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# Development of a coupled numerical and experimental approach to hydrodynamic noise estimation

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## Abstract

The hydroacoustic signatures of ship propellers can be identified experimentally through measurements of cavitation-induced pressure fluctuations and the accompanying noise distribution at model scale. These measurements have to be performed in a cavitation tunnel at the propellers operating conditions and with sufficient accuracy. In comparison, the numerical approach can be used to present a good general idea of the predicted results. Numerical methods can provide highly accurate tools for noise level and propagation prediction, as well as giving insight into the flow field and other key aspects. They are also not influenced by signal conditioning or disturbance sources present in a physical environment. So we trade scope and precision of the results for time and cost reduction. In this paper, we described both experimental and numerical methods currently in use and present advantages and limitations of the practical application of both.

**Keywords:** Hydroacoustics; URN; Noise estimation methods; CFD modelling; Signal processing; Experimental methods; Model scale tests

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# 1 Introduction

The sources of marine noise pollution caused by human activity include maritime transport, natural resources exploitation, sonar and experimental acoustic sources, underwater explosions, engineering activities and offshore structures. The hydrodynamic shipping noise having negatively impact not only the people on ships but also marine life has attracted considerable attention in recent years. Noise radiated by ships into the underwater environment can be divided into three main components: machinery noise, propeller noise and noise caused by the flow of water along the hull. In this paper, we focused on the ship propellers as one of the main sources that can generate high sound pressure levels, but can also be moderated through a hydroacoustic approach to propeller design [1–3]. The noise detected in the fluid can be generated either by a vibrating structure or by fluid fluctuations. Although the structural noise is very important and studied by many researchers [4–6,13–20], in the present work the vibration of the propeller structure is not considered and only the flow noise is studied. The hydroacoustic signals generated by ship propellers can be investigated experimentally by measurements of the cavitation-induced pressure fluctuation at model scale in cavitation tunnels at propeller operating conditions corresponding to those in the wake field, as well as hydroacoustic measurements. Background noise and the underwater radiated noise (URN) emitted by a propeller as well as the phenomena of underwater sound propagation in a closed tunnel have to be accounted for. On top of that, proper signal conditioning techniques within the measurement system have to be ensured. On the other hand, the numerical approach can give us a good general idea of the predicted results and does not require so many computing power to perform. It is also not influenced by signal conditioning or noise sources present in a real environment. So each method has significant advantages and drawbacks. Now the next logical step is to combine the individual experimental and numerical approaches into a coupled system to improve the precision of final hydrodynamic noise estimation significantly. In this paper, we described both experimental and numerical methods currently in use and present the advantages and limitations of the practical application of both. We also outlined the concept of their precision development individually and their ultimate evolution into a coupled approach towards final noise estimation.

# 2 Hydroacoustic noise field modelling

Mathematical modelling of hydroacoustic phenomena is, in general, a difficult task, as mathematical models should be reasonably easy transferable to numerical models that should be easy to implement and calibrate. The fundamentals of analytical and numerical models for pressure fluctuations and hydroacoustic signatures have been given in, e.g., [7–12]. The experience of numerous authors [2,5,13–20] proves that the practical application of numerical modeling of hydroacoustic phenomena emerges as an important and effective completion of extremely expensive experimental research. However, it should be noted that the numerical simulation should be precise and reliable so that the experimental verification in laboratory conditions can be achieved.

## 2.1 Experimental approach

The noise measurements are usually performed in order to predict the full scale acoustic source strength of the cavitating propeller with respect to the underwater radiated noise for a wide range of frequencies. The full scale sea trials provide a verification opportunity for both numerical and model scale predictions of the propeller generated noise. Usually, the model scale and full scale experiments require the same general elements to be performed, including measurement setup, hydrophones – underwater electroacoustic transducers, signal conditioning, (computer based) data acquisition and signal processing systems, and facilities/software for presentation of results. As compared to the numerical approach, the experimental one has to identify and include many more variables and phenomena and it is a complex issue because the requirement to identify and assess them may go beyond the experimenter's capabilities [21]. However, alike the numerical approach the experimental methods are constantly being developed in order to adapt to the ever growing requirements for data quality and certainty as well as to the growing knowledge of hydroacoustic phenomena and their impact on us and our surroundings.

Model scale experiments can be conducted in much better controlled environment than the sea trials, their source signal distortions can be usually well defined and considered, but their results are dependent on various scaling effects. The standard approach to the cavitating propeller noise consists in conducting the cavitation tunnel model scale tests. For this purpose, the propeller is mounted at the upper portion of the tunnel test section- behind a dummy body and/or a wake grid, which can be used for a reasonably accurate reproduction of the hull wake. During the tests, the noise measurements are performed with a hydrophone located in a hydroacoustic chamber, directly below the test chamber. Model scale measurements are set up and performed according to the International Towing Tank Conference (ITTC) guidelines [8]. A typical set up for model scale measurements is presented in Fig. 1. The obtained data can be scaled up to the full scale

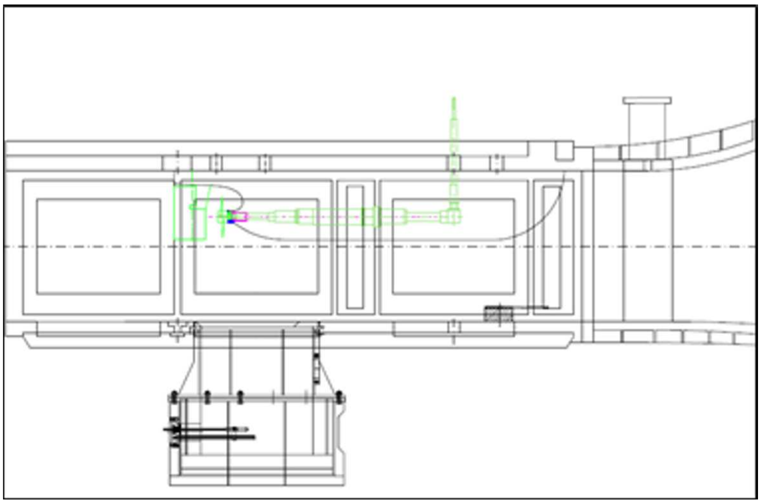

Figure 1: Cavitation tunnel test section.

with a suitable margin of error. Since most experiments were carried out at the reasonable time model scale the knowledge of scale effects is important mainly to be able to apply the solution to a real ship. Although the impact of the scale effect on the steady performance of the conventional propeller is quite well known [22], its impact on the pressure field responsible for the noise generation is still under a pending investigation. This is important because the scale effect on the effective wake can have a significant impact on the cavitation dynamics [23].

## 2.2 Numerical approach

Since the advanced numerical methods in fluid mechanics constantly evolve, the development of an approach to modeling and analysis of hydroacoustic noise began as well. Their progress has been followed for some time now by that of numerical modelling and quite a lot of articles about this topic can be found, e.g., [2,13,14,16,22]. The development of numerical prediction tools of noise emission, with particular emphasis on ship propeller noise, including the wake and hull-propeller interaction is an important step in order to acquire the skills necessary to perform this prediction. After taking into account the cavitation characteristics, the pressure oscillations associated with this phenomenon are calculated during the assessment of hydrodynamic pressure distribution in the near flow field. In most cases, this is done using an unsteady boundary element method (BEM) approach, where the occurrence of cavitation on operating propeller in an unsteady inviscid flow is included by means of an additional model. This approach is described in detail in [20]. The other one is finite volume method (FVM), where the variable of interest is located at the centroid of the control volume. This method is easy to apply for unstructured grids and often used in solving the three-dimensional fluid mechanics problems. The hydroacoustic analysis is carried out using the Ffowcs-Williams Hawkings (F-WH) approach. The basic equation F-WH was proposed by J. E. Ffowcs-Williams and D. L. Hawkings in [10] and uses generalized functions to extend the Lighthill's acoustic analogy approach to the aerodynamic noise generated by rotating bodies such as helicopter rotors or fan blades. This equation has also been applied to operation in water for the noise generated by ship propellers. In situations where detailed data on the turbulent phenomena in the near-field can be obtained, the Ffowcs-Williams Hawkings equation can be also used to broadband noise prediction. Most currently available commercial computational fluid dynamics (CFD) codes contain an integrated time-domain integral solution method based on the F-WH equation. These models use time-accurate solutions of the flow field variables, such as a pressure, in order to evaluate the surface integrals. Many of the codes can support rotating sources, such as propellers, as well as static surfaces, with the only real limitations being that sound must be radiated into free space. The frequency-domain spectral data at specified receiver locations can then be calculated using a fast Fourier transform (FFT).

In this paper numerical modelling is based on a commercial CFD code with conventional mass, momentum and energy balance equations. Computational fluid dynamics, naturally joining mass, momentum and energy equations into one common base for discretization and numerical solving, experienced rapid development in 1970–1980s. In the last years tools allowing for description of each particular turbulent vortex and a boundary layer have been also developed. These tools include direct numerical simulation (DNS) and large eddy simulation (LES) [24]. But application of these methods is very time-consuming. The other tool, much cheaper, is based on solution the Reynolds average Navier-Stokes (RANS) equations. The application of RANS equations allows to build up and solve the governing equations over each control volume in a reasonable time and allows to keep good results at effective time of calculations.

As usual, in the case of turbulent flows, apart from molecular momentum and energy fluxes, turbulent momentum and energy fluxes appear, which must be modelled additionally. The most commonly used turbulence model in technical devices is two-equation $k$-$\epsilon$ model originally developed by Laudner and Spalding [25]. The other one is two-equation $k$-$\omega$ model. In this case the two-equation the $k$-$\omega$ SST (shear stress transport) turbulence model was used. The $k$-$\omega$ SST turbulence model combines advantages of the $k$-$\epsilon$ and $k$-$\omega$ models and introduces an additional element limiting overproduction of the kinetic energy of turbulence in the areas of strong positive pressure gradients. The first one model the turbulence in the free stream and in shear layers well and has a low sensitivity to the inlet conditions for the data describing the turbulence. Model $k$-$\omega$ is a better model of the turbulent flow in the boundary layer but is very sensitive to the values of turbulent data in a free stream. The desirable features of both models were combined by connecting them into one model. Additional, the limiter SST limiting the principal stresses of the flow was developed. The Reynolds stress is solved by means of the $k$-$\omega$ turbulence model which has an advantage over the $k$-$\varepsilon$ model of improved performance for boundary layer under adverse pressure gradients. The additional feature of SST is limiting the main stresses within the flow [26].

# 3 Governing equations

## 3.1 Pressure fluctuation

The principal measured property of noise is the time-varying pressure component, $p(t)$, at specified location. The measurement of acoustic pressure that is conventionally reported is the root mean square (RMS) value of pressure fluctuation over the interval -T/2<$t$< T/2

$$\overline{p}_{rms} = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} p(t)^2 dt}, \tag{1}$$

where $t$ is time.

## 3.2 Sound Pressure Level (SPL)

In the context of noise assessment, the sound pressure level (SPL) is the fundamental quantity of sound pressure, and it is defined in terms of a pressure ratio logarithm as follows:

$$L_p = 10\log_{10}\left(\frac{\overline{p}^2_{rms}}{p^2_{ref}}\right) , \tag{2}$$

where $p_{ref}$ is the reference pressure RMS fluctuation set normally to 1 $\mu$Pa for water.

# 4 Noise field analysis

According to the fundamentals of hydrodynamic signal analysis [29] as well as to the methodology of hydrodynamic noise analysis, the presentation methods include:

1. Sound pressure level (SPL) broadband and narrowband spectral densities. These are the classic logarithmic (referenced to 1 $\mu$Pa, Eq. (2)) spectral densities. That means spectra where the frequency increment is linear and normalized to 1 Hz. Broadband and narrowband refer only to the width of the frequency band being analyzed and are somewhat relative terms. For this purpose we can assume that broadband is a frequency band where a part of the signal is already dominated by background noise, so the signals overall level distribution relative to the noise can be observed (Figs. 2–3). Narrowband is the frequency band where the necessary information lies (Fig. 3), this can be blade passage pulses, significant harmonics, higher noise levels, etc.

2. Sound pressure level 1/3 octave spectra. These stem from the nature of the audible range and human sound perception. In an audio signal, tones one octave apart differ by a factor of 2 in frequency. Going from lower to higher frequencies, each successive octave band doubles in width. Pitch is perceived as changing with the ratio of frequencies, not by linear increase. To more naturally group frequencies of audio signals as they are perceived, and to distribute signal power so that the data are better scaled for analysis, measured signal power is often analyzed octave-by-octave. The audible range is spanned by just a few octaves, so octave analysis produces a relatively coarse categorization. Resolution is improved by breaking the octave bands into sub-octave bands, preserving the ratio band spacing. Usually, the octaves are separated into 3 parts, each successive 1/3 octave band increases in width by a factor of $\sqrt[3]{2}$. The 1/3 octave center frequencies have been marked on the frequency axis in Figs. 3 and 4. From a signal analysis point

of view it can be also seen that the corresponding 1/3 octave SPL plot is a simple form of weighted average plot of the spectral density.

3. A spectrum with the mean amplitude values of significant harmonics and sub-harmonics relative to the highest blade passage pulses, including the continuous part. These are needed to exclude the smallest pulses which in model testing may be a result of scale effects, but also to find any excitations which would introduce unwanted distortions to the measured signal (Fig. 5).

4. Since the measured cavitation noise levels can be influenced by the background noise of the test set-up and the facility, the background noise should be independently measured and analyzed according to the methods described above.

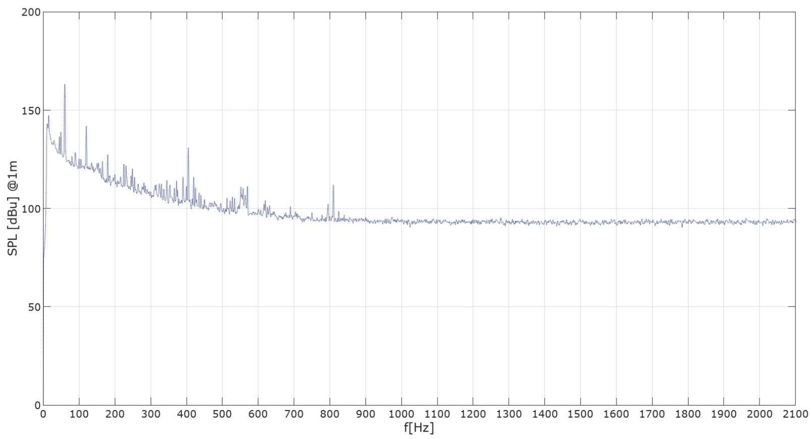


Figure 2: Example of a broadband sound pressure level spectral density.

Now keeping these fundamental guidelines in mind, the development of the spectrum and its individual components over the simulation and experiment time may be tracked. This can be achieved by performing low pass (LP) and high pass (HP) filtering, a sensitive pressure fluctuation time course analysis and spectral estimation [27]. The described statistical and spectral moments method is useful not only for the determination of stationary ranges of signals, but in modified form it can be used as an indicator for non-stationary phenomena, like the occurrence of cavitation impulses and the corresponding noise which is the basis of the concept presented in this paper.

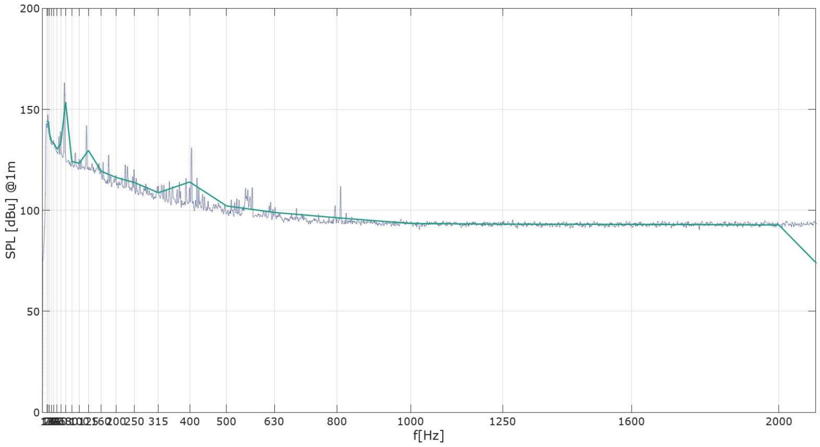


Figure 3: Example of a broadband sound pressure level spectral density and broadband sound pressure level 1/3 octave spectrum.

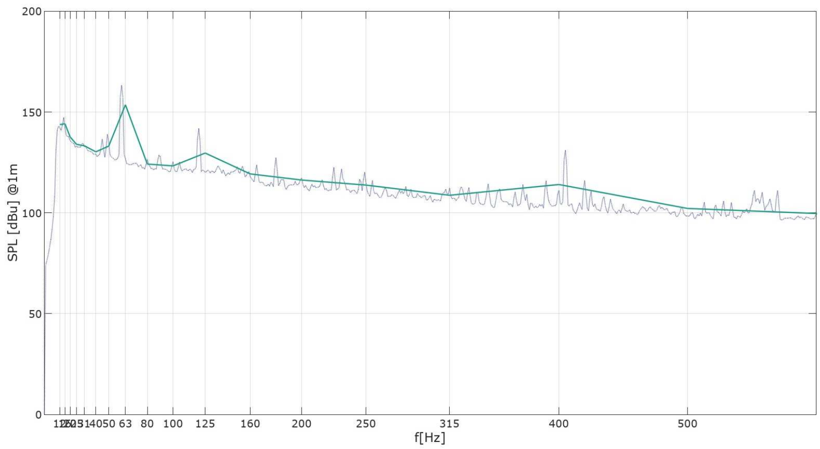


Figure 4: Example of a narrowband sound pressure level spectral density and narrowband sound pressure level 1/3 octave spectrum.

Such an extended approach opens up additional analysis capabilities. If we could manage to capture the cavitation and corresponding noise inception points combined with the surroundings parameters exactly, we could upgrade the identification method from subjective observation to objective definition of the cavitation initiation conditions, through specific hydroacoustic and hydrodynamic signal analysis. This would offer not only greater result accuracy, but also the possibility

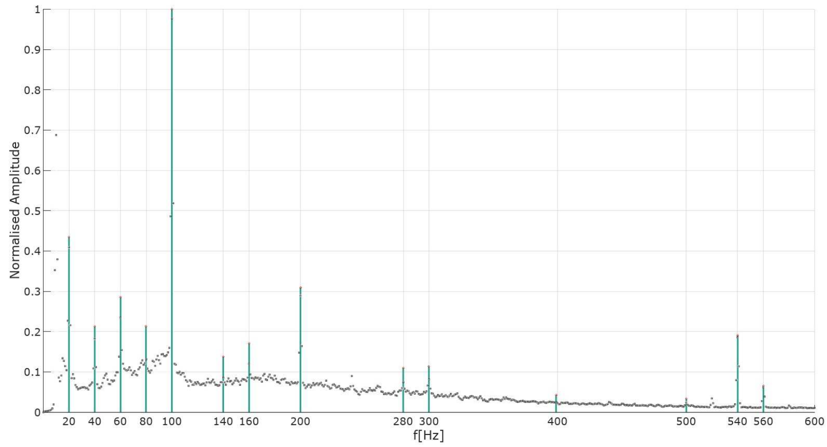


Figure 5: Example significant harmonics relative to the highest blade passage pulses, including the continuous part.

to detect and identify phenomena that are hard or impossible to observe using conventional techniques.

For this purpose the numerical simulation was performed starting with a non-cavitation model, followed through cavitation inception, until the operating conditions are achieved. The corresponding model scale experiments in the cavitation tunnel were arranged in a way that enabled the pressure sensors and the hydrophone to capture cavitation signals while continuously decreasing the tunnels static pressure until the assumed operating conditions were reached.

As outlined in the first section of this paper we would like to present the concept to develop the capabilities of both the numerical and experimental methods to the level at which they can be integrated with one another in order to achieve a coupled system.

As a first step the numerical and experimental methods were analyzed individually. The systems were not significantly changed and to acquire the most information mainly the processing method was developed to apply the described extended time-frequency decomposition method. The following results were achieved.

Please consider reformulation: the transition from the non-cavitation to cavitation condition follows distinctively from the CFD calculation (Fig. 6) while it is hardly visible in the experimental results (Fig. 7). However, through the spectral decomposition of both spectrograms (Figs. 8–9) we can identify an unmistakable threshold. Before this threshold is reached we can identify two significant frequency components, the BPF and its second harmonic and after this threshold

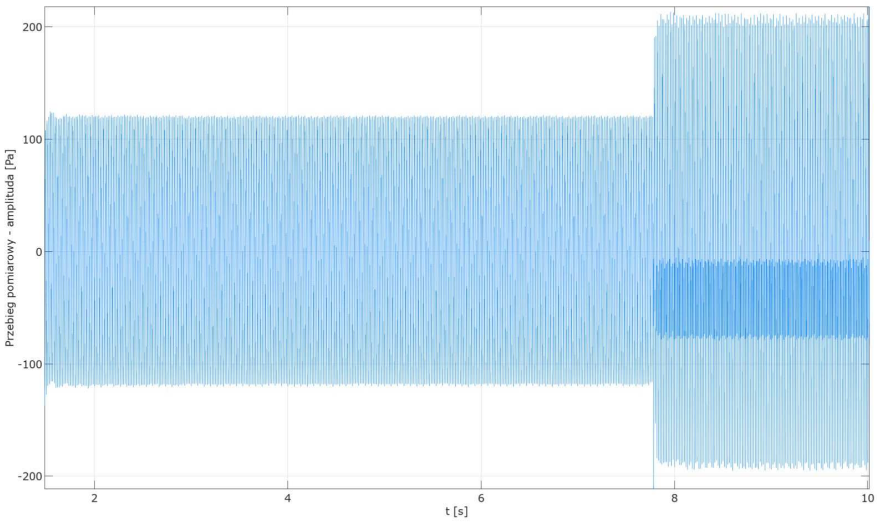


Figure 6: Pressure fluctuation time course – non-cavitation to cavitation transition (simulation).

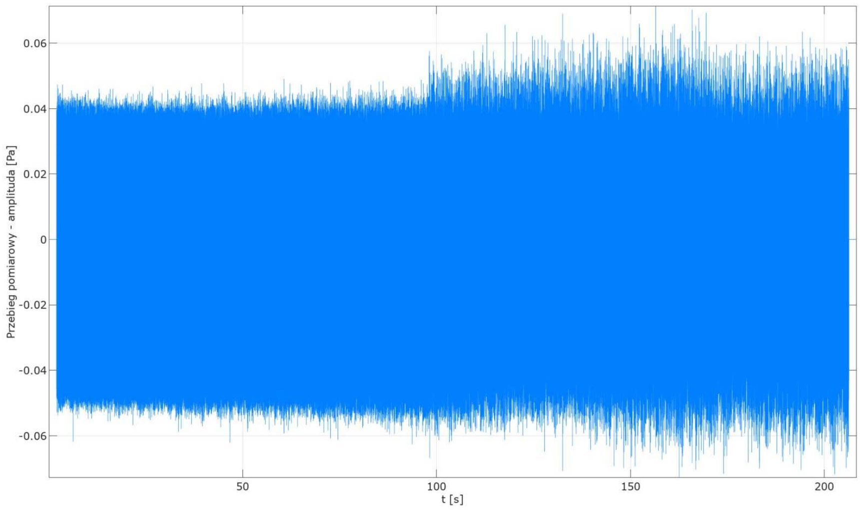


Figure 7: Pressure fluctuation time course – non-cavitation to cavitation transition (experiment).

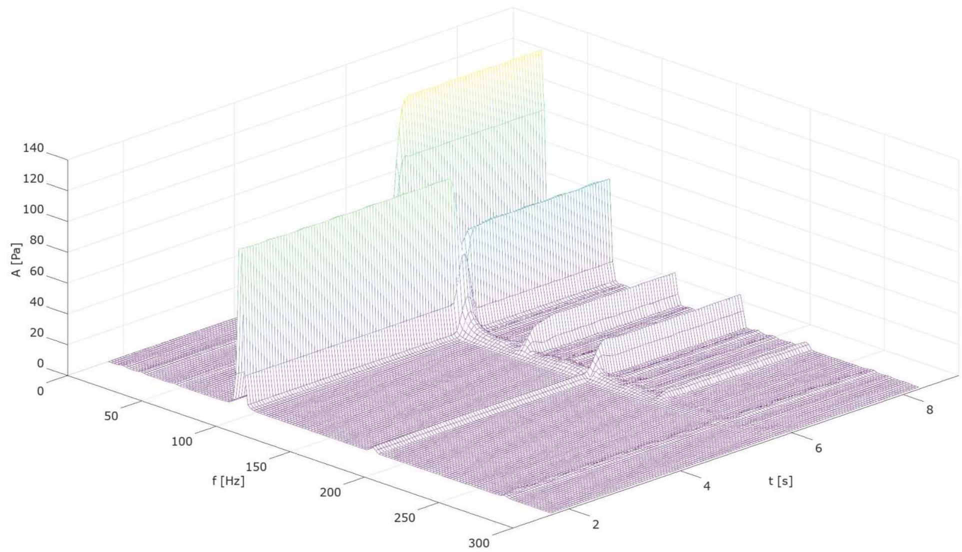


Figure 8: P3D spectrogram – simulation.

is passed we can see in both cases the influence of the non-linear effects resulting in a noticeable increase in the number of the significant frequency components.

To analyze the significant spectral components over time in every analyzed time window a more accurate estimation of the levels as well as the frequencies according to [28] was performed. This way development of the specific components and the stability of their corresponding frequencies could be followed. For this analysis the fundamental blade passage frequency, as well as its harmonics and subharmonics, were taken into account. Since the decomposition results which were very sensitive to experimental conditions, their achieved settings varied slightly from the simulation conditions The emphasis was put on the presentation of the concept itself, which was shown in Figs. 10 and 11.

In the top part of the figures the frequency instability over time is clearly evident. The bottom part of them shows the change of the individual amplitude components. The coincidence of numerical calculations and experimental results is satisfactory as far as identification of cavitation inception point is intended. There is also satisfactory conformity between the signals above 100 Hz. Signals within the lower bands show only qualitative similitude. We can intuitively identify the point of cavitation inception and couple it with the increase in noise levels.

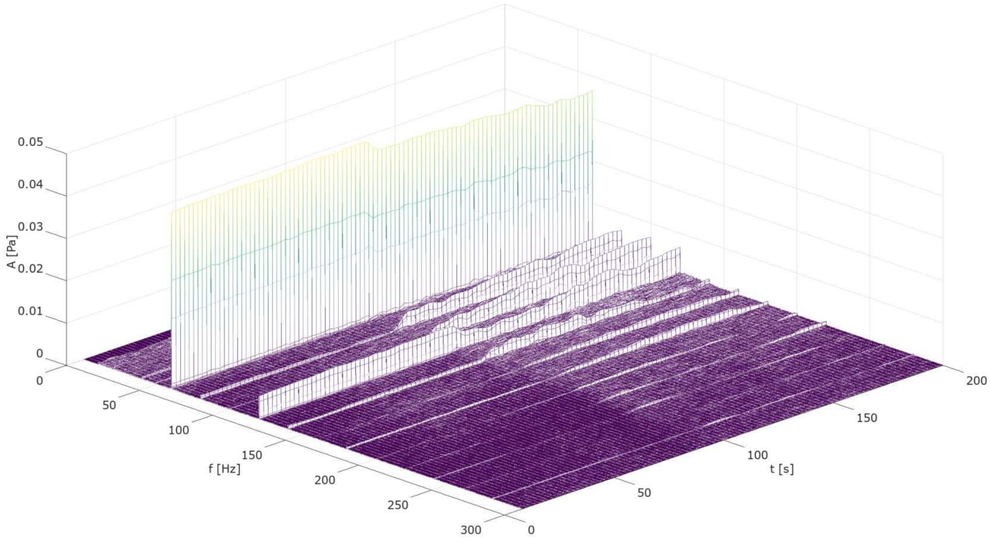


Figure 9: 3D Spectrogram – experiment.

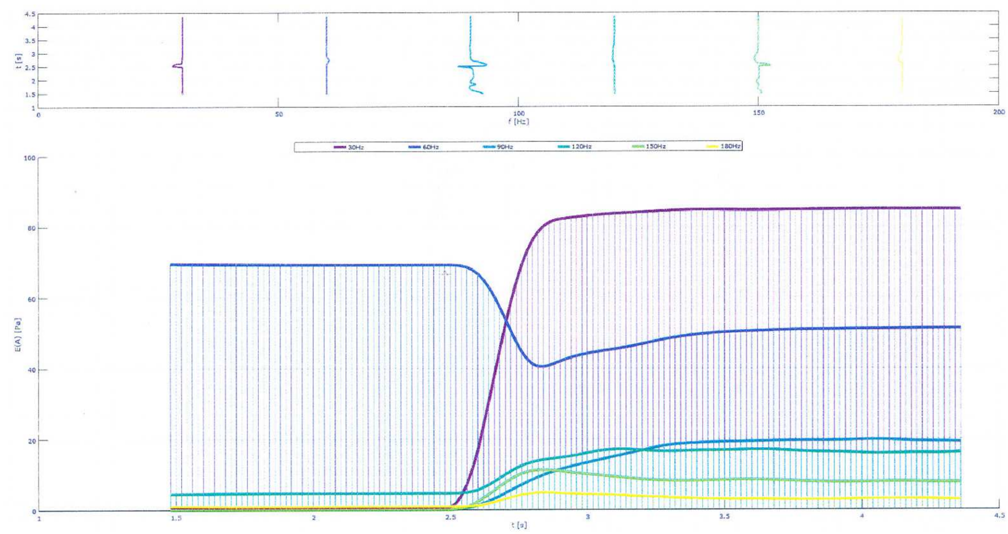


Figure 10: Significant frequency components analysis – simulation.

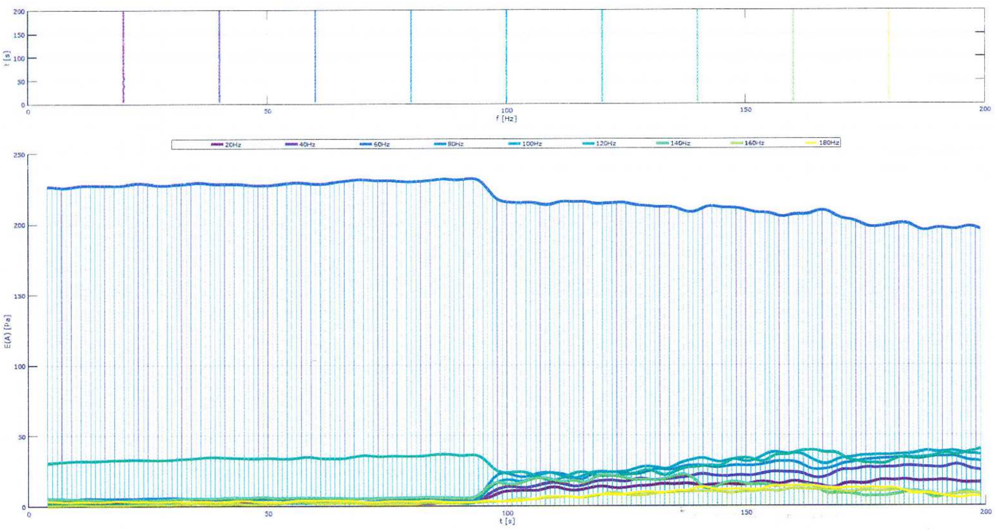


Figure 11: Significant frequency components analysis – experiment.

In both cases we can observe good stability of the frequency components. In the CFD results a slight tremble in the 1st, 3rd, and 5th frequency line can be observed. This may be caused by a limited frequency resolution due to a shorter simulation time.

In both cases we can see an interesting result: with inception of an explicit form of cavitation the main blade passage frequency (BPF) component gets attenuated and its harmonics and some subharmonics get amplified. As shown in Fig. 10 and in fact in most performed CFD simulations we can see the $\frac{1}{2}$ subharmonic getting significantly amplified with the introduction of cavitation. In comparison, the experimental results show the sub-harmonics amplified as well but exceeding the amplitude of the main blade passage component. Both these phenomena provide an indication of the complex nature of cavitation inception and thereby require further investigation.

Performing such a decomposition allows for observation of the basic forms of cavitation encountered at ship propeller blades of cavitation like laminar and bubble. The presented results provide a good insight into the possibilities of the numerical and experimental cavitation detection and noise identification methods. Now the challenge is, of course, to capture all the forms that could develop on any given propeller and to identify their corresponding noise distribution.

Creation of a concept to extend the possibilities of both existing methods individually to the level at which they can be integrated with one another to achieve a coupled system is the one aim of this work. This will include the implementation of new experimental hydroacoustic models in the numerical method, the expansion of the measurement system, including its specific structure, signal propagation characteristics and conditioning requirements and finally – development of an unified and tailored signal processing and data analysis methodology. An important possible application could be the generation of template data based on numerical simulation and implementation in smart filters for specific signal detection including interference, noise and cavitation. This would give access to information that was out of reach for any of the approaches individually and in this way both methods will serve for validation of each other, which will greatly improve the quality of final results.

## 5 Conclusions

The hydroacoustic techniques mainly related to the underwater noise emission of marine propellers enjoy a rising interest now. It is connected with the current problem of underwater noise pollution, which effects especially on marine life. With ship transportation picking up pace, the environmental effects of it is now facing. This issue, although not new, in view of its complex nature remains difficult to predict. However, works to reduce this kind of noise emission and providing more data are still in progress. Studies are being conducted to understand effects of noise pollution on marine life in a much better way. A lot of data from cavitation tunnels and CFD computations are available, but the sea trials results are necessary for verification purposes. The AQUO project [30], realized also with the Ship Design And Research Centre – CTO in Gdansk contribution, provides a lot of information and data helpful for full scale analyses.

The main interest for the authors of the current paper was the hydrodynamic and hydroacoustic noise investigation. Understanding the complexity of the cavitation process is crucial for correct assessment of the hydroacoustic phenomena. The numerical approach is treated as complementary to the experimental task since during the numerical simulation full information about investigated process is easy to extract. As a result of this study the hydroacoustic characteristics were obtained. The skills of propeller noise prediction in model and full scale are important in order to create a synchronized measuring system with the correlation possibilities for CFD calculations.

Development of this system is one of the final goals of our study. This will contribute to creation of the whole system, which could connect the experimental data and computational results. The obtained comparison may be correlated with the sea trials results if they are available. Such data sets allow to verify the obtained results and provide the final data from one complex system.

Making a profound analysis of the relative importance of propeller noise, including the cavitation phenomena, in comparison with the total noise levels would simplify the background noise estimation.

Meaningful skills were acquired through direct research in sea trials and carrying out the experiments in the cavitation tunnel. Currently, the numerical tools are developed for cheaper and less time-consuming techniques of noise emission prediction. However, this is a quite long process to create the optimal universal tool. But it is possible because the achieved results are encouraging and provide a strong basis for further research in this area.

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