NEAR FIELD PROPELLER RADIATED NOISE MEASUREMENTS: MODEL AND FULL SCALE EXPERIMENTAL DATA COMPARISON

by

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ABSTRACT

The ever rising interest related to the underwater noise originating from cavitating propellers prompted the Italian Navy to study this aspect of naval architecture in an experimental way.

This was accomplished carrying out extensive model tests in the Italian Navy cavitation tunnel (CEIMM) and full-scale tests in cooperation with CETENA.

This paper outlines the measuring technique the acoustic behaviour of the cavitation tunnel as well as the measuring technique and analysis of full scale tests carried out with hull-mounted hydrophones.

Some problems arising from both these kinds of measurements and their analysis methodology are highlighted. A technique to take account hull boundary and hull vibrations, during full-scale tests, is also discussed.

Finally some results of "near field" propeller noise, obtained from both model and full-scale measurements, are shown and compared.

INTRODUCTION

The noise radiated by the external elements of the ship's propulsion system and in particular by the propeller can become predominant and representative of the global noise level if the operative conditions of the propeller are such as to cause inception and development of cavitation phenomena on its blades /1/.

Under these conditions, the propeller radiates directly into the flow a noise level, which not only consists of a certain number of distinct lines in the low frequency range (linked to the blade frequency and to its multiples), but also becomes predominant in the whole field of high frequencies which are essentially related to cavitational phenomena.

It therefore appears obvious how important the propeller is in the "acoustic signature" of a ship and thus in the possible identification of the ship itself by modern detection systems of underwater weapons.

In this light one of the main aims of the measurements carried out by means of hydrophones, located at the ship stern above the propeller disk, consists in defining both this source of noise and its levels related to the various operative conditions of the ship.

The problem of propeller radiated noise is furthermore considered to be a subject for experimental research at cavitation tunnels world-wide and in particular at the Italian Navy Cavitation Tunnel /2/.

The present method of recording and analysing noise data at this specific tunnel has been established as a result of numerous tests, carried out both on two-dimensional foils as well as on propeller models in order to optimise the calibration of the adopted measurement set-up and essentially to investigate the effects, in terms of acoustic noise, which the inception of the various types of cavitation involve /3/, /4/.

One of the aspects which is still under investigation in this model experimental research is a univocal definition of the parameters able to formulate correct transfer laws, from model to full-scale conditions, of the noise level generated by the propeller .

To this purpose and independently of the various solutions to this problem formulated by different researchers, the availability of full-scale experimental data of the quantities under review, provides a useful opportunity to verify the prediction laws adopted.

This report describes the testing methodology and the setting-up of the tests, used both in model and full-scale conditions.

Some of the results obtained from this experimenal investigation are described below.

1 TESTING METHODOLOGY AND SETTING UP OF INSTRUMENTATION

1.1 FULL-SCALE MEASUREMENTS

The usual assessment of this kind of test consists in installing some (generally two) hydrophones at the hull bottom above the propeller disc as well as a number of pressure transducers (4-6) and a number of accelerometers located in proximity of the hydrophones themselves.

The hull transducers, used for noise measurements, are B&K hydrophones, type 8103 (the technical characteristics and relative response curve are well-known). The signal, via a B&K amplifier, type 2635, is visualized during the acquisition on an oscilloscope and recorded directly onto magnetic tape, "Scotch 3M" using a Nagra IVS.J. tape recorder (recording speed : 38 cm/sec).

The transducers used to measure the pressure induced on the hull are of the inductive type P11 from HBM, whereas the accelerometers located close to both the pressure transducers and the hydrophones are of the B&K type 4371, with a cut-off frequency of around 2500 hz.

The signals of the pressure transducers and of the accelerometers, suitably amplified, are recorded on magnetic tape by means of a Sangamo tape recorder for further processing.

A general outline of the set of instruments used is shown in fig.1 in which, the dislocation along the ship of the various transducers and of the acquisition terminal is also shown, for the measurements which constitute the subject of this paper. The positioning on the hull of the two hydrophones and of the pressure transducers is better illustrated in fig.2 in which the stern area of a naval vessel, on which this kind of measurements were performed, is shown.

More details on the instrumentation set adopted by CETENA in such full-scale tests is reported in /5/.

1.2 NOISE MEASUREMENT SET UP AND ACOUSTIC CHARACTERISTIC OF THE C.E.I.M.M. CAVITATION TUNNEL

- Measurement chain

The noise measurement chain used at the C.E.I.M.M. tunnel is illustrated in the block diagram in fig.3. It corresponds, essentially, to the one suggested by the ITTC /6/.

- Positioning of the hydrophone receiver

Several experiments and measurements were carried out in order to establish the best geometric position for the hydrophone receiver and the most suitable link between the structure of the tunnel and the casing of the hydrophone, so as to reduce to a minimum the signal distortions /7/, /8/.

The hydrophone positioning used at the present by C.E.I.M.M. for noise tests is as follows (compare fig.4) :

a) in correspondence with the propeller plane, in a water filled box mounted on the testing section, from which it is separated by a perspex window which guarantees acoustic trasparency. This box is resiliently mounted on the tunnel window;

b) at 1,65 m from the propeller model, either wall flush-mounted or in a water filled box resiliently mounted on the tunnel wall.

- Acoustic characteristic of the tunnel

The frequency responce of the working section of the tunnel has been obtained by using a hydrophone emitter placed in correspondence with the propeller shaft. This type of hydrophone emits a noise signal, produced by a generator and then amplified, its spectral components being uniformly distributed along the frequency range concerned (white noise).

In order to check the acoustic characteristics of the tunnel testing section, two series of tests, using the same C.E.I.M.M. measurement set up, were carried out at I.N.S.E.A.N. towing tank basin n.1 (430mx13mx6.80m). These experiments were carried out by placing the hydrophones along the centre line of the basin, at a depth of 3.4 m, at a distance between the emitter and the receiver of respectively 0.4 m and 0.8 m. The results of the above-mentioned tests are shown in fig.5 from which the following observations can be deduced :

a) the acoustic characteristic of the tunnel is fairly similar to that of the basin;

b) it is possible to transfer with fair approximation the noise levels obtained, from measurements carried out at 0.4 m (tunnel) between the source and the receiver to the standard distance of 1 m, between the propeller and the receiver, by applying the law of spherical propagation of sound.

- Background noise of the tunnel

The reliability of the measurements carried out on propeller models depends to a large extent on the acoustic behaviour of the tunnel.

The C.E.I.M.M. tunnel was built (1962-1964) without specific consideration for the attenuation of the background noise.

In order to identify both the frequencies themselves and their ranges influenced by background noise in the tunnel (due to : dynamometer, main rotor, stator, etc.,) a series of experiments were carried out, systematically varying the number of revolutions of the dynamometer, the number of revolutions of the main rotor and the pressure in the testing section.

The results of the investigation have shown that the pressure in the testing section, the flow speed and the number of revolutions contribute in different ways to the background noise :

- the variation in the number of revolutions of the dynamometer has most influence on the background noise and it becomes louder as the speed of the water decreases

- the variation of the pressure in the testing section influences the background noise on frequencies above 10 KHz

- the variation of flow speed in the testing section influences the background noise at flow speeds of more than 9 m/sec.

The experiments carried out until now have, moreover, shown noise levels for some frequencies for which the relevant source has been identified.

It is, however, important to stress that the background noise can be disregarded when the noise level of the propeller under testing is relatively higher (10 dB) than the background noise level associated with the same functioning conditions. Otherwise, the levels and the noise spectra of the propeller must be corrected for the level of the background noise.

The background noise of the C.E.I.M.M. cavitation tunnel, recorded for the experiements carried out until now, has always been negligible, particularly in the frequency field typical of cavitation.

- Testing methodology

The tunnel cavitation experiments are carried out disregarding the Froude number parity in order to achieve, for a given cavitation index and a given advance coefficient, a Reynolds number sufficiently high to reduce as far as possible cavitation scale effects.

This essentially involves carrying out the experiment using a high number of propeller-revolutions, the highest possible in relation to the strength of the model and therefore at a higher static pressure than would be necessary to adopt according to Froude's law.

Such a testing method also has advantages related to noise testing, as it allows a reduction in the quantity of air bubbles which form in the testing section thus ensuring the correct acoustic transmission of the water.

It should also be noted that by using high pressure values it is possible to perform the tests with a fairly high air content (around 0.6) which is positive for what concerns the tunnel-sea correlation in terms of cavitation phenomena /2/.

2 ANALYSIS METHODOLOGY AND DATA PROCESSING

Given the complex nature of the acoustic noise signal, the methods of analysis of the signal can be differentiated, depending on the type of information which needs to be obtained.

There are basically two ways of analizing the radiated hydrodynamic noise :

a) the so-called "broad-band" analysis which, depending on the type of analyser, can be carried out in octave bands, one third octave bands (more common), one tenth octave bands, etc.

b) the "narrow-band" analysis which involves analysing the signal with a higher frequency resolution so as to define the energy content of the noise on a much higher number of frequencies.

The first is typical of the noise measurements radiated at relatively long distances from the ship ("Far-Field") and the results are shown as a function of the values of the central frequency of the various bands as being twenty times the logarithm of the root mean sqared value (R.M.S.) of pressure referred to a reference value (Po = 1 μ Pascal), thus :
(Band level) $Bl = 10 \lg [\hat{P}^2 rms/\hat{P}^2 o] = 20 \lg [\hat{P}rms/\hat{P}o]$.

Generally, the "level" is shown in a spectral form (and thus corrected for the width of the band so as to refer it to 1 Hz according to the formula :
("Spectrum Level") $SL' = Bl - 10 \lg (\Delta f)$,
and finally reduced to the distance of 1 metre from the source, by means of the formula :
("Spectrum Level") $SL = SL' - 10 \lg (R/1\ m)$,
where R = distance in metres, according to the hypothesis of omnidirectional spherical waves. The usual notation is thus as follows :
"Spectrum Level" SL (dB) : ref 1μPa, lm, 1 Hz.

The second type of analysis, on the other hand, provides more detailed information about the frequency field by identifying all the predominant lines of the spectrum. The presentation is simply made in terms of "levels" (referred to 1μPa and to 1 m), indicating the width of the narrow band used.

2.1 TECHNIQUES USED

Both of these analysis techniques were applied to the data obtained.

The broad-band analysis was carried out in one third octave bands using a Bruel & Kiaer type 2131 analyser which supplies, directly onto video, the acoustic "levels" as a function of the frequency centres of the various bands starting from 1.6 Hz up to 160 KHz. The levels were obtained with linear averages and relative mean times of 32-64 seconds.

Some results will be illustrated in the next paragraph.

The full scale data analysis was limited to the up frequency of 20 KHz and all the relevant results are reported in /9/.

As far as the analysis relative to the signals of the pressure transducers and the accelerometers placed on the ship stern is concerned, this was carried out using the Fast Fourier Analyzer, type .P. 5451 B, in use at CETENA Data Processing Centre, which allows the spectral distribution of the pressure values induced by the propeller and the vibration values in terms of local acceleration, to be obtained. All the relevant results are reported in detail in /10/.

2.2 EFFECT OF THE HULL ON THE FULL-SCALE MEASUREMENT AND CORRECTION METHODS

The complementary measurements carried out by means of pressure and accelerometer transducers aim to define both the pressure levels induced by the propeller at low frequencies (first blade frequency and its multiples) and the local as well as global vibration levels which occur in correspondence with the hydrophones thereby affecting the response.

The simultaneous analysis of these signals allows the right corrections at noise level picked up by the hull-mounted hydrophones to be carried out so as to eliminate both the effect of the presence of the hull (solid boundary) as well as the effect due to the vibrations of the hull itself.

The corrective factor due to the first effect is defined as the relationship between the pressure measured at the hull and the pressure radiated in the free field and it is of course, a function of the form and material of the surrounding surface.

In the case of a rigid plate of infinite dimension, this factor takes on the value 2. Moreover, this value has been confirmed also for stern shapes similar to those of the above-mentioned ship as proved by previous experimental tests /11/.

Therefore, all the collected pressure values must be divided by 2, which means a reduction of 6 dB (in the low frequency range) on the directly measured noise levels.

A second problem which must be taken into consideration is that of the global and local structural vibrations (of panels) to which the hydrophones, rigidly mounted on the hull, are subjected.

It is above all the local vibrations which can induce very high pressure values in the immediate vicinity of the hull surface so that the hydrophone in the hull also records the effects of this contribution due to the vibrations.

In order to obtain noise levels comparable with the tunnel test results, it is therefore necessary to establish the influence of the global and local vibrations and thus the pressure by them induced.

As far as the effect of the global vibration of the hull is concerned, it is necessary to measure the pressure and the vibration both in conditions of forced excitaton (by means of a hydraulic exciter) as well as in natural excitation when the ship is underway.

Relative to the effect of local (panel) vibration, a series of additional measurements, using accelerometers, are needed by locally exciting the panel in order to define its resonance frequency (or frequencies). By simultaneously recording the signal from the hydrophone mounted on the panel the transfer function between pressure and vibration can also be obtained.

For frequencies near the local resonance frequency of the panel, variations of pressure can be found in the nearby flow which can even be far higher to those induced by the cavitating propeller, as experimentally proved by several researchers /12/, which require corrections of up to 15 dB on the spectral content of the measured noise levels.

A measure on the effects of the vibration of the ship stern structure, by means of accelerometers, was carried out during the trials the results of which are discussed in this report.

The pressure due to the global vibrations was obtained from these measurements and was of the order of 5% of the total one for the first blade harmonic and of the order of 25% for the second one.

This requires a further correction of the noise level measured by the hydrophone of the order of 1-2 dB.

The local panel vibration measurements, for which it is necessary to use an accelerometer (piezoelectric) with a high cut-off frequency (with a linear response from 0 Hz to at least 12000 Hz) were not carried out on this occasion. Therefore a check on the actual correction to be made to the spectral noise levels, due to this local vibrational effects, was not possible.

The uncertainty concerning the validity of a comparison between noise levels remains, within the middle-frequency range, even if these experiments have enabled a more correct methodology to be identified, both for acquisition as well as analysis to be used in the future.

3 PRESENTATION OF RESULTS

All the results obtained from the experimental full-scale trials performed on an Italian Navy frigate are reported in detail in /9/.

Measurements and analysis of propeller radiated noise have been carried out at increasing ship speed from a ship' $F_N = 0.140$ up to $F_N = 0.400$ in order to investigate both on the effects that the different propeller cavitating conditions have on the radiated noise as well as on the efficiency of two air insufflation system with which the ship is equipped.

In this report the radiated noise spectrum levels measured by means of the hull flush-mounted hydrophone for two most significative ship speeds ($F_N = 0.246$, corresponding to back shet and tip vortex cavitation inception, and $F_N = 0.400$ corresponding to the highest investigated speed) are reported.

The two noise spectrum levels are shown in fig.6 and 7 respectively, where the corresponding spectra obtained from test carried out in model scale at Cavitation Tunnel for the same propeller operating conditions, are shown and compared. In the same figures the "far field" ship radiated noise spectra, as measured by the fixed hydrophones of an acoustic range, are also indicated.

The transfer laws adopted to scale-up both frequencies and sound pressure levels from model to full scale conditions are summarized in fig.8 and are basically derived from ref. /13/.

As concern the two respective propeller cavitation patterns observed both in full scale and model conditions, they are shown in figg.9, 10 where the extent of suction and pressure side cavitation is illustrated.

4 OBSERVATION AND COMMENTS

From the results discussed in this paper the following can be noted :

- the noise spectra measured in the tunnel and scaled are lower than those obtained in full-scale conditions.

Possible explanation for this discrepancy can be found from the following factors :

- in the tunnel the noise emitted from the propeller alone is measured whereas in full-scale, the measurements are also influenced by the global noise produced by the ship

- the extent of the cavitation on full-scale propeller blades, although fairly reproducing the simulated one in the cavitation tunnel, shows some varied local phenomena which are unreproducible in the tunnel due to many phisical reasons, not least different manufactoring tolerances /14/ between the model and full-scale propeller

- the adopted noise scaling law, according to the TNO formulation /13/, should be refined on the basis of both further tunnel and full-scale experiments.

In this context it must be pointed out that one of the main recommendations put forward by the last ITTC'84 Cavitation Committee concerns "the implementations of noise scaling laws by utilizing results from this kind of full-scale tests".

5 CONCLUSION

This report has described some fundamental aspects related to the problem of noise radiated by a ship (in particular by its propeller) at sea and some general concepts relating to experimental techniques and noise processing are also summarized.

Prediction of the propeller radiated noise in full scale conditions is not yet assessable in a reliable and univocal way.

The results obtained to date show that :

- the testing methods both in model and full-scale conditions have been adequately checked and has proved their reliability also in terms of the instrumentation used

- the hydrophones mounted on the ship hull, despite the complexity of the signal conditioning as already mentioned, offer the opportunity of having a qualitative noise spectrum even without an acoustic range and, additionally, provide the opportunity to monitor possible damage and/or modifications occurring on the propeller blades

- to compare directly the propeller noise spectrum obtained from measurements carried out on model scale (Cavitation Tunnel) with results obtained by means of hydrophones mounted on the ship hull, it is necessary to take into account the different boundary conditions between the two measurement systems, which can be adequately evaluated using complementary measurement techniques as already mentioned

- the cavitation tunnel with its instrumentation equipment represent a flexible and reliable facility for a relative evaluation of the noise levels associated with various propeller cavitational phenomena. As a confirmation of this statment some results of comparative noise measurements, suggested by ITTC Cavitation Committee carried out by some international tunnels on the same propeller model under different cavitating conditions are reported in figg.11÷13, where CEIMM' result are also shown and compared /15/.

It is the authors' and their respective Organizations' aim to continue the studies concerning correlations of both noise levels and propeller induced pressures between model (Cav. Tunnel) and full-scale experimental conditions.

Of course the amount of full scale experimental data will definitely be increased once an acoustic range is available in Italy.

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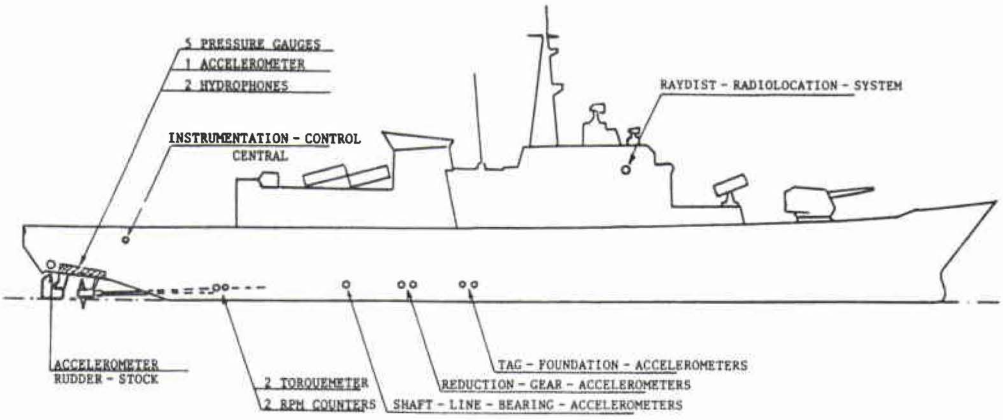


Fig. 1
Dislocation of instrumentation set adopted by Cetena for noise and vibration measurements on a naval vessel

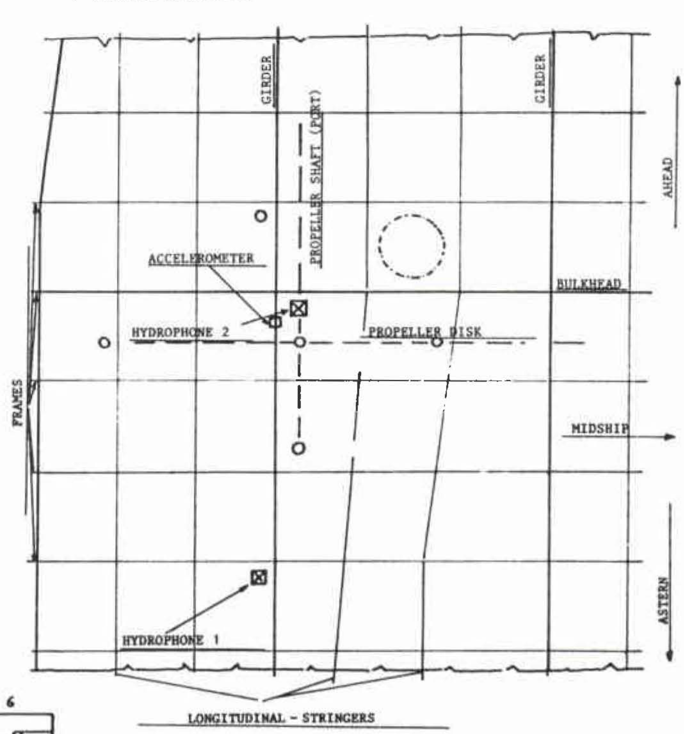


Fig. 2
Naval vessel stern area top view - transducers positioning

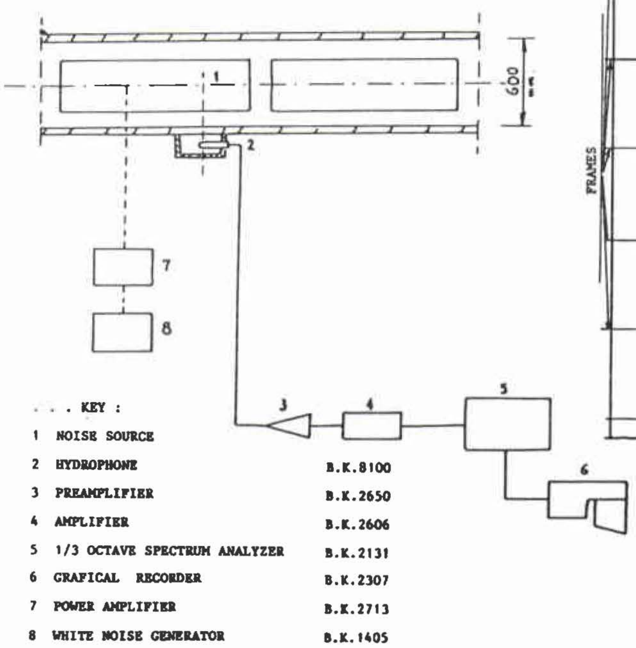


Fig. 3
CEIMM cavitation tunnel - noise measurement set-up

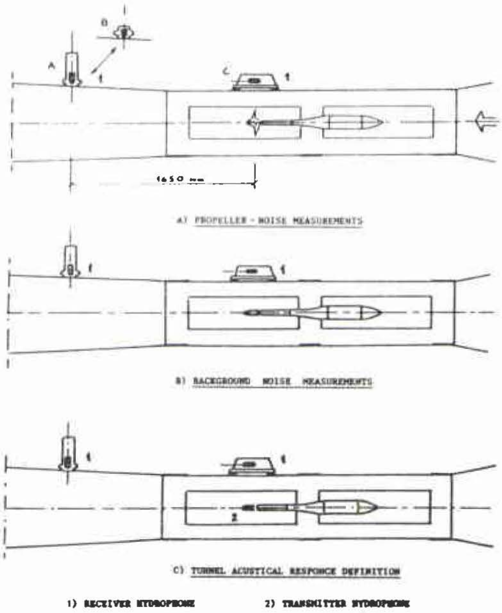


Fig. 4
CEIMM cavitation tunnel - hydrophone positioning

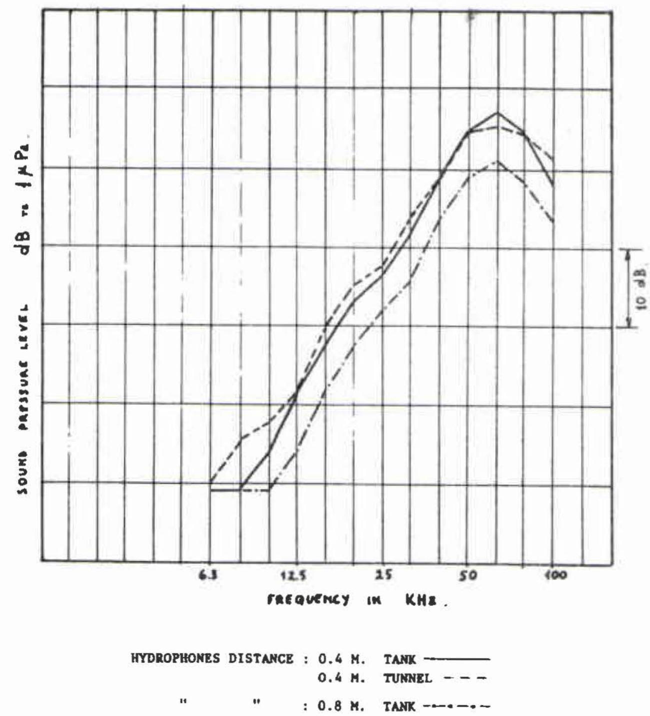


Fig. 5
Acoustic characteristic response of insean towing tank and CEIMM cavitation tunnel

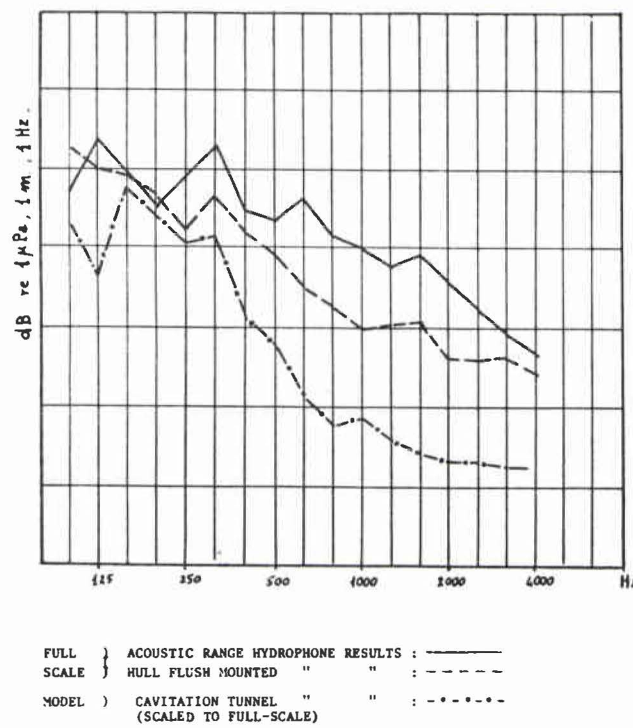


Fig. 6
Sound spectrum levels comparison
Ship's $F_N = 0.246$

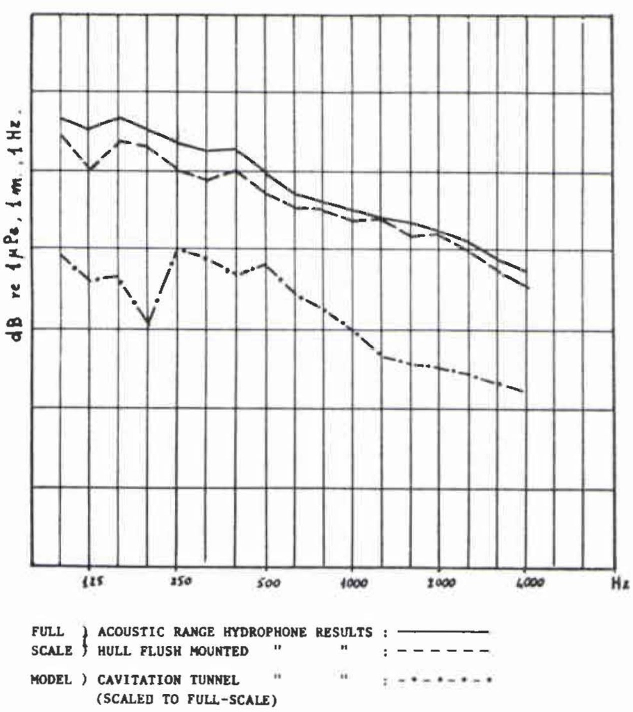


Fig. 7
Sound spectrum levels comparison
Ship's $F_N = 0.40$

SCALATURA FREQUENZA

(coefficiente adimensionale

$$\sigma_f = R f \left(\frac{\rho_w}{p_e}\right)^{1/2}$$

R = raggio della bolla
f = frequenza del rumore
ρ_w = densità del mezzo
p_e = pressione esterna

Con prove condotte a pari indice di cavitazione

$$\sigma_{nm} = \sigma_{ns}$$

$$\frac{p_{em} - p_{vm}}{1/2\, \rho_{wm} N_m^2 D_m^2} = \frac{p_{es} - p_{vs}}{1/2\, \rho_{ws} N_s^2 D_s^2} \qquad (1)$$

$$\frac{p_{es}}{p_{em}} \text{ proporzionale a } \frac{N_s^2 D_s^2}{N_m^2 D_m^2} \qquad (2)$$

$$\sigma_{fm} = \sigma_{fs}$$

$$R_m f_m \left(\frac{\rho_{wm}}{p_{em}}\right)^{1/2} = R_s f_s \left(\frac{\rho_{ws}}{p_{es}}\right)^{1/2} \qquad (3)$$

$$\frac{D_m f_m}{p_{em}^{1/2}} = \frac{D_s f_s}{p_{es}^{1/2}} \qquad (4)$$

$$\frac{p_{es}}{p_{em}} = \frac{D_s^2 f_s^2}{D_m^2 f_m^2} \qquad (5)$$

$$\frac{D_s^2 f_s^2}{D_m^2 f_m^2} = \frac{N_s^2 D_s^2}{N_m^2 D_m^2} \qquad (6)$$

$$f_s = f_m \frac{N_s}{N_m}$$

SCALATURA LIVELLO PRESSIONE

$$\sigma_p = \frac{r^2 \langle p \rangle^2}{\rho_w c_w R_o^3 p_e N_o}$$

r = distanza elica punto osservazione
$\langle p \rangle^2$ media quadratica della pressione sonora nel punto di osservazione
R_o = raggio max bolle di cavitazione
N_o = numero delle bolle di cavitazione generate per unità di tempo
ρ_w = densità fluido
p_e = pressione ambiente
c_w = velocità del suono nel fluido

assumendo

r proporzionale a D
N_o " " N
R_o " " D

$$\frac{r_m^2 \langle p_m \rangle^2}{\rho_{wm} c_{wm} R_{om}^3 p_{em} N_{om}} = \frac{r_s^2 \langle p_s \rangle^2}{\rho_{ws} c_{ws} R_{os}^3 p_{es} N_{os}} \qquad (7)$$

$$\frac{D_m^2 \langle p_m \rangle^2}{D_m^3 p_{em} N_m} = \frac{D_s^2 \langle p_s \rangle^2}{D_s^3 p_{es} N_s}$$

$$\frac{\langle p_m \rangle^2}{D_m p_{em} N_m} = \frac{\langle p_s \rangle^2}{D_s p_{es} N_s} \qquad (8)$$

$$\frac{\langle p_m \rangle^2}{\langle p_s \rangle^2} = \frac{D_m p_{em} N_m}{D_s p_{es} N_s} \qquad (9)$$

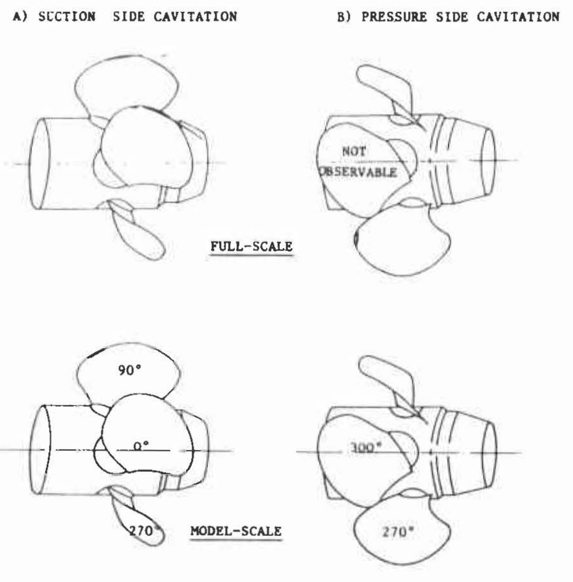
ricordando la (2)

$$\frac{\langle p_s \rangle^2}{\langle p_m \rangle^2} = \lambda^3 \frac{N_m^3}{N_s^3} \qquad (10)$$

da cui

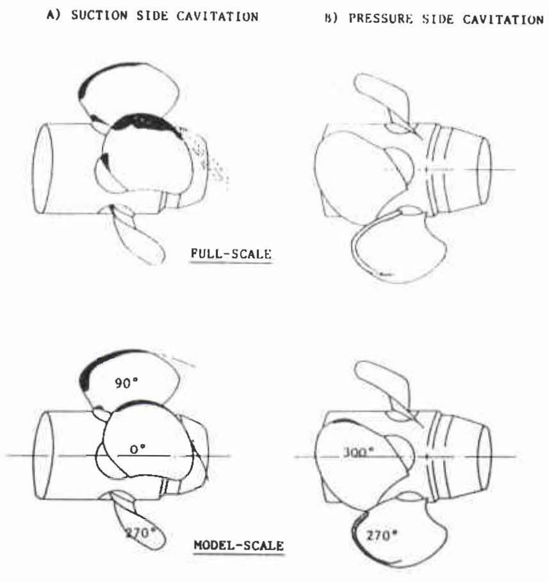
$$L_{p_s} - L_{p_m} = 10 \log \lambda^3 \frac{N_s^3}{N_m^3}$$

Fig. 8
Frequency and sound pressure level scaling laws



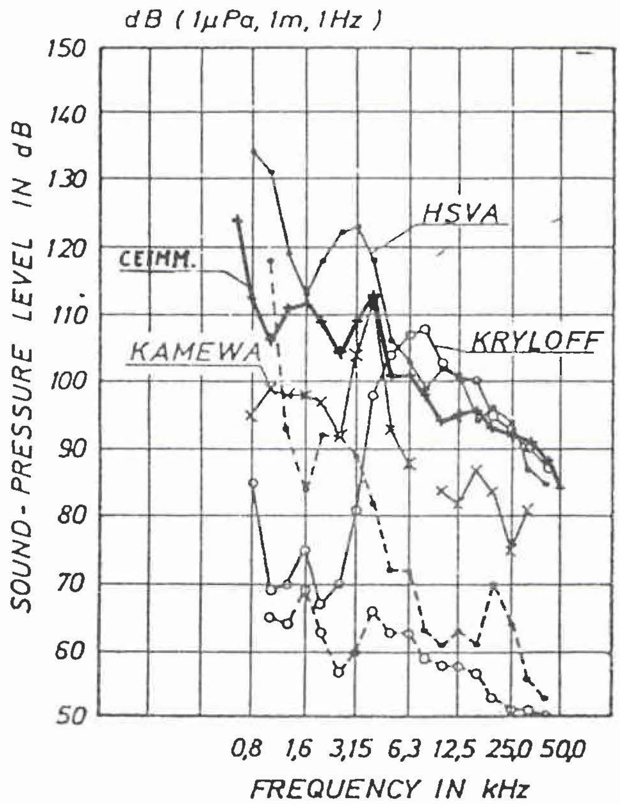
SHIP FROUDE NUMBER : F_N = 0.246
CAVITATION INDEX : σ_N = 6.72
TORQUE COEFFICIENT : K_Q = 0.0473

Fig. 9
Propeller cavitation pattern observation



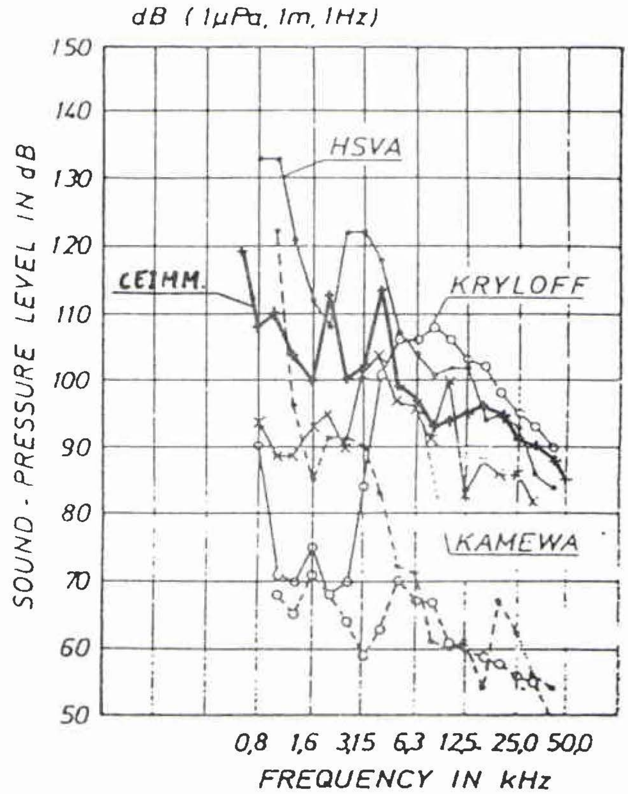
SHIP FROUDE NUMBER : F_N = 0.400
CAVITATION INDEX : σ_N = 2.307
TORQUE COEFFICIENT : K_Q = 0.0508

Fig. 10
Propeller cavitation observation



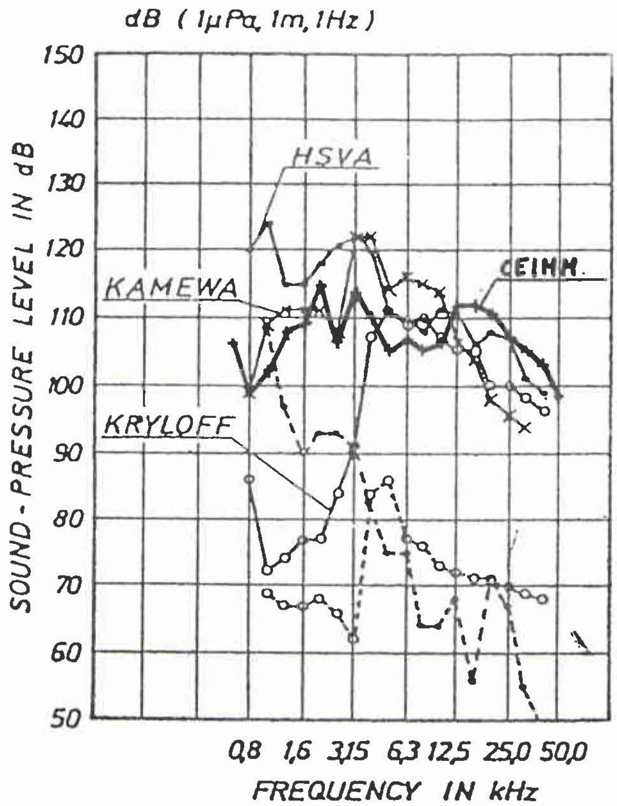
—— Cavitating propeller noise
--- Background noise

Fig. 11
Noise measurements of conventional tunnels (suction side cavitation)



—— Cavitation propeller noise
--- Background noise

Fig. 12
Noise measurements of conventional tunnels



—— Cavitating propeller noise
—— Background noise

Fig. 13
Noise measurements of conventional tunnels (pressure side cavitation)