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ON THE POSSIBILITY OF ESTIMATING SHIP PARAMETERS USING ACOUSTICAL LLOYD'S MIRROR EFFECT

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The Lloyd's mirror effect is an acoustic effect taking place when a source of noise moves parallel to a reflecting surface. In the case of ships, the underwater sources of noise, mainly the propeller, are at constant depth, i.e. a constant distance, from the free surface that can be considered a perfectly reflecting surface. In such a configuration, a destructive-constructive interference pattern is generated in the time-frequency domain by the combination of the direct and surface-reflected sound waves. As the shape of the acoustic patterns depends on the speed of the ship, the relative distance between the ship and the hydrophones and the sound celerity, it is in principle possible (it has been successively done for aircrafts) to derive the above mentioned characteristics simply analysing the corresponding Lloyd's mirror effect. This is particularly interesting when monitoring shipping noise traffic when data regarding ships cannot directly derived by the Automatic Identification System (AIS). In the paper a set of measurements carried out in the framework of two EU FP7 European Projects are analysed to discuss about the possibility of estimating ship parameters using acoustical Lloyd's mirror effect. During the measurements the main ship parameters have been monitored by GPS therefore representing a good reference test.

Keywords: underwater noise; ship noise; Lloyd's mirror effect.

1. Introduction

In the last decades the continuous increasing of human activities in the ocean has focused the attention of local and international institutions on the underwater noise pollution due to shipping traffic. While for military purposes the topic of ship noise played a fundamental role since the WWII, in the civil field only recently standards for measurements have been issued. Furthermore, in the next future, the enforcement of compulsory limits is foreseen. The topic of ship noise control is high in the agenda of both the International Maritime Organization (IMO) and the European Union (EU). Several documents have already been issued addressing the problem [1], [2], [3], [4] and it is found that a priority is the monitoring of the underwater noise emitted by ships in areas interested by intense ship traffic. Such monitoring can be carried out both experimentally and numerically by means of simulations. As regards the experimental monitoring, it is typically carried out by deploying one or more hydrophones in area with intense ship traffic. As regards numerical simulations, they are performed by evaluating the noise emitted by individual ships transiting in a specific area, propagating in the acoustic medium [5] and summed up in order to predict the overall shipping noise contribution. In performing such simulations the ship noise source level is estimated by means of models [6], based on some macro parameters. Examples of such parameters are the ship type (e.g., class and dimensions), position and operative conditions (e.g., speed) which are generally gained by the Automatic Identification System (AIS).

However, this approach poses the problem of selecting an absolute depth, ranging from the free surface to the ship draught, where the equivalent noise source has to be placed. All those spectral models [6] depict the ship as a single point-like source, that is usually located at a depth range within the propeller disc, since the propeller is considered to be the major contributor of ship noise (i.e., propeller spectral lines and propeller cavitation). This parameter is depending on the actual ship draught and the location of the propeller disc, information that are difficult to retrieve in many circumstances (including the access to the AIS). The source depth is therefore usually derived from typical ship non-dimensional ratios [7] or assigned to be an a-priori value (e.g., 1 m below the sea surface), introducing a systematic error that affect the performance of the simulations. In the present work, the possibility of deriving such parameters (i.e., ship speed, position and equivalent point-like source depth) from ship noise measurements by means of the acoustic Lloyd mirror effect (LME) is evaluated by considering the effect on uncertainties in the estimation of their values. The LME takes place when an acoustic source is moving close to a reflecting surface. It depends on the source speed and on the distance from the receiver position. In the case of ship noise, the LME is a well know effect, visible in many experimental measurements because of the presence of the flat free surface, thanks to the high acoustic impendence difference between air and water, which results in a reflecting surface. The investigated technique has been already proposed to derive such kind of information for aircrafts flying close to the ground [8]. The noise data used in the analysis have been recorded during supervised ship passages nearby the receiver system (adopting the ANSI/ASA standard [9]), while monitoring the ship speed and position (via GPS and on-board instrumentations). Such monitoring system has allowed to address the feasibility of the investigated technique in estimating the considered ship parameters from the observed LME.

2. Lloyd’s mirror effect characteristics

The Lloyd’s mirror effect is a phenomenon taking place when a source of noise is moving parallel to a reflecting surface (see Figure 1). In this configuration, the sound field at the receiver is the sum of the direct and surface reflected paths. Depending on the frequency, the phase difference among the two contributions can give either a constructive or destructive interference pattern. See for example Figure 2 where a simulated example is shown. As it can be seen, a succession of arch-shaped curves, representing the variation in time of the destructive interference can be easily identified. The shape of those curves depends on a series of both environmental characteristics and on the moving object ones.

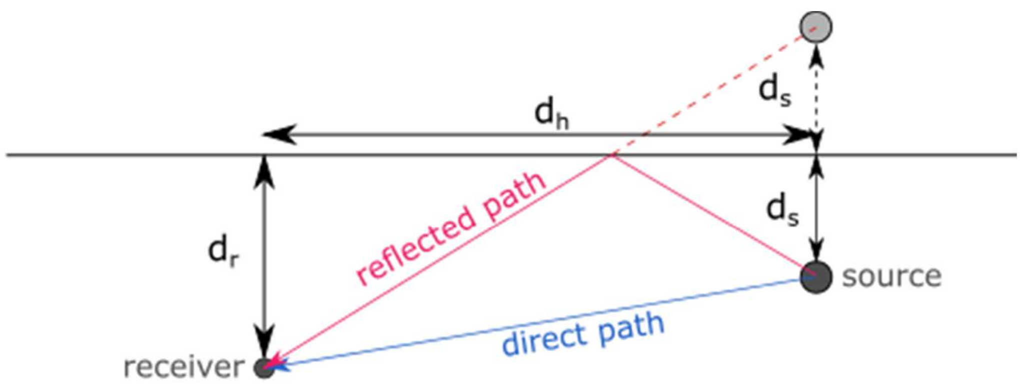


Figure 1. Lloyd’s mirror effect pattern.

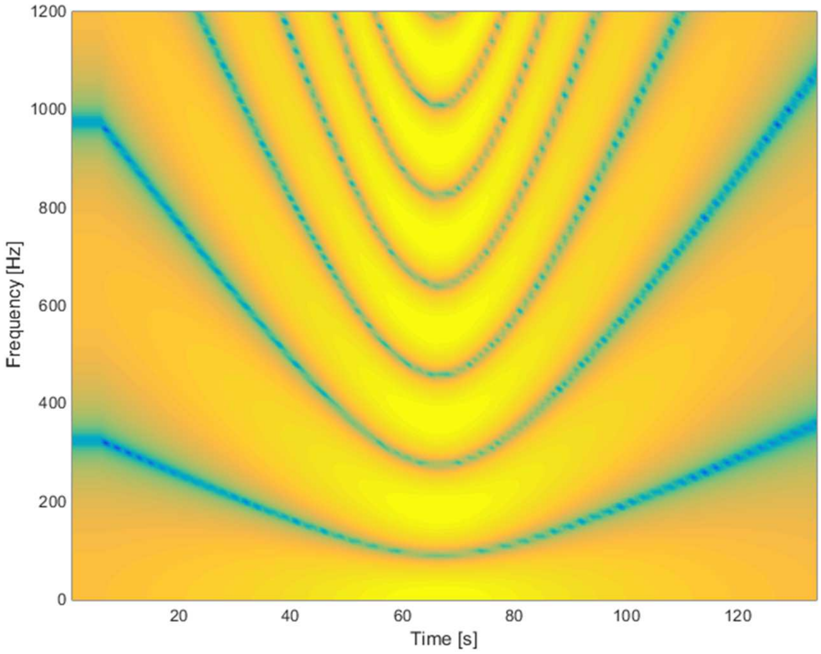


Figure 2. Simulated time-frequency distribution.

In order to derive the shape of the interference curves the quasi-stationary approach suggested by [10] is followed. The direct and the surface-reflected paths can be derived making reference to the sketch of Figure 1. The direct path can be written as

$$R_d(t) = \sqrt{v^2(t - t_{CPA})^2 + d_{CPA} + (d_r - d_s)^2}\ , \quad (1)$$

while the surface reflected path is

$$R_d(t) = \sqrt{v^2(t - t_{CPA})^2 + d_{CPA} + (d_r + d_s)^2}\ , \quad (2)$$

where v is the ship speed in m/s, t_{CPA} is time when the ship passes at the closets point of approach (CPA) in *s*, and d_{CPA} is the horizontal distance between the ship and the receiver at the CPA in *m*. Destructive interference occurs when the phase difference between the direct and reflected path is equal to an odd integer multiple of π. Considering the free surface as a perfectly reflecting plane due to the large difference in the impedance between air and water, the reflected wave does not feature a change in phase. With this hypothesis the destructive interference occurs when

$$2\pi f_n(t)\frac{R_r - R_d}{c} = (2n-1)\pi,\ n = 1, 2, \dots, \quad (3)$$

where c is the sound propagation speed in m/s and n the order of the n-th harmonic frequency. Therefore the variation of frequency in time is

$$f_n(t) = \frac{c}{R_r - R_d}\frac{(2n-1)}{2},\ n = 1, 2, \dots . (4)$$

Equation (4) identify a succession (i.e. a family) of curves in the time-frequency domain representing the destructive interference patterns such as, for instance, those plotted in Figure 2. In principle the time t in the above formulas should represent the radiating time, i.e. the time at which the signal is radiated by the source in the environment, and it is different from the time τ at which the signal is received. The relation between the two is

$$t = \tau - \frac{R(t)}{c}, \quad (5)$$

where R is the total distance between source and receiver, and therefore the ratio in the equation represent the sound travel time form the source to the receiver. In the specific case of ships analysed in the present paper this phenomenon produces a small effect (see Figure 3) due to the high sound speed and the relatively close distance between source and receiver. Such effect is therefore neglected.

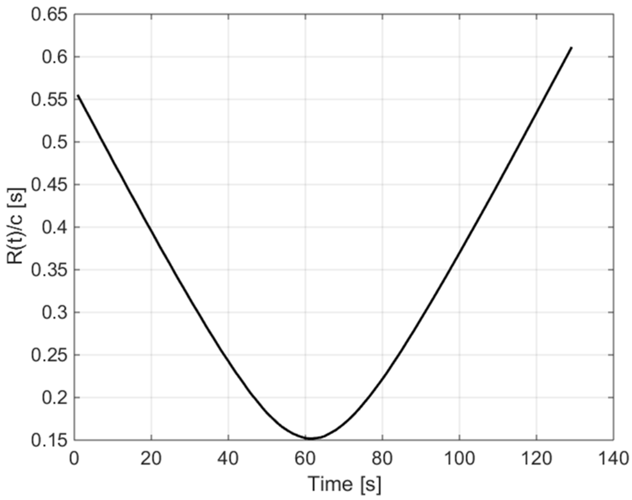
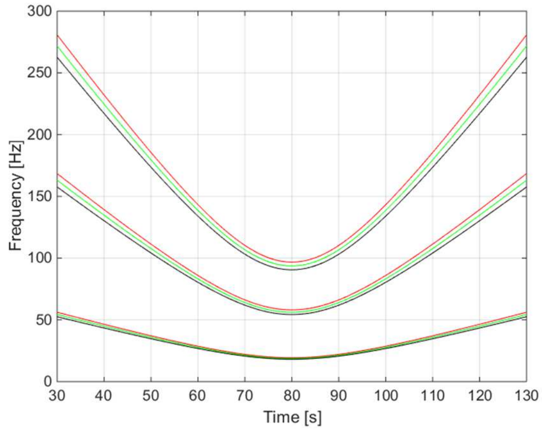


Figure 3. Time variation of the arrival time.

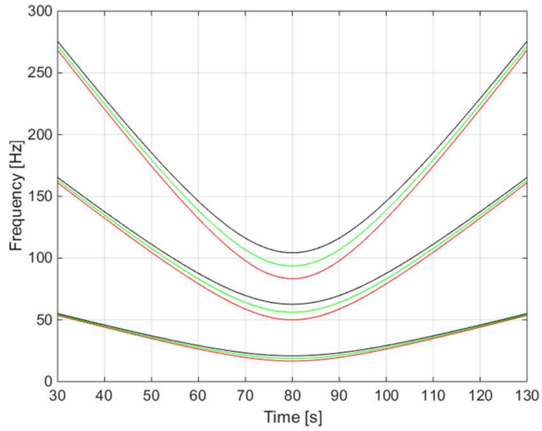
3. Parameters influence

Given the fixed position of the receiver, i.e. the hydrophone, four ship parameters (v, t_{CPA}, d_{CPA} and d_s) and one environmental characteristic (sound celerity) influence the shape of the destructive interference curves (see Figure 4).

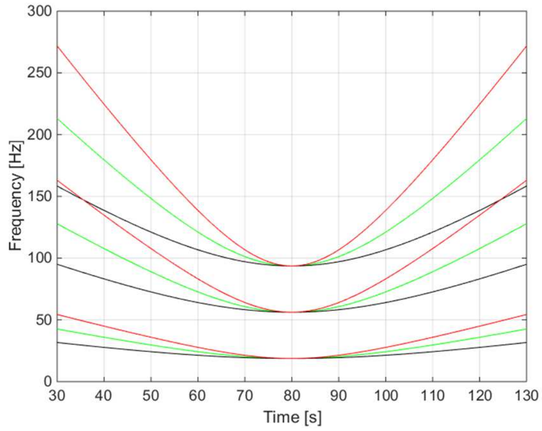
Looking at Figure 4a) and e) it can be seen that both the sound celerity and the source depth have a limited influence on the shape of the curves featuring an almost constant shift in frequency with a directly proportional behaviour in both cases. This is also due to the fact that the range of variation for both the cases is very limited. The distance at the CPA, Figure 4b) have the effect of stretching the curve by moving its minimum towards lower or higher frequencies in the same direction of d_{CPA} variations. Consequently, larger effects appear at times close to the t_{CPA}. On the contrary the effect of the ship speed, Figure 4c) does not affect the minima of the curves that remain fixed; the effect is to “open” or “close” the curve changing the slope of the two arches before and after the t_{CPA}. Finally, the effect of changing the t_{CPA}, Figure 4d), results in a constant shift of the curves in time.



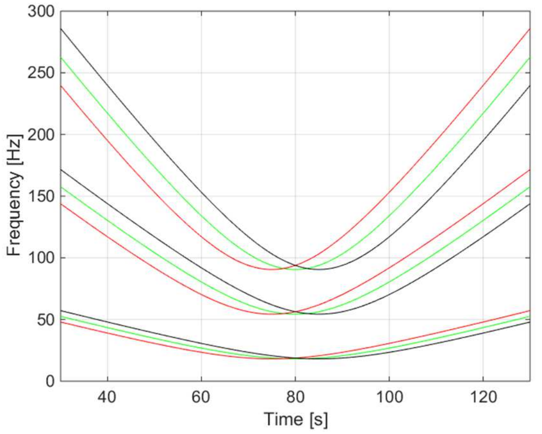
a) Influence of the sound celerity: 1500 m/s (green), 1450 m/s (black) and 1550 m/s (red).



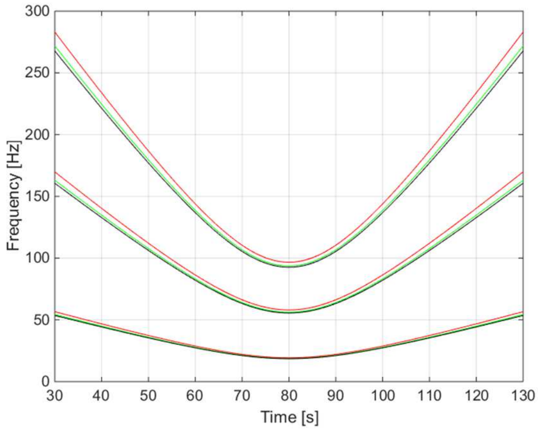
b) Influence of the d_{CPA}: d_{CPA} (green), d_{CPA}+25m (black) and d_{CPA}-25m (red).



c) Influence of the ship speed (v): 15 kt (green), 10 kt (black) and 20 kt (red).



d) Influence of the t_{CPA}: t_{CPA} (green), t_{CPA}-5s (black) and t_{CPA}+5s (red).



e) Influence of the source depth (d_s): 2m (green), 0.5m (black) and 6m (red).

Figure 4. Influence of the various parameters on the shape of the interference pattern (order 1, 2, 3).

4. Analisys of ship full scale measurements

In the following, data coming from the experimental campaigns carried out in the framework the two EU FP7 collaborative projects SILENV and AQUO are analysed. Measures have been carried out following the ANSI/ASA standard [9] with the ship passing abeam a string of hydrophones deployed in the water column. During the trails both the buoy position (from which the hydrophones were deployed) and ship position and speed were monitored via GPS. The sound speed profile were measured by CTD.

In Figure 5 the measured spectrogram of a ship passage is reported together with the one simulated using the data monitored during the trails.

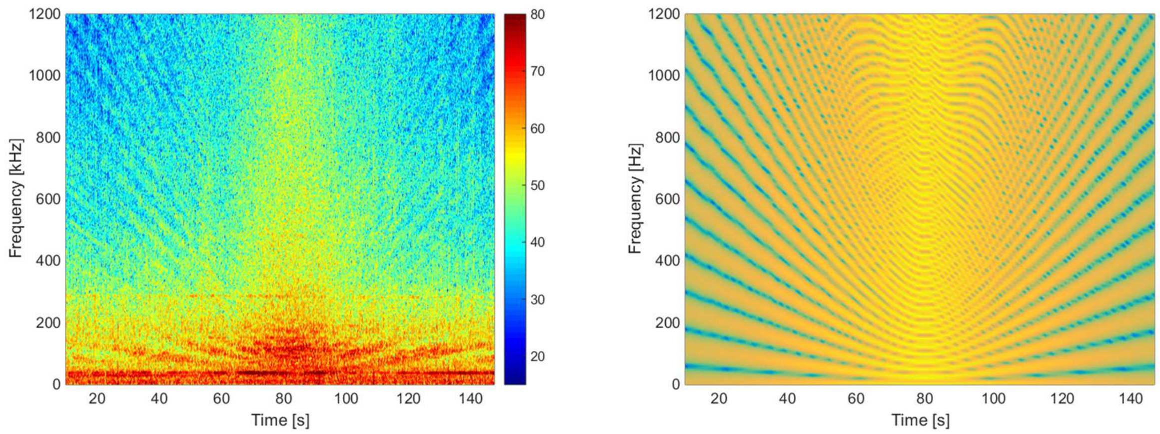


Figure 5. Measured (left) and simulated (right) spectrogram featuring the peculiar pattern of the Lloyd's mirror effect.

Looking at Figure 5 (left) the typical Lloyd's mirror effect pattern can be noted. Comparing it with Figure 5 (right) the detectability of the descriptive interference is influenced by the intrinsic frequency content of the ship source that results in a spectral shape with an energy concentration below 200 Hz and a constant decay at higher frequencies. Such effect it is not present in Figure 5 (right) because the simulated has equal levels for each frequency. In addition to this, background noise is present because measurements have been carried out in open sea and, even if no ships were present in the vicinity, sound propagates very well at sea so very far shipping traffic noise can anyway affect the measurements. Nevertheless, by comparing the two plots of Figure 5 a good agreement between the two patterns can be identified.

In order to investigate the possibility of estimating ship parameters starting from charts like that presented in Figure 5 (left), the curves, as defined in Equation 4 and evaluated using the real ship parameters monitored during the measurements, are superimposed to the experimental spectrogram (see Figure 6). The black dotted curves represent the best estimation of LME that can be achieved as the ship parameters have been directly measured during the trials. Nevertheless, looking at Figure 6 it can be noted that the agreement between points and the spectrogram it is not always good. In particular the agreement changes for times before and after the CPA. In principle, such kind of dissymmetry can be due to the Doppler effect, as before the CPA the ship is approaching the receiver while after CPA the ship is moving away. In Equation 4 the Doppler effect is not taken into account, but for the low speed of ships compared to the sound celerity this can be neglected and more probably the observed distortion is due to the directivity of the ship radiation pattern. As a matter of fact the major source of noise is the propeller which is located at the very stern reflecting on noise levels that are higher when the ship overcame the CPA and the propeller is in view of the hydrophone. Other aspects that cannot be taken into account in the simple formulation here presented are the sea surface roughness and the possible interaction with the sea bottom if measurements are not carried out in deep waters.

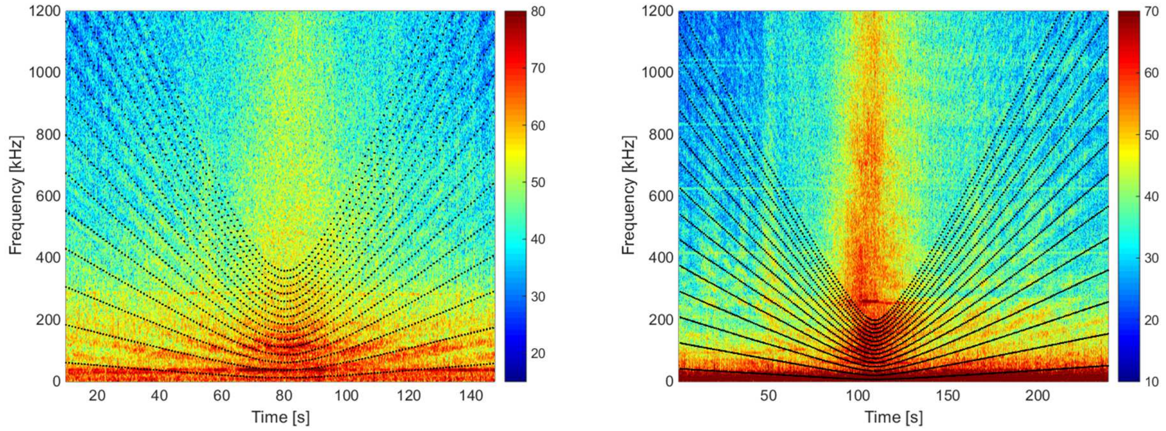


Figure 6 Superimposition of estimated Lloyd's mirror pattern (up to 15th order) and spectrograms for two different ship types measured in different environments

5. Final considerations

In this paper the characteristic of the pattern generated by the Lloyd's mirror effect (LME) in the underwater noise emitted from a ship has been analysed. The effects that the different parameters related both to the moving ship and to the scenario characteristics have been separately analysed in order to highlight the single contribution that each of them have on the LME pattern.

Some data from experimental campaigns aimed at characterising the underwater signature of commercial ships have been analysed. The possibility of estimating ship parameters by the LME is discussed by comparing simulated patterns with measured ship spectrograms. The simulated patterns are derived using the ship parameters measured during the sea trials. This way the curves represent the best possible LME pattern simulation that can be obtained as the inputs are affected by small uncertainties. The general agreement between the measured and simulated patterns is good but some sources of uncertainties linked to the environment and to the ship source peculiarities produce some discrepancies. The effect of such discrepancies on the ship parameters estimation has not been directly evaluated in the present work but looking at Figure 5 and Figure 6 a rough estimation of the error can be made.

In order to set up a procedure to automatically estimate ship parameters two main aspects need to be analysed: the extraction of the patterns curves form the spectrogram by image processing techniques and the parameters estimation by optimisation techniques for the best curve fitting,.

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