Model scale measurements of surface ship radiated flow noise

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Introduction

Advances in weapon and sensor capabilities are driving an increased interest in the control of underwater signatures of naval platforms. The control of machinery and propeller noise is well understood, but there is a shortfall of knowledge of the mechanisms that govern noise due to the flow around the hull of a surface ship. The subject has been investigated in the US/NL collaborative project "Mechanisms and Prediction of Surface Ship Radiated Flow Noise" [1], which was carried out between 2004 and 2008 by NSWCCD (US) and TNO and MARIN (NL). The project aimed to determine and quantify the sources of flow noise generated by surface ships in terms of ship speed and hull shape. The focus was on the underwater noise generated by turbulence excited hull plating vibration and noise resulting from breaking bow waves. A combination of full scale, large scale, model scale tests and computational fluid dynamics was used. The paper discusses only the test set-up and results of the model scale underwater acoustic experiments which were made in MARIN's towing tank.

Surface ship flow noise

Figure 1 gives an overview of the known phenomena in the flow around a surface ship hull that produce radiated noise. Surface ship radiated flow noise involves a combination of hydrodynamic and acoustic mechanisms. The approach taken is to identify the acoustic sources by analysis of the hydrodynamics and then to predict the noise generated by these sources using acoustic radiation models. The hydrodynamic sources include turbulent boundary layer pressure fluctuations, wave dynamics and bubble generation, which radiate sound directly or via flow driven hull plating & hull structures.

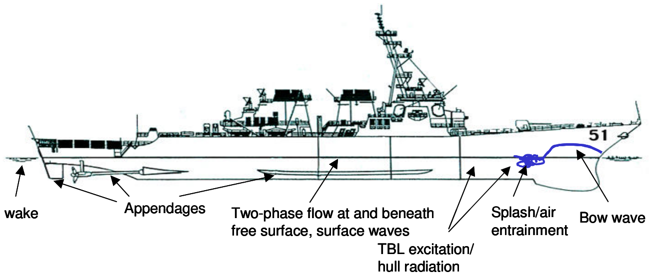

Figure 1: Surface ship flow noise mechanisms.

In the initial survey phase of the program, the choice was made to concentrate on two main flow noise mechanisms:

1. Bow wave breaking

It is well known from ocean acoustics that wave breaking causes bubble generation noise (e.g. [2]). Wave breaking in the flow around a surface ship is most prominent in the bow waves and the stern wave. It was decided to analyse the bow wave noise only, to avoid the complex interaction between propeller noise and flow noise in the stern wave.

2. TBL radiation and hull excitation

The turbulent boundary layer (TBL) that develops along the hull of a surface ship is a possible source of underwater radiated noise by two mechanisms; direct (quadrupole) radiation from the turbulence, and radiation from hull plating driven into vibration by the unsteady turbulence pressures. It has also been investigated to what extent the TBL around a surface ship hull is influenced by free-surface and two-phase flow effects.

Small-scale model experiments

Scale model experiments with frigate type hull forms have been used to investigate these two flow noise mechanisms. In global terms, they depend on the non-dimensional Froude, Reynolds and Weber numbers, on the turbulence intensity and also on the water quality. To scale the wave pattern correctly, scale model experiments have to be performed at a Froude number that is identical to the full-scale. Hence, towing tests for a geometrical scale factor λ are carried out at a speed that is a factor $\lambda^{1/2}$ of the full-scale speed. Since it is not possible to scale all parameters correctly, model experiments will not provide a direct scaled result for the underwater-radiated flow noise, but a means to increase the understanding of the relevant mechanisms and possibly to obtain experimental evidence of scaling laws. To minimize Reynolds and Weber scaling effects, the scale factor was chosen as large as possible, resulting in a model with length between perpendiculars of 11.65 m.

Generally, towing basins are an inappropriate environment for acoustical measurements. The towing carriages and other equipment generate a strong background noise. To solve this problem, a 'silent' towing system has been developed for the flow noise tests at MARIN. The hard walls of the basin cause strong reflections, resulting in a highly reverberant environment. Therefore, the underwater noise measurements have been carried out with a specially designed near field acoustic antenna, which reduces the influence of reverberation and allows for localization of acoustic sources along the length of the hull. TBL hull pressure fluctuations are measured with flush mounted pressure transducers. The acoustical measurements are combined with video observations of the flow around the hull. A separate series of measurements was used to observe the bubble generation by means of video, both under and above the water surface, and to quantify the underwater bubble size distribution by means of ultrasonic measurements.

Silent towing carriage

The MARIN Depressurized Towing Tank (DTT: 240 m long, 18 m wide and 8 m deep) in Ede has the capability to carry out noise measurements, used for cavitating propellers. However, the background noise level of the regular towing carriage is too high for the expected flow noise levels. For that reason a new silent towing carriage has been developed. The silent towing carriage (Figure 2) consists of a lightweight carriage, composed of truss bars, driven by a geared belt suspended between two frames. One frame is attached to the tank wall whereas the other frame, which includes the driving engine, is attached to the regular towing carriage which remains static. The weight of the towing carriage excluding the towing legs is 750 kg. The velocity variation of the carriage with a large size model (3650 kg) is smaller than 1% up to a velocity of 3.5 m/s within an effective constant speed run length of 15 m.

Figure 2: The specially developed ‘silent towing system’ in the towing tank of MARIN at Ede.

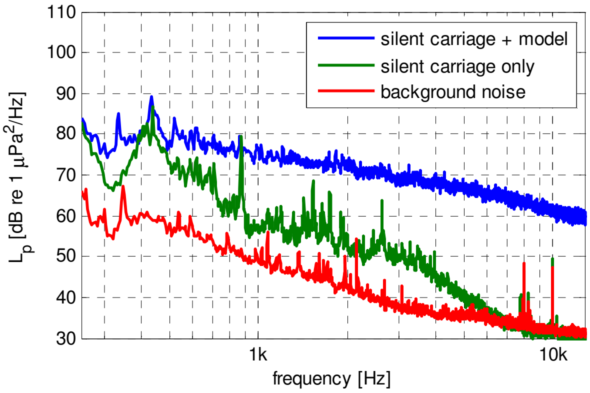

Figure 3: Underwater sound in the tank at a towing speed of 3.5 m/s when the new silent carriage is towing the scale model hull (blue line). The green line gives the noise of the carriage without model at the same speed and the red line gives the background noise in the tank.

Figure 3 gives an example of the measured noise levels in the tank. The noise of the new towing carriage is more than 10 dB below the measured flow noise levels for frequencies above 1 kHz. This noise could not be measured with the regular towing carriage. The remaining noise levels of the new carriage are caused by air-borne transmission of the noise due to the driving engine and gearing wheels.

Underwater acoustical antenna

In order to localize the acoustic sources along the hull of the scale models and to suppress the effects of noise and reverberation in the towing tank, TNO has designed, built and tested a special acoustical antenna. Mainly based on budget limitations, the choice was made to design a sparsely populated linear array of 15 hydrophones, see Figure 4. The total length of the antenna is 1.6 m, eight hydrophones are spaced at 2.5 cm, and eight at 20 cm distance. With the governing acoustical wavelength in water, this antenna is able to focus in a frequency range between approximately 1 kHz and 30 kHz. The array is mounted in parallel with the towing track, at 2 m distance and 0.7 m depth. Because the array is relatively close to the sources, the array is focused at the track by applying the appropriate time delay to the hydrophone signals. The signals of the 8 hydrophones with a 2.5 cm spacing are cross-correlated with the signals of the 7 other hydrophones, resulting in a ‘virtual’ full array. Next, plane wave decomposition is performed using a double (temporal and spatial) Fourier transform. The influence of the reflections in the tank is averaged out by tracking the focus of the array along with the model during pass-by.

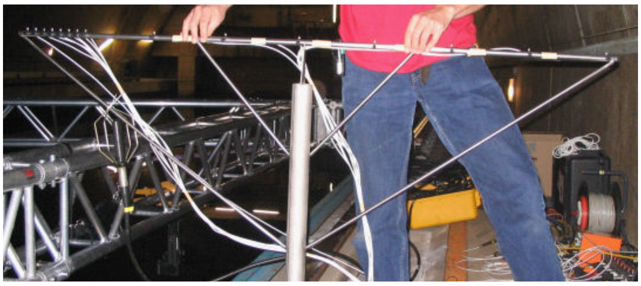

Figure 4: Special acoustical antenna (sparse line array), consisting of 15 B&K 8103 hydrophones.

Wave breaking noise

Measurements with the acoustical antenna have resulted in plots of the spatial distribution of noise sources along the hull for a series of speeds, which are shown in Figure 5. The antenna output shows peaks that correspond with the location of breaking of the first and second wave crests of the bow wave system, see Figure 6. The plots also show a strong peak due to wave breaking at the stern of the hull, but this noise source has not been investigated, due to the absence of propeller and appendages..

The location of the breaking of the second bow wave crest moves aft and its width increases with increasing speed, proportional with the square of the towing speed. No wave breaking of the second bow wave crest is observed at the highest model speed. Hence, also the second bow wave peak in the underwater noise disappears in Figure 5. The first bow wave crest does not break at speeds below 2.5 m/s

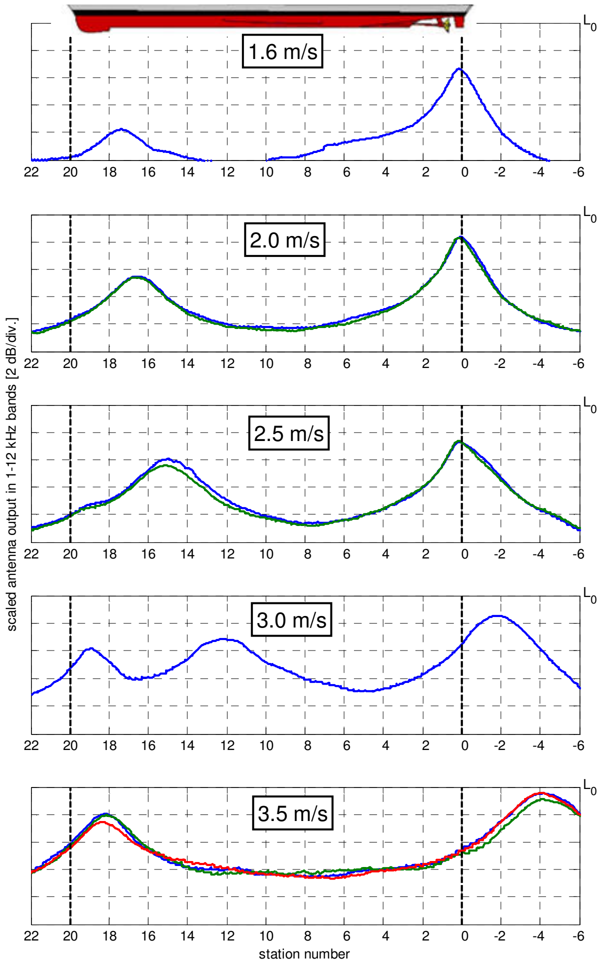

Figure 5: Spatial distribution of the flow noise sources along the hull at (from top to bottom) 1.6 to 3.5 m/s model speed. The labels of the x-axis refer to 'station numbers' (20 equal stations along the length at the water line). Multiple lines in one figure are from repeat. The vertical scale gives the broadband noise in the 1 to 12 kHz band in dB relative to an arbitrary reference L_0 (2 dB per division).

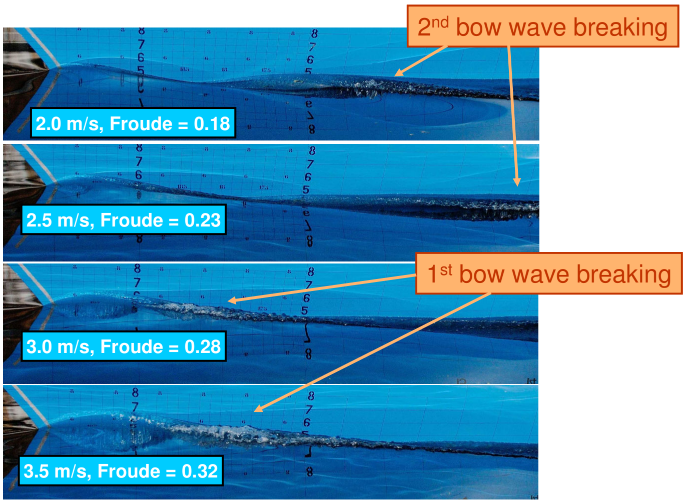

Figure 6: Observation of the bow wave breaking for the model at four towing speeds. The Froude numbers are based on ship length

Bubble size distribution

The generation of air bubbles plays an essential role in the generation of bow wave flow noise. Important parameters are the bubble creation (air entrainment) rate, the bubble size distribution and the void fraction. A PIE 250 medical ultrasound scanner with a 3.5 MHz linear transducer array and imaging hardware was used to measure the bubble size distribution in the flow around the frigate-model in the towing tank. The scanner head was put in a streamlined housing to reduce its influence on the flow, see Figure 7. It can be used to generate an image of the individual gas bubbles in a planar area of approximately 10×20 cm. Advanced image processing techniques are used to derive the bubble size distribution from these images. Figure 8 gives a typical example of a bubble size distribution, as it is observed under the breaking bow wave. Bubble diameters between 0.01 and 1 mm are found. These correspond with bubble resonance frequencies in the range between 6 and 600 kHz. The acoustical measurements in the tank were limited to frequencies below 25 kHz, corresponding with bubble diameters larger than 0.24 mm. The bubble measurements suggest that noise will be radiated at higher frequencies as well. Note, however, that underwater noise is mainly produced by newly created bubbles. The measured bubble distribution also contains inactive bubbles, which have been generated earlier and are convected into the plane of view. The bubble distribution is influenced by bubble break-up due to turbulence and bubble coalescence.

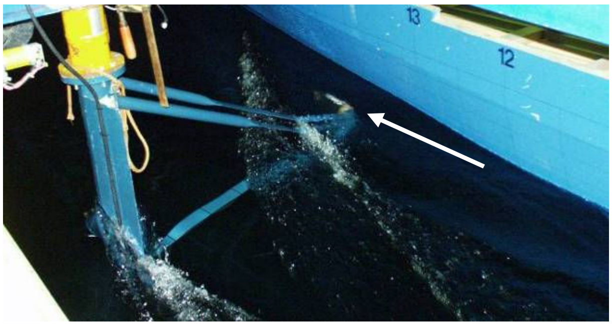

Figure 7: The white arrow points at the sensor of the ultrasonic scanner, mounted in a streamlined housing and positioned in the flow near the ship model during towing.

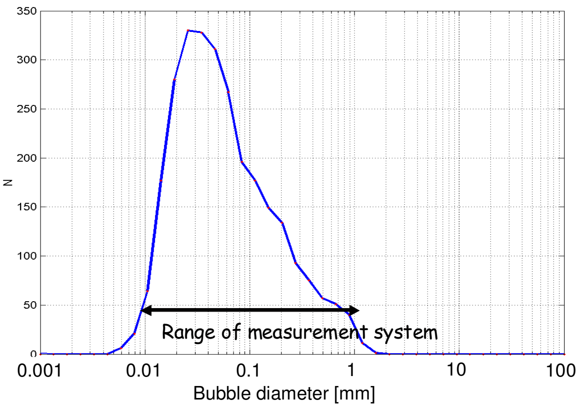

Figure 8: Typical example of a cumulative bubble size distribution for one position in the flow. The arrow indicates the limits of the measurement system.

TBL hull pressures

The scale model tests included measurement of turbulent boundary layer (TBL) surface pressure spectra at several positions along the hull. Various sensors were installed as vertically- and streamwise-spaced pairs to provide information on the spatial correlation characteristics of the surface pressures.

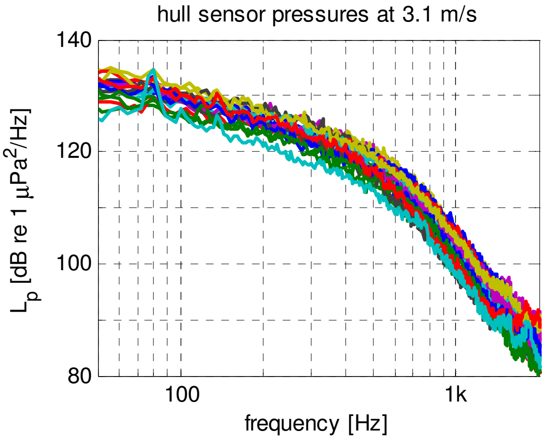

Figure 9: Example of measured hull pressure spectra at 18 different sensor positions along the hull, at a model speed of 3.1 m/s.

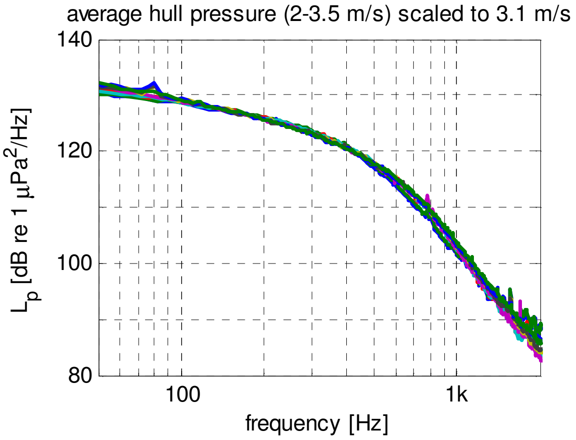

Figure 10: Hull pressure, averaged over the 18 sensors at 6 different model speeds between 2 and 3.5 m/s, with equilibrium boundary layer scaling to a single speed of 3.1 m/s.

Figure 9 illustrates that there is limited variation between the hull pressure spectra measured by the various hull sensors during the scale model tests. Only in the region immediately down-stream of the bow and very near to the free-surface the hull pressure deviates from that of a typical flat plate equilibrium boundary layer. These spectra have not been corrected for the size of the hull sensor area, which affects all data at frequencies above 100 Hz in the same way.

Figure 10 shows that the average hull pressure spectrum scales with speed as a flat-plate equilibrium boundary layer (frequency ~ 1/speed and L_p ~ speed^3). Hence, it is possible to predict the hull pressure spectra on a large part of the hull using a flat-plate equilibrium flow model. Of the many models for the surface pressure spectrum that have been developed, the model proposed by Goody [3] has been used in this project. This model was developed with the specific aim of application to the type of high Reynolds number, low Mach number flows typical of underwater applications. The model is a simple function of the ratio of the time scales of the outer to inner boundary layer and incorporates the effect of Reynolds number through a ratio of the two time scales.

Estimating the response and radiation from turbulent boundary layer exciting hull plating directly follows the developments provided by Rumerman [4,5]. Hull plating can be modelled as rectangular plates stiffened by ribs. The plates are assumed to be driven by a wavenumber-white excitation field at wavenumbers in the neighbourhood of the plate's fluid-loaded bending wavenumber. Radiation from the flow excited plating can be related to the forces imposed on the plate by the stiffening ribs that effectively cancel plate motion at the frames. Proper account needs to be made of the effects of fluid loading on plate radiation efficiency.

The small-scale ship models used in these experiments are made of wood and represent only the ship hull shape and not its structure. That means that these experiments can not be used to validate these estimations of underwater radiated noise due to TBL excitation and hull radiation.

Conclusion

With the tools developed in this programme, surface ship flow noise measurements can be performed in a hydrodynamic towing tank. These measurements demonstrate that the flow around the hull of a surface ship generates underwater noise due to bubble creation when surface waves are breaking and to turbulent excitation of the ship hull. The small-scale model experiments have provided valuable information about the relevant mechanisms.

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