n(a,z)\, da \tag{9}$$

An adequate threshold is then searched for the detection of bubbles. A threshold of $S_v = -50$ dB for the 120 kHz echosounder effectively separates bubbles and plankton scattering contribution. For a depth of 9 m (included in the layer between 2 m and 4 m under the sonar) the void fraction corresponding to -50 dB is $2.2 \cdot 10^{-10}$. Indeed a lower volume backscattering strength corresponds to an insignificant bubble density. All these elements lead to the calculus of a “bubbled” ping ratio (ping with $S_v > -50$ dB) at different layers for all stable periods.

The influence of sonar frequency on bubble detection is shown in Fig. 4. The graphic on the left represents the ratio of bubbled ping (with a -50 dB threshold) for the mean wind speed of the measurement periods and for the different sonar frequencies. The detection of bubble is higher for 120 kHz and slightly lower for 70 and 200 kHz. The detection is reduced for 38 kHz, and almost nonexistent for 18 kHz. This evolution can be explained by the distribution of bubbles, characterized by a majority of less than 100 μm radius bubbles. Such bubbles have high resonance frequencies as can be seen on the right graphic for a 50 μm radius bubble, which resonance frequency is close to 120 kHz.

The use of the echosounder ER60 at 120 kHz seems therefore the most appropriate to study bubbles generation under the hull. In the following section the results are presented for this frequency.

3. Analysis of IBTS data

Previous studies have shown the main role of pitch motion on bubbles generation. The purpose of this research is both to have a better understanding of pitch motion influence and also to study the influence of other parameters such as wind speed and natural aeration in the open ocean.

3.1. Influence of pitch and wind speed

The first part of the study has been made with data from IBTS 2010 and 2011 and the first week of the 2013 survey. Following the analysis described above, a matrix of data is obtained. Each line of this matrix corresponds to a measurement period defined in Section 2. Each row corresponds to a navigation parameter mentioned above or an indication of bubbling. These data are illustrated in Table 1, where are given the minimum, mean and maximum on all the periods of the mean value of the true Wind (W) and the ship Velocity (V), the standard deviation of Pitch (σP), Heave (σH) and Roll (σR), the mean and standard deviation of S_v and the ratio of “Bubbled” Ping (BP) as index of bubbling.

In order to highlight the most important parameters for the generation of bubbles, the correlations between the main characteristic parameters mentioned above and the ratio of “bubbled” ping have been studied. Delacroix (2015) has shown that ship velocity, heave and roll play an insignificant part in the phenomenon occurrence. In this work, we focus on the role played by the pitch and the wind speed on bubble clouds appearance. To this aim, Fig. 5 represents the ratio of “bubbled” ping in a period as a function of the pitch standard deviation.

The influence of pitch motion on bubble generation and propagation under the hull is thus shown. The index of correlation

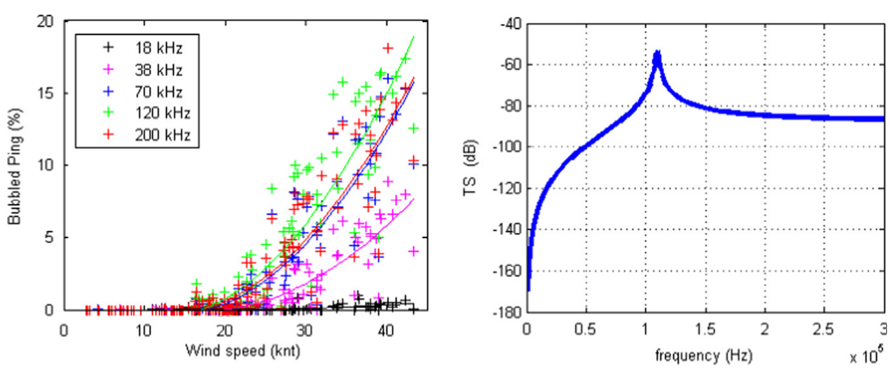

Fig. 4. Left: influence of sonar frequency on bubble detection. “Bubbled” ping vs pitch in the layer 2–4 m under the hull. Right: target strength vs frequency for a 50 μm radius bubble at 9 m deep.

Table 1
Minimum, mean and maximum of the main parameters over all the periods.

Values	W (kt)	V (kt)	σP (deg)	σH (m)	σR (deg)	S_v (dB)	σS_v (dB)	BP (%)
Min	3	6	0.1	0.0	0.3	−97.6	2.6	0
Mean	21	11	0.6	0.2	0.9	−87.2	9.7	2.9
Max	43	13	2.6	0.9	2.4	−67.8	21.2	20.4

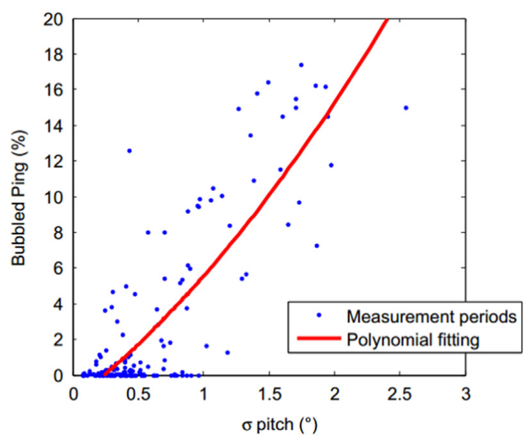

Fig. 5. Influence of pitching on bubble generation. "Bubbled" ping vs pitch in the layer 1 (2–4 m under the hull) for all measurement periods and 2nd order polynomial fitting.

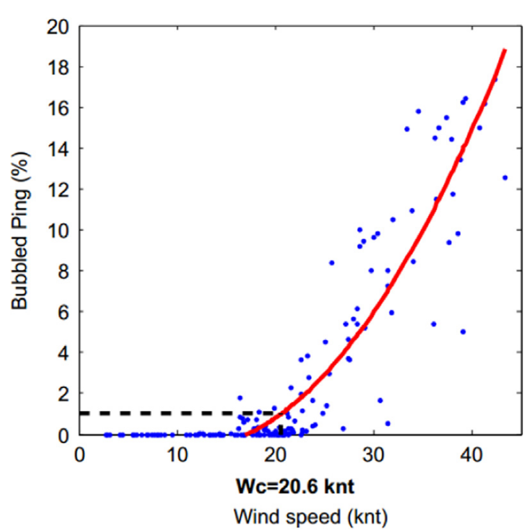

Fig. 6. Influence of wind speed on bubble generation. "Bubbled" ping vs wind speed in the layer 1 (2–4 m under the hull).

used is the coefficient of determination R^2 defined as:

$$R^2(X,Y) = \left(\frac{COV(X,Y)}{\sigma(X)\sigma(Y)}\right)^2 \quad (10)$$

where $\sigma(X)$ is the standard deviation of the variable X, and $COV(X,Y)$ the covariance between X and Y. As expected, there is a strong link between bubbling and pitching ($R^2 = 0,72$). Bubbles are always present for a pitch standard deviation higher than 1°.

The correlation between the generation of bubbles and the wind is even stronger. Fig. 6 represents the ratio of "bubbled" ping as a function of the wind speed. The coefficient of determination is this time higher: $R^2 = 0.84$. A critical value of the wind speed (W_c) can be defined, corresponding to the minimum of wind speed to observe a non-negligible bubbles density in this layer. This value is obtained when the best second order polynomial fitting reach a ratio of "bubbled" ping of 1%. In this layer, the wind speed critical value is $W_c = 21$ knots (10 m/s).

These calculations have been repeated for the three other layers under the first one (layers 2, 3 and 4 respectively between 4 and 6 m, 6 and 8 m, 8 and 10 m under the sonar) as shown in Fig. 7. The shapes of these graphs are similar to that for the first layer but the ratio of "bubbled" ping decreases with depth. On the contrary, the wind speed critical value increases with depth as reported in Table 2.

These observations confirm the interest to install transducers at the greater possible depth. Whenever possible, sonar mounts like keel fairing or gondola will increase the wind speed critical value and increase therefore workable sea states, which would be an important achievements for the productivity of the ship.

Pitch and wind speed are also correlated between each other. Periods during which the standard deviation of pitch is higher than 1° correspond to wind speed higher than 25 knots (12.75 m/s). It is therefore difficult to distinguish causes and consequences but the stronger correlation between bubble generation and the wind speed suggests that the wind is the major factor of bubble clouds generation in these cases. For some high wind speed values, the pitch can reach low values as well as very high ones. Moreover for some low values of pitch (standard deviation $< 0.5°$), important ratio of "bubbled" ping can still be observed (more than 10%).

It is therefore rightful to wonder if these bubbles are generated by the ship itself or if they are naturally created by surface turbulence at high wind speed. For that reason a horizontally steered echosounder has been used during the 2013 survey, to study bubbles occurrence close to the free surface of the sea without ship influence.

3.2. *Analysis of horizontally steered echosounder data*

During fishery acoustic surveys, a horizontally steered ER60 echosounder at 120 kHz can be mounted in a tube located at the center of the vessel in order to cover the acoustic surface blind zone of the vessel and then reduce possible bias in the assessment with vertical echosounders. This sounder is oriented horizontally, to starboard (see Fig. 8), allowing the observation of the sea surface layer to assess the quantity of bubbles in the water column. The objective is to distinguish bubbles generated by ship motions from natural bubbles present below the ocean surface, as we can see in Fig. 9.

The analysis of horizontally steered echosounder data requires some precautions. First of all, a layer must be determined sufficiently far from the ship to make sure that the reflections measured are not due to the bubbles generated by its motions nor its bow wave. It has been demonstrated by Lord Kelvin in 1887 that ship bow generates a wake with a constant angle of 19.5° from the ship's route. Taking into account the beam of the ship (14.90 m), this bubbly wake would be up to a distance of 20 m from the horizontal echosounder at midship. The signal may also be reflected by the free surface or the seabed, especially when the ship is rolling. For these reasons data have been filtered to take into account in the analysis only the pings corresponding to a roll between 0° and 2° toward the seabed. Considering all these elements, a layer has been chosen between 30 and 32 m from the sonar. In this layer, the minimum depth reached in the beam width at −3 dB is 5.6 m with a roll of 0°, and the maximum is 9.5 m with a 2° roll.

The mean depth seen by the horizontal echosounder is 7 m while the mean depth of the first layer for the vertical echosounder is 9 m. It has been shown in Section 2.2 that a threshold of −50 dB corresponds to a void fraction $VF = 2.2 \cdot 10^{-10}$ for a depth of 9 m. Taking $d = 1$ m in the distribution of bubbles (Eq. (7)), n_0 is obtained and the distribution of bubbles at 7 m depth is

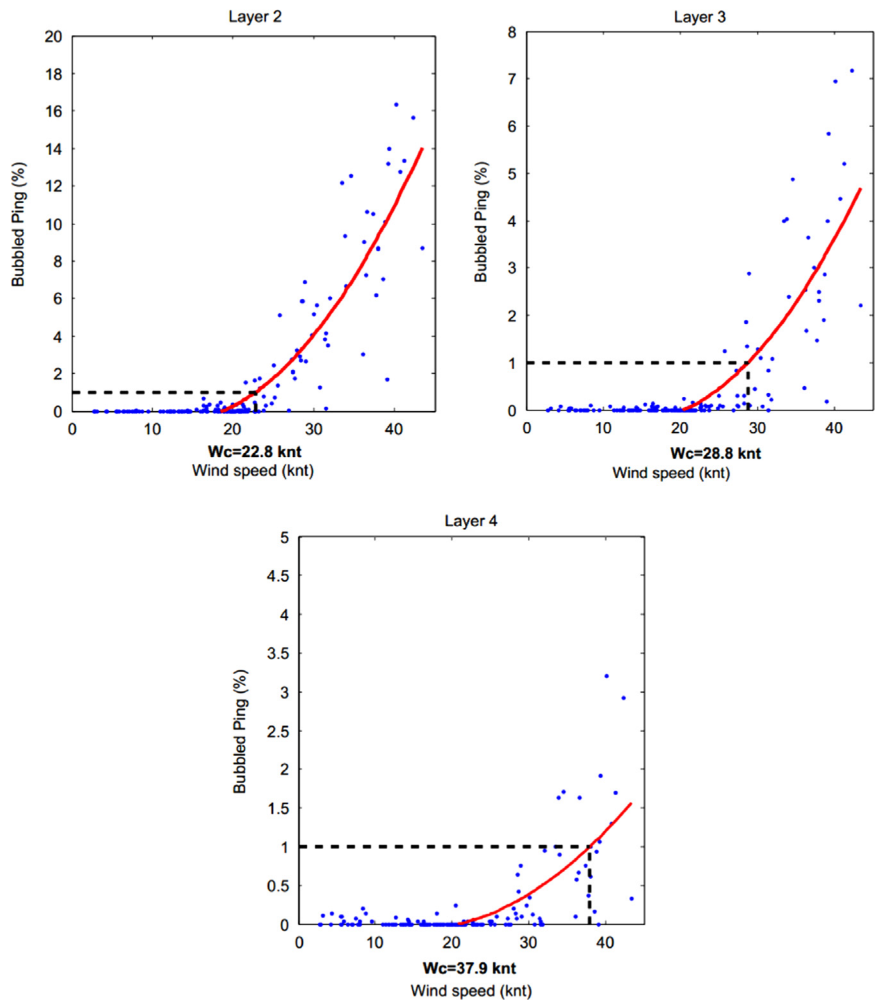

Fig. 7. Influence of depth on bubble generation: ratio of "bubbled" ping vs wind speed for layers 2, 3 and 4 respectively between 4–6 m, 6–8 m and 8–10 m under the sonar.

Table 2
Distance under the sonar, mean depth, maximum of "Bubbled" ping and critical wind speed for the 4 layers.

Layer	Distance (m)	Mean depth (m)	BP max (%)	W_c (knt)
1	2–4	9	18	21
2	4–6	11	16	23
3	6–8	13	7	29
4	8–10	15	3	38

determined:

$$n(a,7) = n_0 \cdot \exp(-7/d) \cdot \exp(-a/34) \tag{11}$$

The void fraction is thus higher, $VF = 1.6 \cdot 10^{-9}$, and corresponds to a higher volume backscattering strength: $S_{v7} = -41.5$ dB.

The same analysis as in the previous section has been undertaken with the S_{v7} threshold in order to take into account the depth difference between the layers. In this case, the ratio of bubbled ping is always under 1%, even with wind higher than 20 knots (10 m/s). The detection of bubbles is significantly higher under the hull than in the natural sea sub-surface layer at the same depth.

However natural aeration can still be observed by the horizontal echosounder. Taking the initial threshold $S_v = -50$ dB, the evolution of bubble detection is very similar to that in the first layer under the hull (Fig. 10). The four periods marked in Fig. 10 correspond to images A, B, C, D from the horizontal echosounder in Fig. 11. The horizontal axis represents the vessel's travel (1 mile between two vertical lines) and the vertical axis represents the distance to the sonar (graduated from 10 to 40 m by step of 5 m). The threshold of visualization is -50 dB. The mean wind speed on these periods are respectively 11; 17; 23 and 27 knots (5; 8; 11 and 14 m/s). Image A, with low wind, is very clean, and disruptions increase with the wind speed until a very noisy state on image D for which the wind begins to be strong.

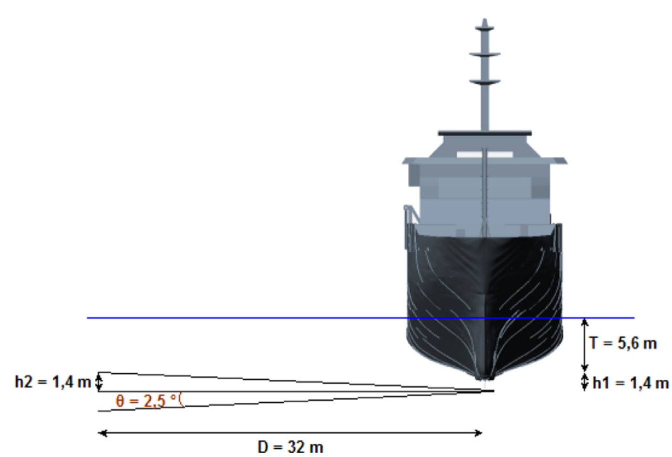

Fig. 8. Drawing of the layer studied with the horizontal echosounder under the Thalassa.

This analysis indicates that the density of bubbles under the vertical sonar is similar to that in the open sea sub-surface 2 m above. The specific flow generated by the ship's motions may carry these bubbles under the hull.

Furthermore it must be specified here that the bubble sweep-down occurrence is underestimated by the methodology of analysis of the vertical echosounder. Indeed a significant part of bubble clouds stays in the layer just below the hull (less than 2 m deep under the hull), where the echo-integration is not available.

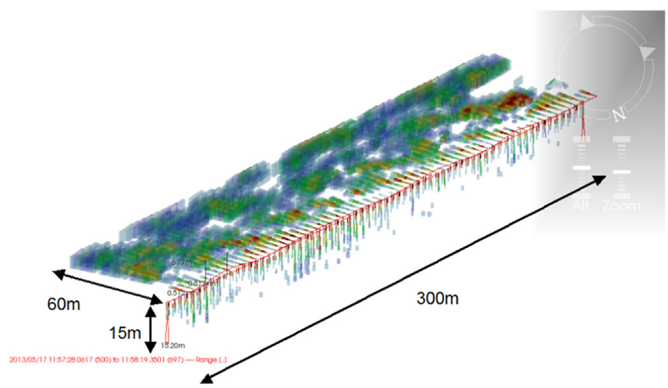

Fig. 9. Illustration of the acoustic perturbations at the sub-surface from horizontal sounder measurements.

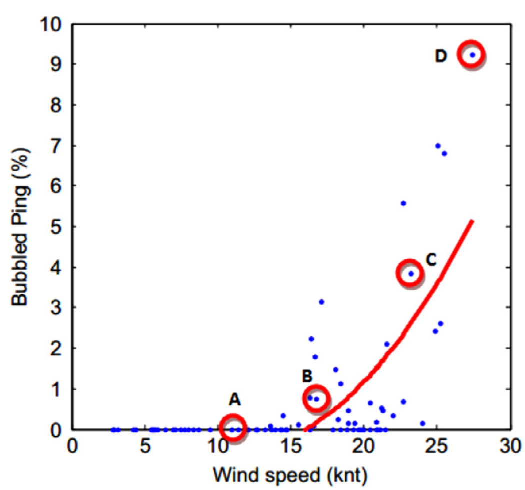

Fig. 10. Influence of the wind on natural aeration: “Bubbled” ping vs wind speed for the horizontally steered echosounder with a threshold $S_v = -50$ dB.

4. Comparison of bubble sweep-down occurrence with the Pourquoi Pas ?

In order to test the developed method for bubble sweep-down characterization and to prove its consistency for another vessel, we analyzed a data base acquired during Pourquoi Pas ? cruises. The Pourquoi Pas ? is the main oceanographic research vessel of Ifremer fleet, equipped with a gondola for acoustic sensors installation (see Fig. 12). Three Simrad EA600 echosounders (12, 38, and 200 kHz) and a Reson ME70 multibeam echosounder in the range 12–100 kHz are installed on this vessel. We use for this study only a data base coming from the 200 kHz sounder EA600 during a transit between Brest (France) and Pointe Pitre (Guadeloupe, Lesser Antilles) in November 2009. During this cruise, a wide variety of conditions has been encountered, with a maximum true wind speed of 73 knots (37 m/s).

The same methodology of acoustic data analysis used for the Thalassa database was applied for the data coming from the Pourquoi Pas ?:

- selection of stable periods in term of velocity (ship / wind) and heading;
- for stable periods (of 20 minutes):
  - ship's motions and wind conditions analysis;
  - acoustic disturbances quantification.

Fig. 13 presents a comparison between Thalassa and Pourquoi Pas ? of the ratio of “bubbled” pings during a period in function of the true wind speed. These results show that the critical wind speed value, from which the number of “bubbled” pings is non-negligible, is the same for both vessels between 20 and 25 knots (10 and 13 m/s). For wind speed higher than 30 knots (15 m/s), the number of “bubbled” pings reaches higher values for the Pourquoi Pas ? than for the Thalassa. For the analysed database, it is quite rare that the number of “bubbled” pings is higher than 15% for the Thalassa while it can reach 40% for the Pourquoi Pas ?. Even if the two databases are not as complete as might be desired, these two vessels seem to have a different behavior from an acoustic point of view.

This result is confirmed by the comparison of the ratio of “bubbled” pings at 200 kHz during a period in function of pitch standard deviation presented in Fig. 14. In this picture, we can see that the ratio of “bubbled” pings is negligible for the Pourquoi Pas ? for a standard deviation of pitch less than 1° while the Thalassa can be affected for small pitch variations. Furthermore, for pitch standard deviation higher than 1.5° the ratio of “bubbled” pings increases very quickly to reach values higher than 20% for the

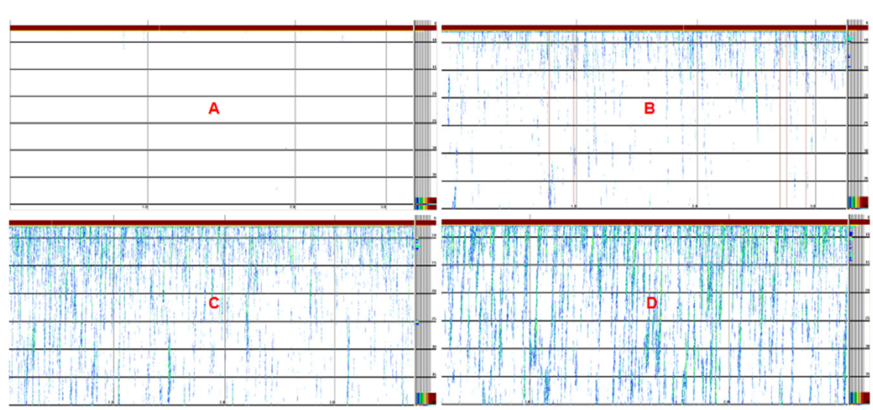

Fig. 11. Visualization of bubbling by the horizontal echosounder for different wind speed. $W=11$; 17; 23 and 27 knots respectively for periods A, B, C and D. The acoustic perturbation levels can be identified by the density of dotted blue lines. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

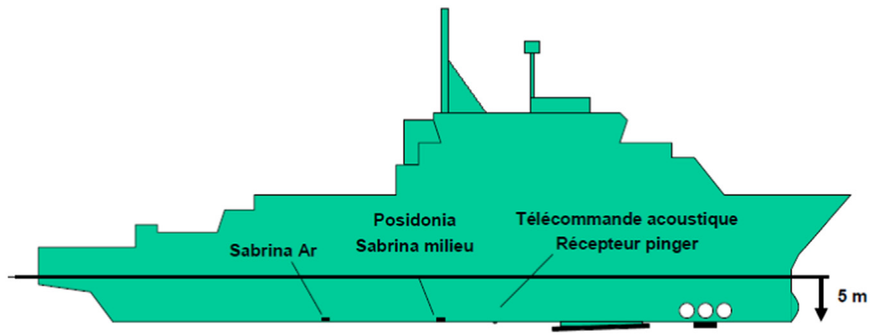

Fig. 12. Pourquoi Pas ? with its acoustic equipment mounted on a gondola.

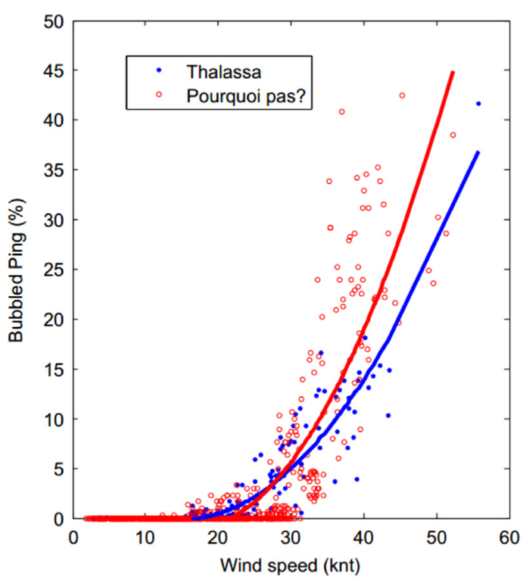

Fig. 13. Comparison between the Pp? and Thalassa of the wind influence on bubble sweep-down.

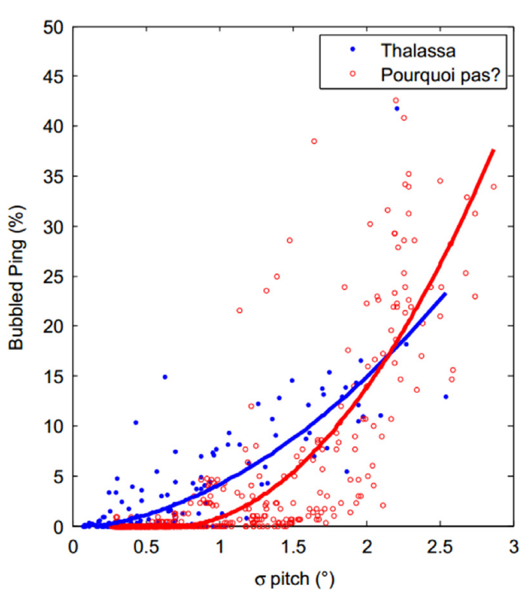

Fig. 14. Comparison between the Pp? and Thalassa of pitching on bubble generation.

Pourquoi Pas, while these values are almost never reached for the Thalassa. Ratio of "bubbled" pings values higher than 5–10% are generally unusable for acoustic surveys.

These results show that this kind of analysis can be done to compare the "acoustic performances" of different kinds of research vessels but also to quantify the limitations in term of condition at sea for acoustic survey (Delacroix, 2015).

5. Conclusion

Direct detection of near resonance bubble clouds at 120 and 200 kHz has been demonstrated using a simple threshold of the backscattered S_v data that effectively separate bubbles from other scatterers as plankton. This method enables us to compare, using calibrated echosounders, the percentage of bubbled pings for different platforms and different sea conditions. Such process has been implemented with both vertical and horizontal echosounder and allows us to monitor bubble clouds just below the transducer but also outside the influence of the vessel. The correlation between the observations of bubbles and wind speed is strong ($R^2 > 0.8$). Bubble clouds under the hull is generated by winds greater than $W_c = 21$ knots (10 m/s). The layer of observation is deep (8–10 m) due to sounder blind zone and transducer near field. For natural bubble entrainments away from the vessel, the depth vary between 5.6 and 9.5 m. The analysis of bubbles distribution indicates that the void fractions in this layer of the open ocean is very similar to that in the deeper layer under the vertical echosounder, which demonstrates the effect of bubble sweep-down.

This study confirms the influence of the sailing conditions on bubble sweep-down occurrence. The relation of this phenomenon with the depth has also been demonstrated. It is consequently appropriate to install the transducers at a greater depth to avoid this kind of problem. Though this precaution is not always sufficient and experiences of some vessels equipped with gondola are not always positive. The work of diminution of bubble propagation under the hull of a ship must start long before transducers mounting, from the design of bow shapes and the dynamical study of the ship.

The database used in this work may not be exhaustive, so further analysis with more sailing conditions and sea states, especially with different sorts of swell (short and large), are necessary. We thought first that in this particular working area of the eastern Channel and the North Sea, with shallow water, specific currents (as the Langmuir circulation) may drag more bubbles clouds under the surface layer than in deeper water. The analysis of data from Atlantic surveys coming from the Thalassa but also from data coming from the Pourquoi Pas ?, with larger swell and greater depth, does not confirm this hypothesis. Indeed, a larger statistical analysis does not give a better understanding of the influence of each parameter. The results presented in the study show that the proposed methodology of acoustic data analysis can be done to compare the "acoustic performances" of different kinds of research vessels but also to quantify their limitations in term of condition at sea for which acoustic survey can be done. The comparison between Thalassa and Pourqoi Pas ?, though limited, allows us to confirm that for wind speed above 20 knots (10 m/s) and pitch greater than 2° the Pourquoi Pas ? is more affected by surface bubbles with twice more bubbled pings observed.

Studies of the influence of meteorological conditions on the bubble distribution in the sea surface must be extended. Analysis of measures from seabed fixed sonar will be undertaken. These data should be compared to the observations made with horizontally oriented ship sonar and with results of previous study in the open ocean (Novarini and Bruno, 1982; Thorpe and Hall, 1983) or in laboratory (Leifer et al., 2006).

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