# THE INVESTIGATION OF PROPAGATION OF ACOUSTIC WAVES GENERATED BY A MOVING SHIP

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*A moving ship is a source of acoustic perturbations resulting from her complex hull being a surface of irregular shape and from a rotational source – the propellers. The sources generate acoustic waves in wide frequency band. In case of a shallow sea the propagation of the acoustic waves for varying source-detector distances and different frequencies are described applying the modes and ray theory.*

## INTRODUCTION

The propagation of acoustic waves under water is essentially dependent on the water depth and the frequency of the waves. Shallow sea is characterized by small value of the depth scaled by the number of lengths of the acoustic wave propagating in the sea. The variability of acoustic wave propagation in a shallow sea is due to the fact that the closeness of the medium borders of different acoustical impedances strongly influences the acoustic field distribution of a source located in the sea. Summing of the direct waves and ones reflected from the border surfaces creates this field. The theoretical description of wave propagation in a shallow sea is a complex issue [1,2] and therefore simplified propagation models are used [3].

## 1. METHOD OF INVESTIGATION

In order to explain this phenomenon simulation of the rays propagation was conducted. For simplification the model it was assumed that the depth of the sea was h = 20m, speed of sound in water - 1450 m/s and the medium was lossless.

In such model we determine the rays of waves that reflect from the medium borders according to the equation: $r = \frac{2h^2}{\lambda}$. The rays was obtained numerically for different wavelengths and the varying distances between source and receiver. In the calculations it was assumed that the maximum wavelength that may propagate at such depth is equal to 40 m (standing wave). The calculations were conducted for waves in the range from 0.1 m to 40 m with resolution 0.1 m. The resulting matrix allowed drafting the propagations of these rays as a function of frequency, shown in fig. 1. The points marked on the ray represent the distance of consecutive waves from a hydrophone. For zero distance, when ship is located directly over the sensor, the length of standing wave is 40 m. The frequency of this wave f = 36.25 Hz is shown on the X-axis. The length of wave determines the creation of a primary mode, which is associated with the depth of the sea:

$$M_p = \frac{2h}{\lambda} \quad (1)$$

Distances determined numerically between sound sources and hydrophones for points marked in figure 1 are equal:

1. Distance $d_1$=200 m for wavelength $\lambda$=24 m.
2. Distance $d_2$=400 m for wavelength $\lambda$=12 m.
3. Distance $d_3$=600 m for wavelength $\lambda$=8 m.
4. Distance $d_4$=800 m for wavelength $\lambda$=6 m.

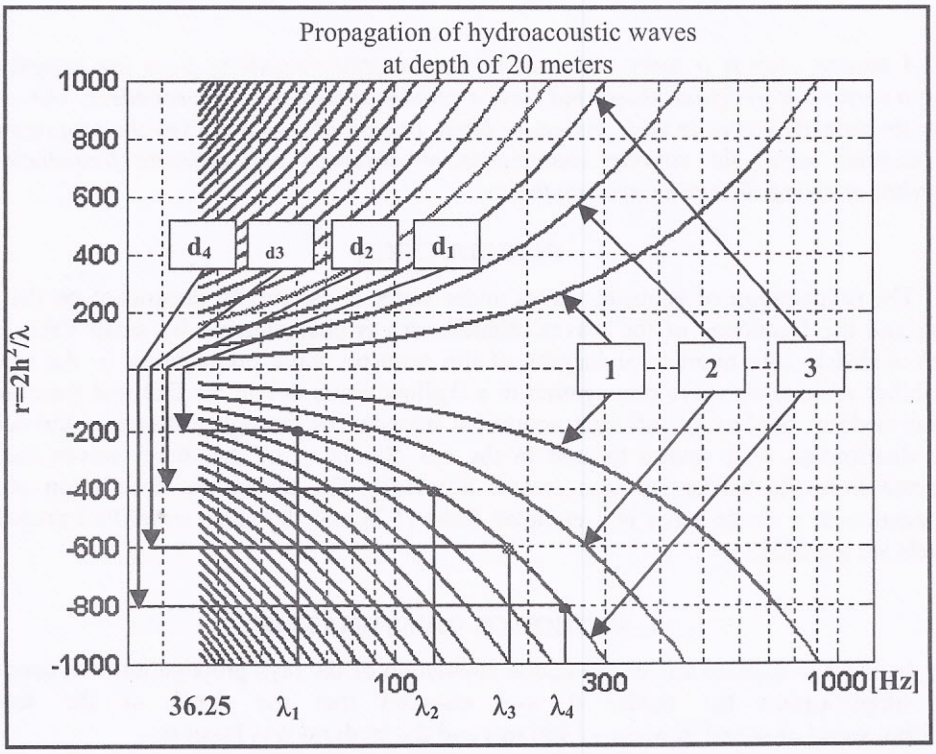


Fig. 1. Model of propagation of hydroacoustic rays generated at depth of 20 meters, where: $d_n$- source - hydrophone distance for a wave of length of $\lambda_n$,

N – propagation of hydroacoustic rays determined by equation $r = N\left(\frac{2h^2}{\lambda}\right)$

## 2. RESULTS OF MEASUREMENTS

Figures 2 and 3 show spectrogams of a hydroacoustic field of a moving ship. In the figures it can be discerned that as a result of a change in distance between the source and the detector certain series of local characteristic amplifications of acoustic pressure appear, starting from a certain frequency, and assume a hyperbolic ray forms more conspicuous for greater distances between source and detector.

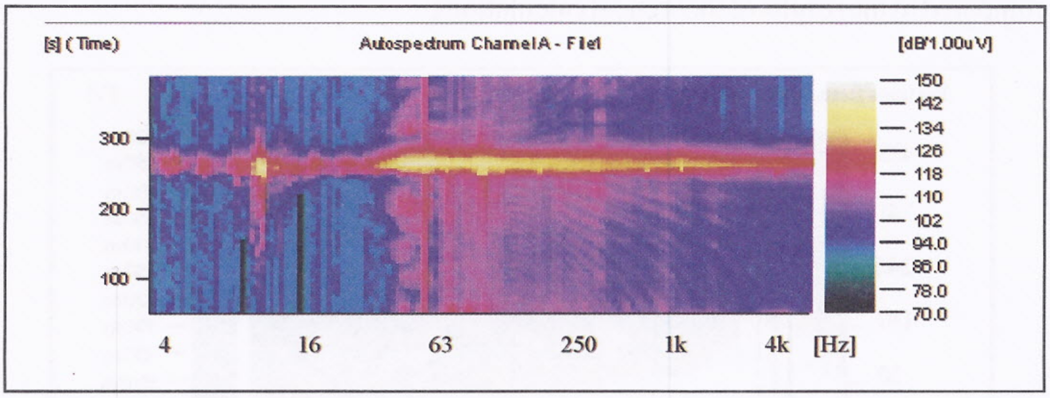


Fig. 2. Spectrogram obtained during ship investigations at a dynamic range at depth of h=10 m for speed of V=9 kts

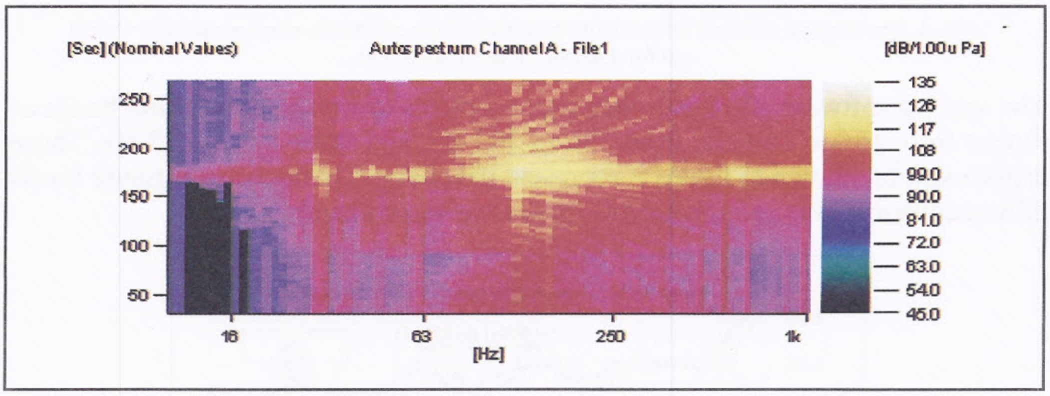


Fig. 3. Spectrogram obtained during ship investigations at a dynamic range at depth of h=27 m for speed of V=15 kts.

The distances of wave modes formation determined numerically were verified with results of measurements of underwater noise of a ship conducted at a acoustic range. The depth of water h=11.75 m was determined from an arithmetic mean of static pressure values evaluated from the indications of six hydroacoustic field sensors HONWELL ST 3000 and depth sensors. The speed of vessel V=9.3 kts was determined from log readings, markings on level register tapes and basing on the determined speed obtained from three sets of analyzers being part of the equipment of the hydroacoustic, hydrodynamic and magnetic field measuring stations.

In the research the application of the analyzer software allowed the tracing of 111 spectra registered every 1 s in the frequency bandwidth up to 1600 Hz with the resolution of 4 Hz. The spectrogram obtained in the research is shown in figure 4. The time axis was recalculated and presented as distance between source and detector. In the figure the waves of frequencies 160, 200 and 250 Hz were marked with cursors. In the marked positions the spectrogram cross-sections were obtained as a function of the distance. Consecutive reflections of these waves from the medium borders were determined from the obtained cross-sections of spectrogram. The results were compared to the results of theoretical calculations.

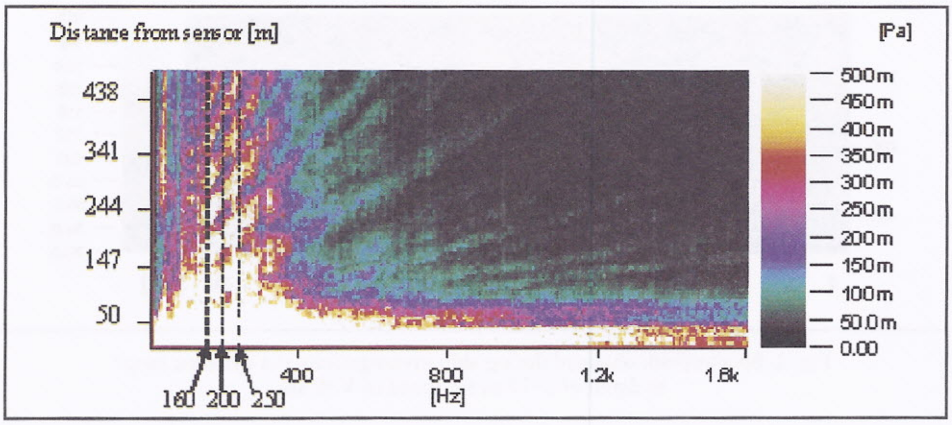


Fig. 4. Spectrogram obtained for a ship moving away from a dynamic range at speed V=9.3kts and for detectors at depth h=11.75m.

The applied software allowed to determine a cross-section of rays within bands of ranges from 156 to 160 Hz, from 196 to 200 Hz, and from 248 to 252 Hz. These cross-sections, shown in figure 5, represent the changes of acoustic pressure levels of the acoustic waves as a function of source - sensor distance.

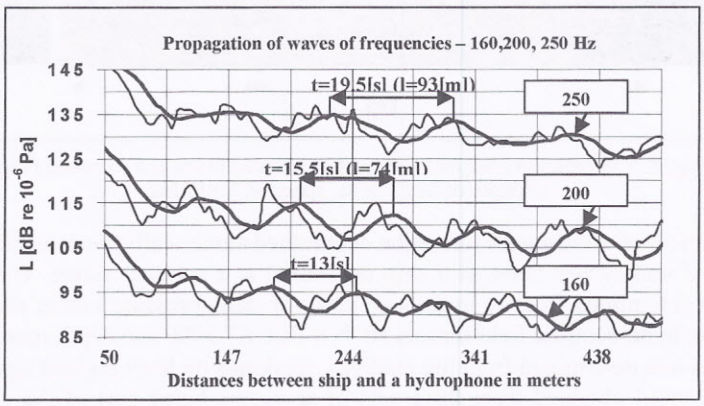


Fig. 5. Shallow sea propagation of waves of different frequencies:

1. wave of frequency 250 [Hz]. Signal amplified by 20 [dB].
2. wave of frequency 200 [Hz].
3. wave of frequency 160 [Hz]. Signal reduced by 20 [dB].

For all considered waves the average trend line was determined by means of calculation from seven consecutive measuring points using the relation:

$$n_k = \frac{\sum_{z=k}^{k+7} L_z}{7} \qquad (2)$$

where: k=1,2 ...
$L_z$ – measured value of pressure level
$n_k$ – point of mean trend line

Over the trend lines the time between consecutive maxima in hydroacoustic pressure values was marked. Knowing the speed of the ship, the time was recalculated into the distance that the ship will cover in that time. The distances were shown in brackets.

Knowing the lengths of chosen waves and the sea depth it was theoretically possible to determine the distances from a hydrophone where modes associated with these waves appear. The results of calculation of consecutive reflections from medium border are presented in table 1.

| f [Hz] | λ [m] | θ [rad] | $l_1 = \frac{2H^2}{\lambda}$ [m] | $l_2=2l_1$ [m] | $l_3=3l_1$ [m] | $l_4=4l_1$ [m] |
|---|---|---|---|---|---|---|
| 160 | 9.0625 | 0.38563 | 60.9 | 121.9 | 182.8 | 243.8 |
| 200 | 7.25 | 0.30851 | 76.2 | 152.3 | 228.5 | 304.7 |
| 250 | 5.8 | 0.24680 | 95.2 | 190.4 | 285.6 | 380.9 |

Table 1. Theoretical distances of appearance of wave modes from an acoustic source for waves of frequencies 160, 200, 250 Hz; Θ - critical angle

The calculated values were compared to values obtained from measurements at the acoustic range. The results of this comparison are presented in table 2.

| f [Hz] | λ [m] | $L_{theoretical}$ [m] | $L_{real}$ [m] | Error [%] |
|---|---|---|---|---|
| 160 | 9.0625 | 61 | 62 | ≈1,5 |
| 200 | 7.25 | 76 | 74 | ≈2,5 |
| 250 | 5.8 | 95 | 93 | ≈2 |

Table 2. Comparison of distance measured between consecutive wave reflections obtained at a dynamic range with results obtained theoretically.

The obtained results may be represented in form suggested in [3,4] taking into account different zones of propagation. This spectrogram is presented in figure 6.

## 3. CONCLUSIONS

From table 2 it may be inferred that the obtained errors between theoretical and real values did not exceed 3%. So small differences which occurred between the two comparisons may be caused by the fact that during the research the speed of sound was not measured for different depths, no bottom samples were taken and it was assumed that the surface was level with the bottom. The conducted calculations and the proposed simulation of propagation confirmed the assumed theory of acoustic rays' creation in the water environment as a result of multiple reflections of waves of different lengths from the borders of the medium.

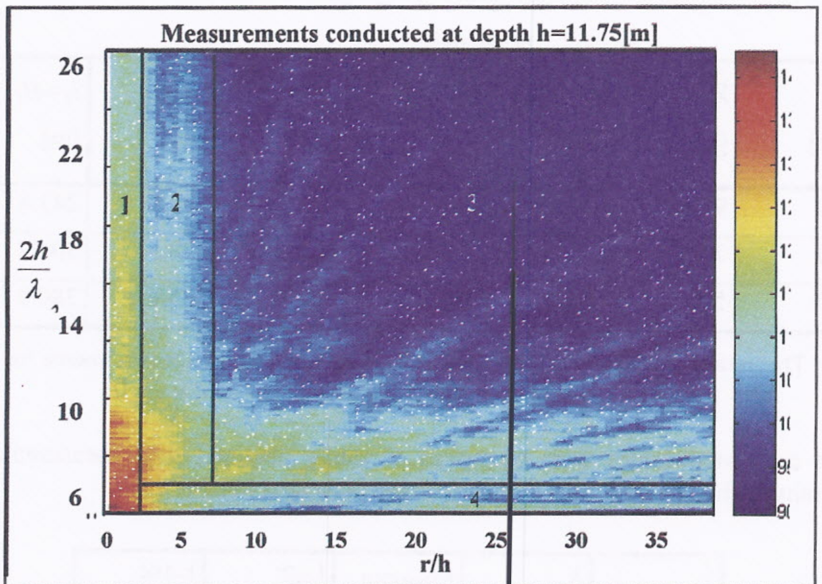


Fig. 6. Division into zones of different type of hydroacoustic wave propagation according to the measurement results obtained at a acoustic range for ship moving at speed V=9.3[kts].
where: 1. Spherical propagation zone.
2. Cylindrical propagation zone.
3. Zone characteristic for modes formation.
4. Bottom propagation zone.

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