2019 IMEKO TC-19 International Workshop on
Metrology for the Sea
Genoa, Italy, October 3-5, 2019

Cavitation tunnel in Naval Architecture: from cavitation prediction to radiated noise

Giorgio Tani[1], Michele Viviani[2], Marco Ferrando[3]

[1] *Università degli studi di Genova, Via Montallegro 1, 16145 Genova,* giorgio.tani@unige.it
[2] *Università degli studi di Genova, Via Montallegro 1, 16145 Genova,* michele.viviani@unige.it
[3] *Università degli studi di Genova, Via Montallegro 1, 16145 Genova,* marco.ferrando@unige.it

***Abstract* – Cavitation tunnels represent one of the most important typologies of model testing facilities used in Naval Architecture. These facilities are employed to study the hydrodynamics of marine propellers, with special attention on cavitation and its side effects. These effects include: loss of propeller thrust and efficiency, erosion, inboard noise and vibration, underwater radiated noise. The latter aspect is one of the hot topics in the field of ship hydrodynamics because of the concerns related to its impact on marine life. This paper presents the general setup and test procedures used to predict the propeller radiated noise based on model tests. In addition, some of the main experimental issues related to these activities are described.**

I. INTRODUCTION

Cavitation Tunnels are well known facilities used by Naval Architects since long time. Their introduction was due to the necessity of studying propeller cavitation phenomena and their effects on propellers; in particular, attention was posed on the verification of propeller design, in terms of existence of cavitating phenomena which could cause blade erosion and check of the possible thrust breakdown due to large extents of cavitation.

Nowadays, the study of the radiated noise of cavitating propellers is a subject of increasing importance because of the concerns about ships noise impact on the marine environment, thus a large number of studies is being devoted to this problem. Currently, among the different approaches used to assess the noise emissions of a propeller, model tests represent the most reliable and commonly used method. Despite this, predicting radiated noise from a marine propeller is still a rather challenging task: results are usually affected by scale effects as well as measuring issues related to the characteristics of the facility in which measurements are carried out. Many researches are ongoing on both subjects, which are indeed interrelated.

For what regards scale effects, the International Community is strongly looking for documented cases of ships for which noise measurement in model and full scale are available, in order to check the existing scaling functions (see ITTC recommended procedures and guidelines, 2017 [1]). Unfortunately, in many cases data are protected due to industrial reasons (or even affected by military issues), limiting the number of open data and thus amplifying the need for further analyses. ITTC is trying to setup a benchmark case for which full scale measurements are available; possible candidates are ships tested recently in European Projects dedicated to the subject of Underwater Radiated noise (SILENV, AQUO, SONIC).

For what regards the effect of confined environment, nearly all model scale facilities are affected, to different extents, by these problems. Recently, in ITTC procedures and guidelines [1], the importance of measuring the effect of the confined environment and correct results by means of ad hoc measured transfer functions has been recognized; however, a common procedure is still pending, which is one of the terms of reference of the Specialist Committeee in Hydrodynamic Noise.

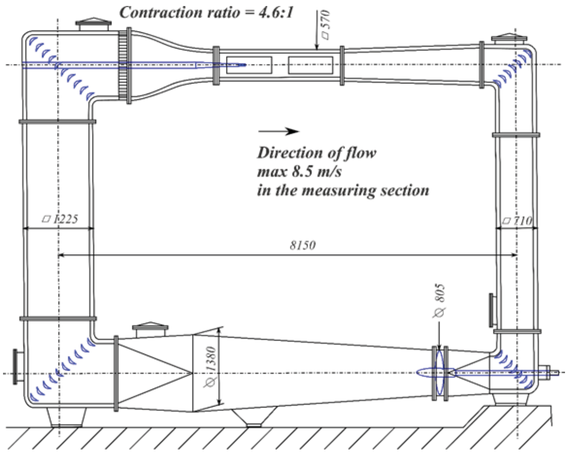

Figure 1: Genoa cavitation tunnel

In the last years, at the Cavitation Tunnel of Genoa University, these issues have been thoroughly analysed, thanks to some EU and Italian projects. This experimental facility (see Figure 1) is rather small compared to other very large facilities such as MARIN depressurized water basin or large cavitation tunnels such as HSVA, KRISO, SSPA, etc.

However, the small dimensions are related to rather small operating costs, thus allowing to carry out systematic tests more freely; this allowed to analyse deeply some aspects [2][3], resulting in some guidelines on how to conduct tests in model scale. In the present paper, some of the main issues related to radiated noise measurements in model scale will be discussed, explaining the main outcomes.

II. TYPICAL EXPERIMENTAL SETUP

The Cavitation tunnel of the University of Genoa is a Kempf & Remmers closed water circuit tunnel featuring a square testing section of 0.57 m×0.57 m, having a total length of 2 m. The maximum speed in the test section is 8.5 m/s whereas a minimum pressure of about 50 mBar can be achieved by means of vacuum pumps.

The tunnel is equipped with a Kempf & Remmers H39 dynamometer, which measures the propeller thrust, the torque and the rate of revolution. The dynamometer can be installed with the propeller in pulling (as in Figure 2) or pushing configuration and the propeller shaft can be inclined -15° to 15°.

Propeller cavitation is observed visually and by cameras with the aid of stroboscopic lights.

The water quality in the tunnel, that is basically the amount of cavitation nuclei, is routinely checked during tests measuring the oxygen content through an ABB dissolved oxygen sensor model 8012/170, coupled with an ABB analyser model AX400. This measure does not allow a direct assessment of the size spectrum of cavitation nuclei, however for a given facility the amount of dissolved oxygen is strictly correlated to the amount of nuclei, being thus indicative of water quality.

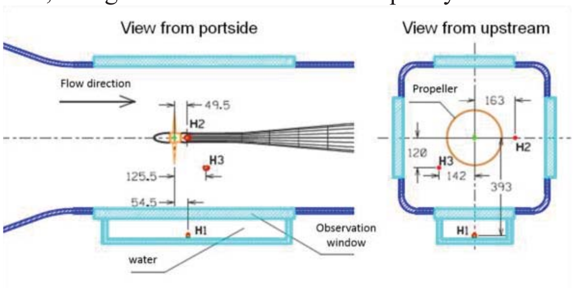

Figure 2: Schematic of experimental setup [3].

Noise measurements are carried out with a multi-hydrophone configuration. Miniaturized hydrophones are adopted, namely one Reson TC4013 and one or two Bruel & Kjaer type 8103. The hydrophones are installed with two typical configurations.

One configuration consists in mounting the hydrophones on streamlined supports positioned inside the tunnel flow and outside the direct propeller slipstream, see Figure 3.

The second hydrophone configuration consists in placing the sensor in a rudimental acoustic chamber positioned on the bottom observation window of the test section, Figure 4.

Both configurations have their own merits and shortcomings, mainly related to issues such as poor signal to noise ratio (SNR), near field effects and noise propagation issues. Consequently, it is preferable to use them simultaneously in order to collect complementary information.

Figure 3: Streamlined support for inflow hydrophone [3].

Figure 4: External hydrophone configuration [3].

In order to properly simulate the propeller functioning, the inflow of the real propeller due to the wake of the ship hull should be reproduced in the test section. In large facilities, this is achieved by installing the propeller behind a complete or modified hull model [4], [5].

In facilities such as the University of Genoa Cavitation tunnel, it is not possible to install a hull model due the to limited dimensions of the test section, hence the propeller inflow is simulated using suitable devices such as wire meshes, parallel plates assemblies, flow liners and parts of the shaft line (e.g. models of the shaft brackets). Vertical flow components are simulated, if present, by inclining the propeller shaft.

One example is shown in Figure 5. This configuration, typically adopted for twin screw ships, is characterized by the presence of a small simulacrum of the hull. This simulacrum is designed to produce a certain wake field and it has no relation with the real hull. Some wire meshes, mounted on this object, are visible. These are used to achieve the required deficit of axial velocity when the effect of the simulacrum is not sufficient. The configuration includes also a model of the shaft brackets and a small portion of the shaft line.

Figure 5: Example of devices used to simulate the propeller inflow [6].

III. TRANSFER FUNCTION MEASUREMENT

Many measurement issues affect the results of noise tests in a cavitation tunnel, within them, one of the most important is the effect of the confined environment.

Actually, the noise measured by the hydrophone in the facility is influenced by the acoustic response of the facility. Actually, with reference to the scheme shown in Figure 6, the facility may be considered as an input-output system, whose output is the hydrophone measurement while input is the propeller noise as it would be measured in free field conditions.

The output of the system is a deterministic function of the input, and, under the hypothesis of linearity, that is reasonable for an acoustic propagation process, this function is represented by the convolution product between the input signal *x(t)* and the impulse response *h(t)* of the system. The transfer function is defined as the Laplace transform of the impulse response.

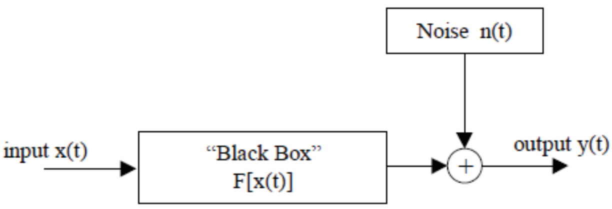

Figure 6: Scheme of input/output system [3].

For the study of propeller noise however, only the frequency response of the system is needed in order to correct measured noise spectra and obtain the corresponding noise spectrum in ideal free-field conditions. In this view, the frequency response of the facility, usually referred to as the transfer function, is the ratio between the power spectrum of the noise measured in the test section and in free field conditions for the same source. Transfer functions are hence measured exploiting electronic noise emitters whose emitting characteristics are known from dedicated measurements in anechoic chambers or at sea.

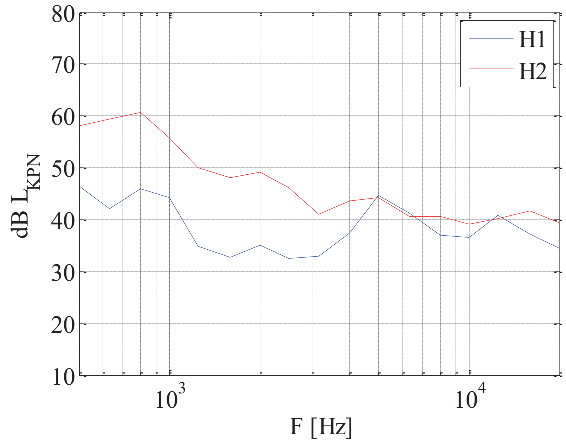

Figure 7: Propeller noise measurements at two locations, not corrected [2].

The direct validation of the application of the transfer function for the noise of a model propeller is almost unfeasible since it is nearly not possible to run a model propeller in free field condition with the same cavitation reproduced in the facility. However, the effects of the transfer function may be indirectly observed comparing measurements obtained by two hydrophones in different configurations. *Figure 7* reports noise spectra measured by two hydrophones mounted with the two configurations previously described: H1 is placed in the acoustic chamber, H2 is installed inside the test section. As it can be seen, the two spectra are significantly different. This is due to the very different noise propagation patterns that result in different transfer functions for the two hydrophones.

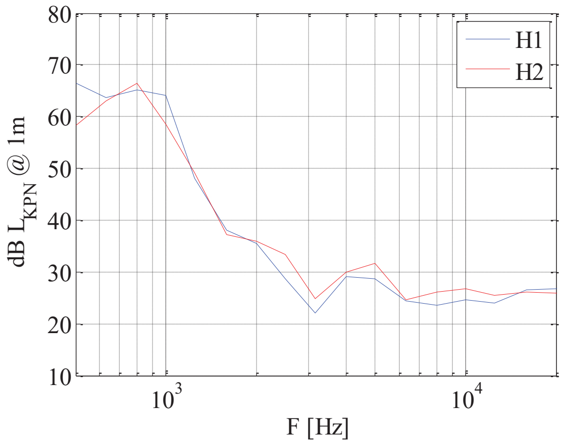

Figure 8: Propeller noise measurements at two locations corrected by means of transfer functions [2].

Correcting the spectra according to the transfer functions measured for the two hydrophones, the results shown in Figure 8 are obtained. The agreement between corrected spectra is significantly improved, as expected in free field condition; the effects of the confined environment are correctly taken into account, at least in terms of differences between the two configurations.

IV. POSSIBLE ISSUES

The basic principles of the measurement of transfer functions are simple: a known and repeatable noise source is measured in the cavitation tunnel and in free field condition. Nevertheless, the measurement of consistent transfer functions is rather complex, as it is discussed in this section.

The main issues related to the measurement of transfer functions of propeller radiated noise are connected to the differences between these two situations: the noise emitted by an electronic transducer and the noise emitted by a cavitating propeller. The acquiring sensors are the same in the two cases, but the noise generation mechanisms and propagation may present some differences.

A. Hydrophones and transducers positions

The position of the noise source may influence significantly the measured transfer function, as shown for example in Figure 9, reporting transfer functions measured for different positions of the source, all belonging to the region occupied by the propeller. Consequently, a correct positioning of the source is crucial; this should be as far as possible similar to the position where propeller noise is generated, that is where cavitation is present.

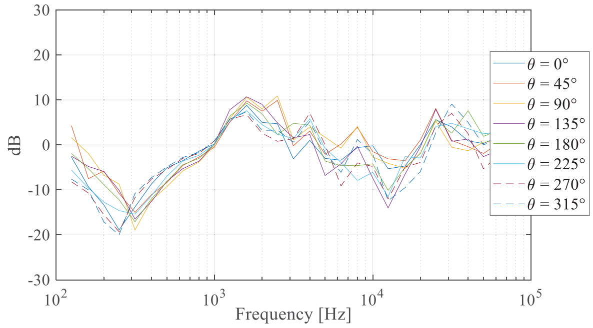

Figure 9: Transfer functions measured for different emitter positions on the propeller disk, r/R=0.75 [3].

Furthermore, one single source position is usually not sufficient to represent the process of cavitation noise. Actually, cavitation noise is the result of the action of many uncorrelated noise sources, i.e. cavitation bubbles, pulsating and collapsing simultaneously in different regions, and moving with the flow.

A practical solution to partially take into account of this aspect, is to measure the transfer function for multiple positions of the emitter, all consistent with the positions where cavitation occurs. Then the incoherent average of the obtained transfer function is computed.

This approach allows also to cope with another typical issue of transfer functions: measured transfer functions usually feature a rather irregular shape, with several peaks and hollows related to the presence of separate propagation modes in the facility and of local interference between the acoustic waves. These phenomena are significantly reduced when considering the propagation of noise generated by cavitation, because of the random nature of the noise sources. The incoherent average of transfer functions measured in correspondence to many emitter positions may be considered also as a method to approximately estimate the transfer function for uncorrelated random noise sources, as cavitation bubbles, by means of a deterministic process as the emission of noise by an electronic transducer.

An alternative solution to cope with this issue is to measure the transfer function while the emitter is in continuous motion. With this approach, deterministic effects are reduced and the obtained transfer function is significantly more regular, as shown in *Figure 10*. In this case the source is rotating end the signal is continuously emitted during rotation. The transfer function measured in this condition (in black) is significantly smoother than the ones measured in correspondence to four fixed positions (colored curves). This could represent the case of a propeller cavitating at all the blades angular positions. In case cavitation occurs only in a limited part of the propeller disk, the noise emission should be triggered with the source angular position.

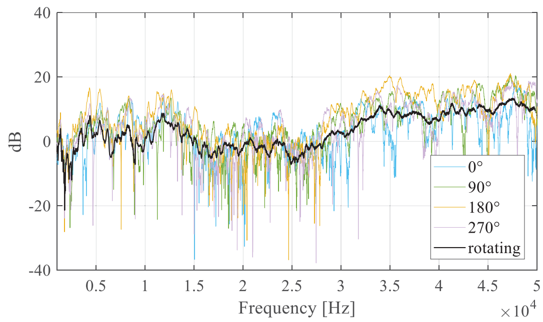

Figure 10: Measured transfer function with fixed and rotating source, narrowband representation [3].

B. Static pressure

The static pressure inside the test section of the cavitation tunnel represents another important difference between the case of transfer function measurement and propeller tests. Actually, transfer functions are usually measured at atmospheric pressure, with the water at rest. On the contrary, during a cavitation experiment, the test section is depressurized and a certain flow speed is present. This results mainly in a different concentration and size of gaseous bubbles in the water. Also, propeller cavitation contributes in shedding bubbles in the flow.

The presence of free bubbles in the flow may affect significantly noise propagation: actually if the bubble concentration is remarkable, the acoustic impedance of the medium may vary. Furthermore, bubbles may dissipate the acoustic energy by vibrating and scatter the acoustic wave.

These effects are shown for example in Figure 11. The figure reports the difference between the transfer function measured for varying tunnel pressure and the reference one measured in atmospheric conditions. As it can be seen, for the present experiment significant differences are observed below 400 mBar.

It must be noted that these results have been obtained for an emitter-receiver configuration that is not consistent with cavitation noise, actually the emitter is positioned far away from the propeller, thus amplifying the above mentioned effect. This measurement represents has thus to be considered only as a qualitative example of the effects of the static pressure, and consequent differences in the bubble population, on noise transmission.

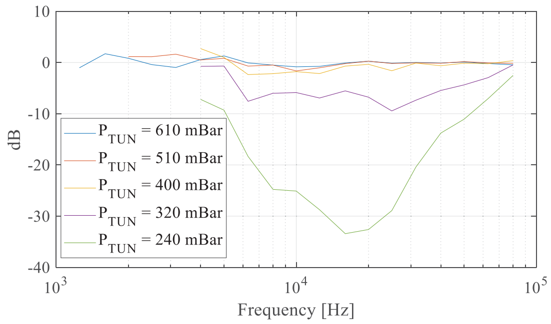

Figure 11: Effect of actual cavitation tests conditions on measured transfer functions [3].

V. MODEL VS FULL SCALE

The comparison between radiated noise predictions based on model tests, and full scale noise measured during the sea trials of a vessel is crucial to validate the overall experimental procedure and post processing adopted.

Full scale noise predictions are obtained scaling the model scale noise spectra, after applying proper corrections, according to suitable scaling laws such as those suggested by the ITTC [1].

It is worth mentioning that only cases for which the propeller is cavitating are here considered. Actually, if the propeller is not cavitating, other noise sources, not reproduced in cavitation tunnel experiments, may characterize the acoustic signature of the ship, consequently the comparison with noise measured at cavitation tunnel could be more problematic.

The results of the complete procedures are affected by several scale effects and sources of uncertainties. The issues related to confined environment effects and to the transfer function measurements, which are reported in present work, are important, but other aspects must be considered as well, a non-exaustive list includes:

- The correct assessment of the hull wake field, including viscous effects on the development of the boundary layer on the hull.
- Viscous effects on the development of the boundary layer on propeller blades and consequent effects on the inception and extent of sheet cavitation.
- Viscous effects on the development of tip vortex cavitation, especially close to inception.
- Scale effects related to cavitation nuclei and bubble dynamics.

In addition, also results of sea trials may be affected by measurement issues and uncertainties, as for instance the determination of transmission loss, which may be crucial, especially in shallow water condition.

Due to this, drawing conclusions for a single test case may be misleading.

Three relevant examples are reported in Figure 12, Figure 14 and Figure 14.

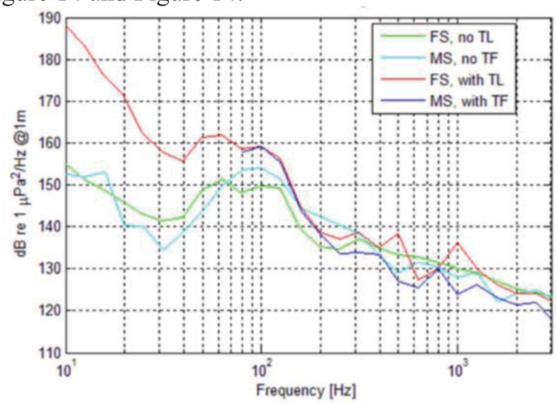

Figure 12: Comparison between model scale noise and full scale noise, case 1 [7].

In the first case, related to a Research Ship [7] a rather good agreement between model scale and full scale results is observed. It must be noted that in this figure results are compared both with and without the application of transfer function correction for model tests and transmission loss correction for sea trials, which were carried out in very shallow water.

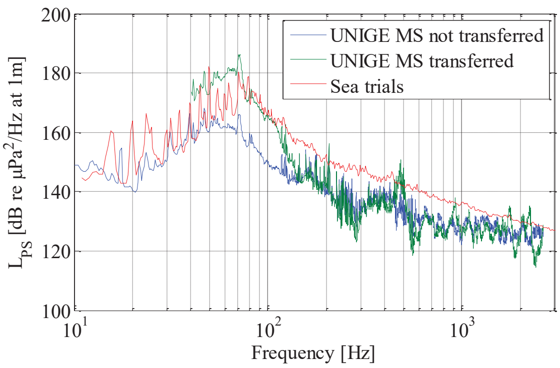

Figure 13: Comparison between model scale noise and full scale noise, case 2 [8].

As it can be seen the agreement is reasonable both with and without corrections, meaning that in this particular case, the transfer functions measured at cavitation tunnel are rather similar to the transmission loss estimated for the sea trials site.

Of course, this result cannot be generalized and in most cases, the agreement is improved applying the corrections, as for example in the case shown in Figure 13 and deeply described in [8], related to a coastal tanker.

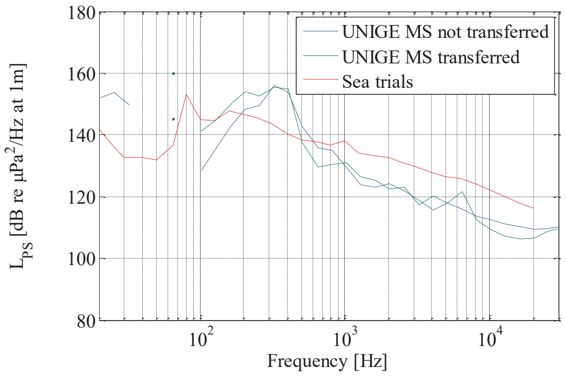

Figure 14: Comparison between model scale noise and full scale noise, case 3 [9].

The example reported in Figure 14, related to a small research vessel (see [9] for more details), shows instead a case for which, independently on the application of transfer function corrections, the comparison between model scale and full scale results is not fully satisfactory, probably because of the issues related to the simulation of propeller inflow and cavitation patterns.

VI. CONCLUSIONS

In this paper, experimental tests carried out in cavitation tunnels, with particular attention given to the facility of the University of Genoa, have been described. In particular, the attention has been focused on radiated noise measurements, representing nowadays one of the most challenging tests performed in cavitation tunnels.

The typical setup and testing procedures adopted has been described and in particular some issues related to the effects of the confined environment and the measurement of transfer functions are discussed. Finally, some examples of comparison between model scale noise predictions and full scale results are shown. From these comparisons it can be observed that adopted procedures generally allow to achieve a fair prediction of ship radiated noise when the propeller is cavitating. However, the accuracy of the procedure may vary significantly case by case. Due to this, it is important to collect as much validation cases as possible, in order to statistically assess the reliability of the procedure and improve the understanding of the issues still to be overcome.

REFERENCES

[1] ITTC, 2017. Recommended procedures and guidelines, Model-scale propeller cavitation. Noise measurements, 7.5-02-01-05, 2017.

[2] G. Tani, M. Viviani, E., Armelloni, M., Nataletti, "Cavitation Tunnel Acoustic Characterisation and Application to Model Propeller Radiated Noise Measurements at Different Functioning Conditions", Proc. Inst. Mech. Eng., Part M: Journal of Engineering for the Maritime Environment; ISSN: 1475-0902, SAGE Publishings, Vol. 230(2), 2016, pp.250-266, doi: 10.1177/1475090214563860

[3] G. Tani, M., Viviani, M., Ferrando, E. Armelloni, E. "Aspects of the measurement of the acoustic transfer function in a cavitation Tunnel", Applied Ocean Research 87, 2019, pp. 264-278, doi: 10.1177/1475090214563860

[4] G. Calcagno, F., Di Felice, M., Felli, F., Pereira, "Propeller Wake Analysis Behind a Ship by Sterep PIV", 24th Symposium on Naval Hydrodinamics, Fukuoka, Japan, 8-13 July 2002.

[5] C. Johannsen, E., van Wijngaarden, T., Lucke, H., Streckwall, J., Bosschers, "Investigation of Hull Pressure Pulses, Making Use of Two Large Scale Cavitation Test Facilities", Proceedings of the Eighth International Symposium on Cavitation (CAV 2012), 2012.

[6] F. Miglianti, F., Cipollini, L., Oneto, G., Tani, M., Viviani, "Model Scale Cavitation Noise Spectra Prediction: Combining Physical Knowledge with Data Science". Ocean Engineering 178, 2019, pp. 185–203, doi: 10.1016/j.oceaneng.2019.02.002.

[7] S., Gaggero, T., Gaggero E., Rizzuto G., Tani, D., Villa, M., Viviani., "Ship propeller side effects: pressure pulses and radiated noise", Noise Mapping Vol.3, 2016, p.295-315, doi: 10.1515/noise-2016-0021

[8] G. Tani, M., Viviani, J., Hallander, T., Johansson, E., Rizzuto, "Propeller underwater radiated noise: a comparison between model scale measurements in two different facilities and full scale measurements.", Applied Ocean Research, 2016, doi: 10.1016/j.apor.2016.01.007.

[9] G. Tani, B., Aktas, M., Viviani, N., Yilmaz, F., Miglianti, M., Ferrando, M., Atlar, "Cavitation tunnel tests for "The Princess Royal" model propeller behind a 2-dimensional wake screen", Ocean Engineering, Vol. 172, 2019, pp 829-843, https://doi.org/10.1016/j.oceaneng.2018.11.017.