SHIP URN: UNIGE activities in the context of LIFE-PIAQUO Project

Stefano GAGGERO[a,1], Tomaso GAGGERO[a], Giorgio TANI[a], Diego VILLA[a], Enrico RIZZUTO[a] and Michele VIVIANI[a]
[a] *Genoa University, Department of Electrical, Electronic, Telecommunication Engineering and Naval Architecture (DITEN)*

Abstract. In the last years, an increasing attention has been devoted to ships Underwater Radiated Noise (URN), with the progressive introduction of Guidelines by international organizations such as IMO, Classification Societies voluntary notations, limits and incentives in specific areas. In this context, a large effort has been spent in the study of cavitating propeller noise since it represents the dominating noise source on ships. UNIGE is currently involved in the EU-funded LIFE-PIAQUO project, in which the main activities are related to propeller design by optimization, onboard cavitation detection during operations, noise mapping. The present paper reports motivations, aims and achievements of these activities in the first half of the project.

Keywords. Underwater radiated noise, Propeller design, Optimization, Cavitation, Cavitation detection, Noise mapping

1. Introduction

The environmental impact of marine transportation has always been a priority for International Maritime Organisation. Most of the attention has been (and still is) devoted to emissions in air (GHG and other noxious emissions), but also other effects have been covered, such as the discharge of noxious liquid or garbage at sea, the chemical emissions in water due to antifouling paints or the biological impact of water ballast exchange, the environmental impact of scrapping etc.

On the other hand, in the last 15 years the acoustical impact of anthropogenic activities on the environment has continuously gained attention. For shipping, such impact takes the form of noise radiation in air and in water. The latter subject has been in the past considered with reference to naval vessels, which need to keeptheir acoustic signature as low as possible in order to avoid threats.More recently, attention has been given to the effects that the anthropogenic underwater noise emissions have on the marine fauna, in particular on marine mammals [1][2]. Accordingly, many studies have been devoted to this issue, as summarized e.g. in [3].

With the aim of the protection of the sea environment, EU has issued the Marine Strategy Framework Directive 2008/56/EC, in which underwater noise is considered as one of the descriptors of good environmental status for the sea. The Directive has

---

[1] Corresponding Author, Genoa University, DITEN Department, Via Montallegro 1, 16145 Genova, Italy; email: stefano.gaggero@unige.it

prompted many monitoring activities in the field of underwater acoustics, but no limits have been prescribed in that context.

In the shipping world, IMO released Guidelines in 2014 [4], aimed at reducing URN from commercial shipping to avoid adverse impacts on marine life. However after this action no further one was carried out until 2022, when a correspondence group was established within IMO for the revision of the 2014 Guidelines, with aim of making them more widely applicable. For what regards Classification societies, starting with DNV Silent Class in 2010 (amended in 2019), many other societies have proposed their voluntary class notations related to URN noise (BV in 2014, amended in 2017, LR and RINA in 2017, ABS and CCS in 2018, further testifying the interest on the topic.

Canada is currently very active in the shipping sector, with several initiatives carried out by Transport Canada about the control of URN emissions from ships. An innovative approach is represented by the discount system introduced by the Port of Vancouver in 2017, based on the ranking of ships in terms of URN radiation.

The University of Genoa (UNIGE) has been involved in a number of activities in the field of underwater radiation of noise from ships, with participation to two FP7 Projects (SILENV and AQUO); these activities are currently carried on in the LIFE-PIAQUO (Practical Implementation of AQUO) project, together with Naval Group, Fincantieri, CETENA, Quiet Oceans, Chorus, Alseamar, Kongsberg, Bureau Veritas. Main objective of the LIFE-PIAQUO project is the reduction of radiated noise generated by vessels and the adaptation of radiated noise in real-time to ecosystems crossed by vessels in order to minimize the impact on the environment. The project has five goals, as follows:

1. Practical implementation of ship radiated noise reduction using improved propellers
2. Practical implementation of ship radiated noise real-time self-estimation and control
3. Inducement of virtuous approaches from ship owners to reduce shipping URN
4. Adaptation of the maritime traffic according to the real-time state of marine ecosystems
5. Setting a broadcasting service for decision making support to reduce shipping noise impact

UNIGE activities are concentrated on the first two points. In particular, within the first goal, UNIGE activity is devoted to the re-design by optimization of the propeller of an existing small passenger ship, with the focus on the URN. The ship is usually operated in the proximity or inside marine protected areas, and the final aim is to substitute the existing propeller with the optimized one, in order to carry out comparative URN measurements.

With the second goal, UNIGE is studying some possible strategies for self-estimation of cavitation onboard ships, with attention on cavitation detection and on estimation of noise in far field starting from onboard measurements. The present paper is devoted at providing an overview of the current status of these activities at project mid-term. In particular, in section 2 propeller optimization activities are summarized, while section 3 is devoted to URN self-estimation, considering cavitation detection (par. 2.1) and far field estimation (par.2.2).

1. Propeller Optimization

The Goal 1 of the PIAQUO project was pursued by designing a new propeller using an optimization-based design approach with the aim of improving the propeller efficiency and simultaneously reducing its radiated noise. These objectives were addressed by a combination of tools (BEM and RANS calculations, semi-empirical models) made possible by the optimization framework. The optimal geometry, in the light of the sea-trials validation activities, was finally selected preferring the reduction of radiated noise.

1.1. Test case description

The reference small passenger ship is a semi-displacement, hard chine with spray rails vessel operating on the North Italian coasts. Its length is about 24 m and it has a maximum capacity of 350 people, with an operative speed exceeding 20 knots. The ship is equipped with two propellers mounted on conventional shaft lines supported by an intermediate bracket and a single strut near the propeller disk as shown in **Figure 1**.

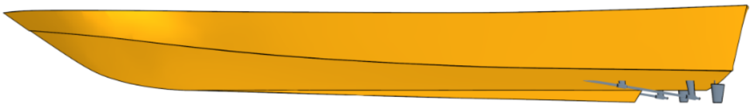


Figure 1: 3-D model of the hull and shaft lines.

Starting from the stability booklet and in accordance with the master experience, three working conditions have been identified:

1. Lightship displacement: defined when the ship is loaded with only 50% of the consumable and no passengers are on-board. This condition is representative of the transfer condition with maximum speed achieved.
2. Heavy displacement: defined when the ship operates at maximum load (all the consumables and all the passengers). This condition can be considered the one when the maximum propeller load is experienced.
3. Intermediate displacement: defined as the most common operational condition (half of the consumables and 250 passengers). This has been considered as most significant design condition.

1.2. Propeller Optimization

The design of the new propeller was obtained by the systematic analysis of thousands of geometries, whose performances were collected and compared to that of the reference (initial) propeller and used as “feedback” to iteratively modify the geometrical parameters of the propellers themselves [5]. This “try-and-error” process was possible thanks to a parametric description of the propeller geometry by means of B-Spline curves, an efficient flow solver based on a Boundary Element Method and an automatic procedure to manage the entire process.

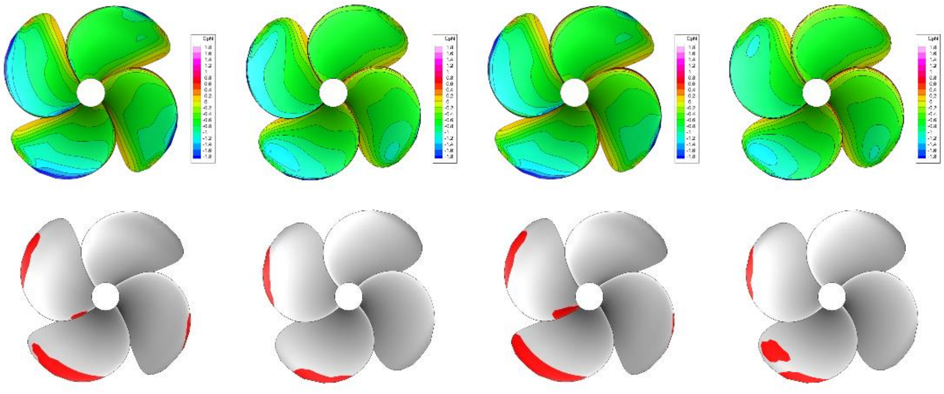
This optimization process started from the hydrodynamic characterization of the reference propeller and from the definition of suitable design objectives. Since the design by optimization is a computationally expensive process even if carried out using an efficient BEM, some simplifications have been accepted. Equivalent steady configurations were considered rather than fully unsteady analysis, covering the three functioning conditions of the ship to account for the risk of different types of cavitation (from severe back cavitation in heavy loading to pressure side phenomena of the lightship condition, considering in all cases also bubble cavitation risk). In the end, the design process was configured as a multi-objective optimization involving:

- 35 input (free) variables, describing, (via B-Spline curves), the pitch, the chord, the maximum camber and the skew radial distributions plus the sectional mean camber line and thickness shape of the blade,
- 18 objectives maximizing the minimum of the pressure coefficient (i.e. postponing the cavitation inception) and 5 minimizing the extension of blade area subjected to pressure lower than saturation,
- 2 additional objectives monitoring the achieved ship speed (intermediate ship displacement) and the engine functioning point,

which was solved using a Multi-Objective Genetic Algorithm on an initial Design of Experiments (DoE) of 2,500 geometries and 50 evolutions, for a total of 125,000 computed configurations.

The design process, finally, was integrated with fully unsteady analyses (using BEM) and equivalent open water RANS calculations to confirm the results of the optimization process based on BEM and to provide additional data for the final selection of the optimized geometry. These calculations were carried out for a subset of geometries extracted from the Pareto frontier of the optimization process, preferring those capable of a significant reduction of the cavitation inception (indirectly, of the radiated noise) with respect to a pure increase of the cruise speed.

RANS calculations in correspondence of “equivalent” advance coefficient were used to check the reduction in the cavitation extension and the risk of cavitation inception, as done during the optimization process with the BEM. Unsteady BEM calculations (see **Figure 2**), were used to characterize the radiated noise using the ETV model [6], which estimates the maximum pressure level for the peak of the tip vortex its frequency. ETV calculations were carried out by CETENA, partner of the project.



(a) Reference, Interm. displacement, design speed

(b) Reference, Interm. displacement, max. speed

(c) Optimized, Interm. displacement, design speed

(d) Optimized, Interm. displacement, max. speed

Figure 2: Instantaneous unsteady pressure distribution (top) and predicted cavity extension (bottom) of the reference and the selected optimal propeller (ID 52214) at the intermediate displacement. BEM analyses.

Combined with the predicted propulsive efficiency, these results guided the selection of the optimized propeller, which was finally identified in the geometry of case ID 52214. Compared to the reference propeller, this geometry provides a slightly lower (predicted) efficiency, corresponding to a reduction of the ship speed at the design point (intermediate displacement) of about 0.1 knots. This is the compromise between the contrasting objectives of the optimization process that was accepted for this specific design. The optimized geometry, indeed, at the cost of this negligible speed loss (compensated, in a certain way, by a 0.3 knot higher maximum attainable speed at the intermediate displacement), realizes a substantial reduction of radiated noise, which was considered the primary objective of the current design activity, higher than 10dB when quantified by the ETV model. Based on these results, alternative solutions, like the ID 102773 or the ID 116171 could provide respectively, a simultaneous increase of ship speed with radiated noise reduction (but halved with respect to the ID 52214) or a further reduction of radiate noise (up to 15dB) but at even lower ship speed. ID 52214, at this stage of the design process, proved to be a reasonable compromise also in the light of the sea trials measurement limits.

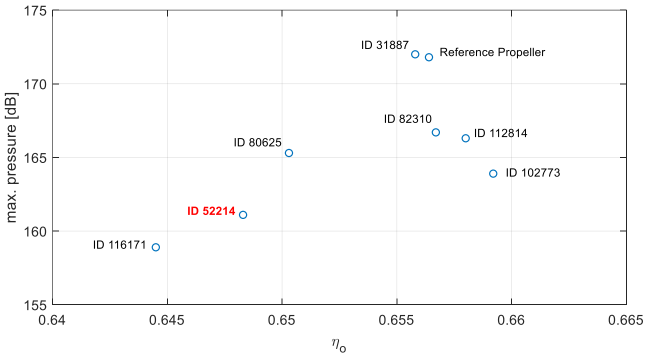


Figure 3: Maximum vortex pressure versus propeller efficiency for some of the Pareto solutions. Design functioning (intermediate displacement) estimated with BEM.

1.3. Model Tests

Model tests on the two propellers have been carried out with a two-fold objective: collecting information on the original propeller useful for the optimization procedure and verify the newly designed propeller. Tests include towing tank open water tests for characterizing the hydrodynamic performances of the propellers and cavitation tunnel tests to assess their cavitation behaviour and resultant radiated noise. The experimental setup adopted at cavitation tunnel is characterised by a 10.5° shaft inclination, with the propeller installed in pulling configuration.

Model tests almost completely confirmed the outcomes of numerical analyses. Observed cavitation patterns on the two propeller models are represented by sketches and photographs in Figure 4. Experiments confirm the remarkable cavitation reduction achieved for the optimized propeller, both in terms of tip vortex cavitation and sheet cavitation. It is worth noticing that also pressure side cavitation was completely eliminated for the intermediate loading condition.

Model scale radiated noise has been measured by two hydrophones installed in the facility test section: one directly inside the flow (but outside propeller slipstream) and another one in a small acoustic chamber adjacent to the bottom of the test section.

Noise records have been acquired with a sampling frequency $f_s = 200kHz$ for a duration of 60 seconds. Signals have been processed according to the ITTC guidelines [7], including background noise correction, distance normalization, confined environment effect correction and full scale extrapolation, thus obtaining the full scale Source Strength Level spectra SL_{FS}. Results are exemplified in Figure 5.

As it can be seen, radiated noise for the optimized propeller is reduced of about 10 dB on average, with even larger reduction at high frequency. This result is consistent with the substantial reduction of tip vortex cavitation, as evidenced also by the reduction of the low frequency peak in the spectrum, typically associated with this phenomenon.

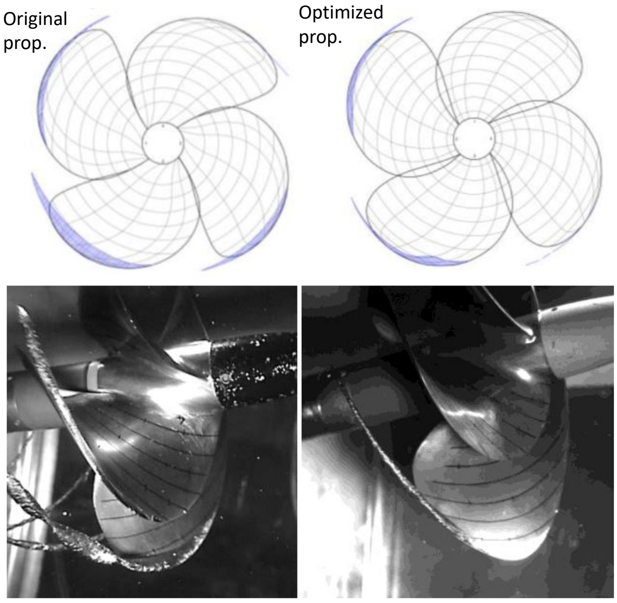


Figure 4: Cavitation pattern at 15 kn, intermediate loading: original propeller (left) vs optimized propeller (right)

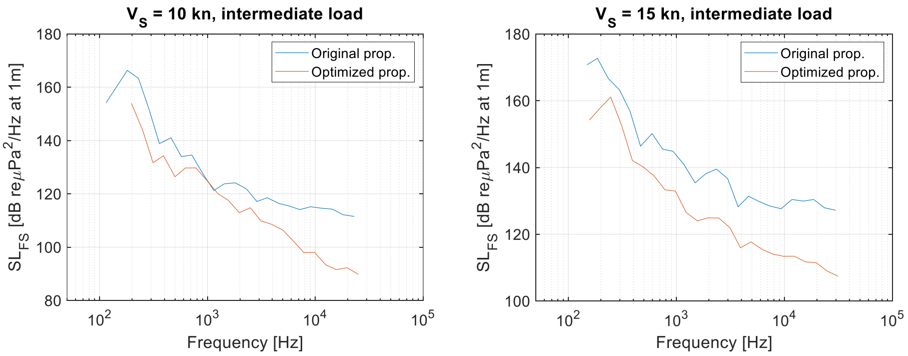


Figure 5: Radiated noise results: full scale extrapolations**.**

2. URN Self estimation

2.1. Cavitation detection

Performing cavitation detection means understanding whether the propeller is cavitating or not based on the signals measured by some sensors on-board a ship. The complexity of the task depends on the type, number, and distribution of sensors. For most practical applications, only few accelerometers are available, because of their simple and non-intrusive installation.

In principle, cavitation could be detected checking the signal power: the onset of cavitation usually generates a sudden increase of noise and vibration levels, at least at some frequencies. However, implementing this approach is not trivial because many other phenomena can affect the vibration levels, causing false alarms. Therefore, such an approach should rely on proper thresholds for the definition of cavitation inception.

Few different strategies have been applied in the current work, among which the most promising are those related to the localization of the exciting source and to the demodulation of cyclostationary impulsive components, similarly to the approach presented in [8].

In order to test the selected methods, a dedicated experimental campaign has been carried out on the model propeller considered in current work.

With respect to standard cavitation tests, more sensors have been installed close to the propeller, including hydrophones, membrane pressure transducer and accelerometers. Tests are carried out with a procedure defined to generate proper detection scenarios, and they can be subdivided in three parts:

- Initial steady condition with known absence (or presence) of cavitation.
- Variation of the cavitation number such to trigger the inception (or desinence) of cavitation
- Final steady state condition with known presence (or absence) of cavitation.

During the whole run, consisting of these three parts, signals from different sensors are continuously acquired, together with the tunnel operational parameters. The detection test is carried out applying the detection techniques to these parts and verifying if they provide consistent indications in terms of presence of cavitation.

Some results obtained by noise source localization are shown in [9], while here the attention is focused on the application of noise demodulation (DEMON technique).

Figure 6 shows the results of the analysis applied to the signal acquired by one accelerometer for three cases characterized by growing cavitation extent. The results include plots of the spectral kurtosis for different frequency bands (the level k expresses the band width) and of the amplitude spectra of the complex envelope of signals filtered on the bands identified thanks to the kurtograms.

The values of spectral kurtosis consistently increase with increasing cavitation, in good agreement with the theory according to which this quantity is higher in presence of transient signal components [10][11]. Spectra of complex envelopes allow identifying the repetition frequencies of the filtered signal components. In all cases the blade passage frequency is well identified in the envelope spectrum, but with different amplitude depending on the presence of cavitation.

These examples demonstrate the capability of the methods in detecting the presence of the propeller itself and of cavitation, however it is worth mentioning that the indication provided by the analysis can be ambiguous in some cases, especially when cavitation events are weak and intermittent, making more difficult the correct identification of the repetition frequency.

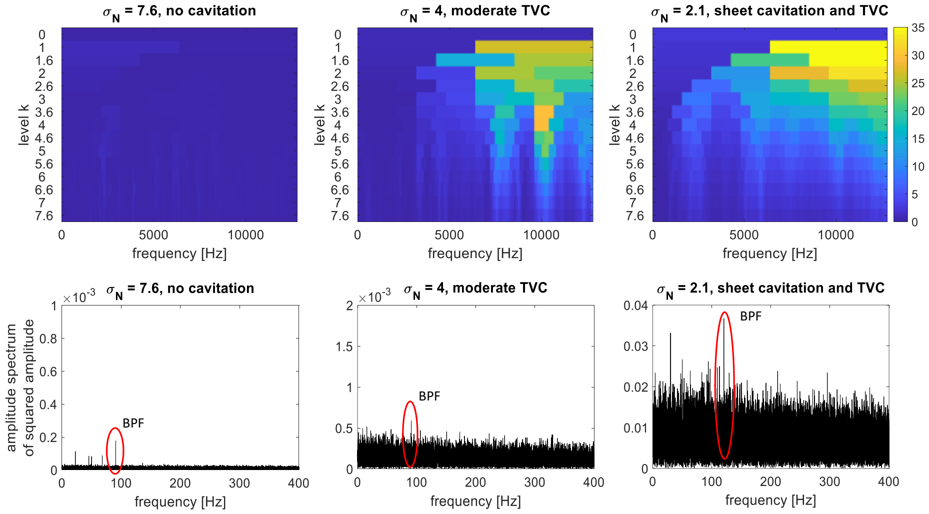


Figure 6: Demon analysis applied to cavitation tunnel vibratory measurements.

2.2. Far field noise estimation

As above mentioned, a possible way to predict the noise emitted by the ship in the far field is to estimate the amount of noise from the vibrations measured by a set of accelerometers. The technique used is the Transfer Path Analysis (TPA) which includes a class of methods to investigate and describe the propagation of sound and vibrations through complex structures and the radiation of noise, in this case outside the ship in water. A complete review of the technique can be found in [12]. The basis of the method is to describe the transfer of sound from several sound sources to the receiver via the relevant transfer paths, which is described by the relevant transfer functions. The classical TPA approach foresees a number of tests in order to determine all the relevant transfer paths by single experiments. As the number of sources and the complexity of the transmissions paths in ships make this approach not applicable, the Operational Transfer Path Analysis is used for the purpose (see e.g. [13]). The main advantage of such approach is that measurements of real operative conditions can be used to determine the transfer functions.

Making the hypothesis of measuring in synchronous the vibrations at a number of accelerometer (12 in this case) and the underwater radiated noise at a number of hydrophones (3 in this case) for a number n of different run characterized by different operative conditions, the problem can be mathematically describe by the following equation, where the matrix Y represents the acoustic pressure measured at three hydrohpones (h1, h2, h3) for n runs (r1,r2,… rn): the matrix X represents the accelerations measured for each run at 12 accelerometers (a1,a2,.. a12) and the matrix H represents the set of transfer functions linking the input (vibrations) to the output (noise).

$$\begin{bmatrix} y_{r1h1}(f_1) & y_{r1h2}(f_1) & y_{r1h3}(f_1) \\ y_{r2h1}(f_1) & y_{r2h2}(f_1) & y_{r2h3}(f_1) \\ \vdots & \vdots & \vdots \\ y_{rnh1}(f_1) & y_{rnh2}(f_1) & y_{rnh3}(f_1) \end{bmatrix} = \begin{bmatrix} x_{r1a1}(f_1) & x_{r1a2} & x_{r1a3} & \cdots & x_{r1a12} \\ x_{r2a1} & x_{r2a2} & x_{r2a3} & \ddots & x_{r2a12} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{rna1} & x_{rna2} & x_{rna3} & \cdots & x_{rna12} \end{bmatrix} \begin{bmatrix} H_{a1h1}(f_1) & H_{a1h2} & H_{a1h3} \\ H_{a2h1} & H_{a2h2} & H_{a2h3} \\ H_{a3h1} & H_{a3h2} & H_{a3h3} \\ \vdots & \vdots & \vdots \\ H_{a12h1} & H_{a12h2} & H_{a12h3} \end{bmatrix}$$

The above system is for one frequency and therefore there should be one system per frequency. The unknowns of the problem are represented by the matrix H that can be found by inverting the matrix X. Usually the matrix X is not squared and therefore it cannot be directly inverted and an approximated method must be applied. Once the matrix H is determined it is possible to predict the radiated noise by simply using realtime data coming from accelerometers placed onboard. The difficulties of applying such technique are represented by both the need of catching all (or most) of the sources and relative transmission paths and to do so for a sufficient number of operative conditions.

The present test case considers 12 accelerometers placed in the following locations: 3 on the stern count; 4 in the engine room and 5 distributed from midship to bow. In Figure 7 an example of a prediction by OTPA technique is given. As it can be seen the technique is promising, taking also into account that the measurements used for the prediction were not designed for this specific aim.

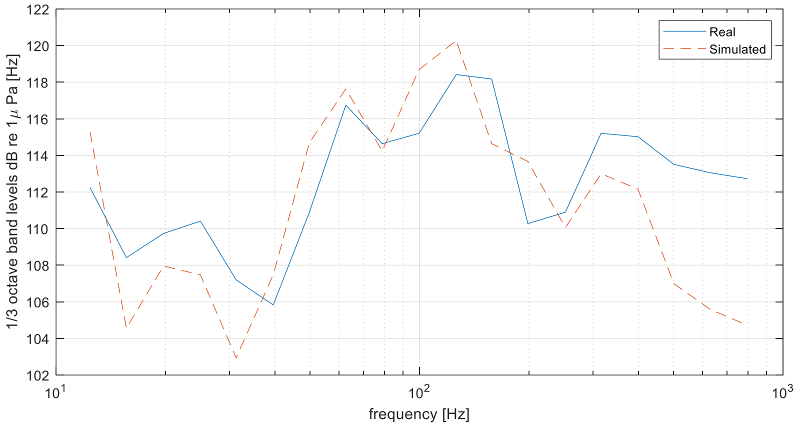


Figure 7: Prediction of 1/3 octave levels URN by OTPA

3. Conclusions

In the present paper, UNIGE activities in the context of LIFE-PIAQUO project have been briefly summarized, giving an overview of their current status at project mid-term.

For what regards propeller optimization, a complete design loop has been carried out, allowing to obtain different propeller geometries, among which an optimal solution has been selected, with the aim of obtaining a significant reduction in URN with a limited reduction of ship speed. The new has already been manufactured and sea trials will be carried out with both original and optimized propellers in order to validate the whole process.

For what regards URN self estimation, two approaches have been described, both for cavitation detection and for far field noise estimation. In both cases, the results are promising, even if further activities are needed to investigate their validity. In particular, for cavitation detection more cases will be considered, including also other ship types with less intermittent cavitation, in order to assess merits and shortcomings, while for far field prediction the method will be applied to dedicated sets of data, when they will become available from sea trials specifically carried out in the project.

4. Acknowledgment

This work was developed in the frame of the project LIFE-PIAQUO (Practical Implementation of AQUO), funded by the European Commission (grant agreement LIFE18 ENV/FR/000308). The Authors wish to express their gratitude to Dr. Federica Valdenazzi (CETENA) for carrying out the calculations with ETV.

References

[1] IMO, 2009. Noise from Commercial Shipping and its Adverse Impacts on Marine Life MEPC 59/19 - 9 April 2009

[2] André, M., Gaggero, T. and Rizzuto, E. 2011. Underwater noise emissions: Another challenge for ship design, Advances in Marine Structures - Proceedings of the 3rd International Conference on Marine Structures, MARSTRUCT 2011, pp. 581-591.

[3] Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A.C., Halpern, B.S., Harding, H.R., Havlik, M.N., Meekan, M., Merchant, N.D., Miksis-Olds, J.L., Parsons, M., Predragovic, M., Radford, A.N., Radford, C.A., Simpson, S.D., Slabbekoorn, H., Staaterman, E., Van Opzeeland, I.C., Winderen, J., Zhang, X. and Juanes, F., 2021. The soundscape of the Anthropocene ocean, Science, Vol. 371, no. 6529, art. eaba4658.

[4] IMO, 2014. Guidelines For The Reduction Of Underwater Noise From Commercial Shipping To Address Adverse Impacts On Marine Life, MEPC.1/Circ.833, 7 April 2014

[5] Gaggero, S., Tani, G., Villa, D., Viviani, M., Ausonio, P., Travi, P., Bizzari, G. and Serra, F., “Efficient and multi-objective cavitating propeller optimization: an application to a high-speed craft”, Applied Ocean Research, Vol. 64, March 2017, pp. 31-57.

[6] Bosschers, J., “A Semi-Empirical Method to Predict Broadband Hull Pressure Fluctuations and Underwater Radiated Noise by Cavitating Tip Vortices”, Fifth International Symposium on Marine Propulsors, smp’17, Espoo, Finland, June 2017.

[7] ITTC Specialist Committee on Hydrodynamic Noise, (2017) “Model-scale propeller cavitation noise measurements.” In: Recommended Procedures and Guidelines 7.5-02-01-05 International Towing Tank Conference.

[8] Lee, J.H., Seo, J.S., “Application of spectral kurtosis to the detection of tip vortex Cavitation noise in marine propeller”, Mechanical Systems and Signal Processing, Volume 40, Issue 1, 2013, Pages 222-236, ISSN 0888-3270, https://doi.org/10.1016/j.ymssp.2013.04.002.

[9] Tani, G., Silvestri, P., Pais, T., Gaggero, T., Viviani, M., “Cavitation detection for a marine propeller based on vibration measurement analysis”, NAV 2022.

[10] Antoni, J., “The spectral kurtosis: a useful tool for characterizing non stationary signals”, Mech. Syst. Signal Process. 20(2006)282–307.

[11] Antoni, J., “Fast computation of the kurtogram for the detection of transient faults”, Mech. Syst. Signal Process. 21(2006)108–124.

[12] van der Seijs, MV., de Klerk, D., & Rixen, DJ. (2016). General framework for transfer path analysis: History, theory and classification of techniques. Mechanical Systems and Signal Processing, 68-69, 217-244. https://doi.org/10.1016/j.ymssp.2015.08.004

[13] Zerbs, C. (2016, August). Monitoring of underwater radiated sound for ships using transfer path analysis model. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* (Vol. 253, No. 3, pp. 5633-5639). Institute of Noise Control Engineering.