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European project "SILENV" – main results and CEHIPAR contribution

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***Abstract* — A 3-years collaborative project under the EC 7th Framework Programme has been closed in October 2012[1] . The main objectives were to elaborate a proposal for noise & vibrations (N&V) limiting target levels for marine vessels and guidelines and solutions to reach these requirements. A brief outlook of the content of the work developed by the partners is given, followed by a description of selected CEHIPAR contributions to the project. The emphasis is on fishing ships N&V combining the efficiency issue. The main achievements of the Consortium, as well as the topics for future work, are also presented.**

Keywords – propulsion, propellers, noise, vibrations, pressure fluctuations, CFD, CLT propellesr, model tests, RANSE code.

I. INTRODUCTION

After years of warnings and some steps of legislation, noise and vibrations (N&V) joined the fuel efficiency as an important issue to be considered in maritime transportation. Moreover, there are evidences of the interaction between them and not always in the same direction.

N&V emissions of the ships are responsible for both internal and external nuisances to the environment. Three categories can be identified. The noise and vibrations onboard (NVB) affect the crew and the passengers with possible negative effects on their health, safety and comfort. The progressively increasing underwater radiated noise (URN) from shipping disturbs the marine fauna, especially the marine mammals for what more evidences are found. The airborne, or harbour radiated noise (ARN) is also a matter to take into consideration, as more ports authorities impose limits to the acceptable level of noise, tending to restrict the entrance of noisy ships. And all this has close relation with the economic aspects of applying abatement solutions.

[1] The research project SILENV was partially sponsored by the European Commission , Grant 234182 of the Seventh Framework Programme.

The European Commission and the industry are financing projects dedicated to study N&V related to marine transport. The present article tries to summarise briefly some of the achievements of the EU collaborative project FP7 SILENV and specifically the main works carried out in CEHIPAR as a partner of the Consortium developing the project. Detailed information about the topics shortly presented here can be found in a series of publications, for example [1] and [2] and multiple deliverables of the project [3].

II. THE PROJECT

Fifteen organizations, including research centres, universities, classification society, one SME and one ship owner, from eight countries led by DCNS (France) formed the Consortium that covered a wide spectrum of activities required by the holistic approach to issue a "Green Label" – pre-normative realistic target level limits for each of the three categories of N&V nuisance mentioned above. These limits, based on existing norms, had to be justified identifying the most critical sources, gaining knowledge of the human and marine fauna response, assessing innovative solutions together with their economical impact.

After reviewing current requirements and regulations, identifying the N&V impact of shipping and the tools for its assessment, the first work package defined and justified realistic targets of the limitations in NVB, ARN and URN. As a result, preliminary SILENV limits (PRSL) have been elaborated and evaluated during the following tasks of the project.

In the second work package the effort was mostly focused in creating a database with experimental data – from old N&V measurements at sea or performing such experiments, to assess the compliance with PRSL and list the available solutions for N&V abatement. The database finally included 171 ships (151 available and 20 new - during the project) onsite measurements, being sufficiently representative of the civil European fleet. Among them, data has been collected or measured for 12 fishing (FV) and fishing research vessels

(FRV). Full noise signatures have been obtained only for 10 of them. The corresponding working package was led by the Spanish SME TSI. The measurements data has been compared with PRSL to extract conclusions with regard to the compliance of all the available vessels. The causes and the necessary effort to comply with PSRL were also studied. It was found that most of the ships (60%) accomplish with ARN limits, a third part (32%) with vibrations on board, meanwhile 11% - with URN limits. Only one ship was in full compliance with the proposed limit for noise on board.

Special attention was dedicated to the situation in the European Fishing Fleet consisting of around 87.000 vessels with 23 years median age of the ships (data from year in 2008). A comparative study based on on-site measurements of the N&V behaviour of two FV – one old (built 1984) and the other a modern one (built 2004) revealed the progress and the necessity for further efforts. Namely, the new ship's spaces complied 35% with the norms for noise on board, being this parameter 11% for the old ship. The vibration measurements showed full compliance (at all measured points) for the new ship and 85% for the old one. Surprisingly the new ship performed worse for ARN, or noise radiated to the harbour, due to the noise emitted by the auxiliary engine exhaust. For URN the spectral analysis of the measurements revealed that both ships at 11 knots do not comply in all frequency range 10Hz-1kHz with the ICES Nº 209 Regulation limits adopted in PRSL for fishing research vessels. The vibration levels for both ships complied with PRSL.

Similar measurements and study were carried out for FRV, already subject to N&V restrictions norm, and for the rest of types of ships covered by the project. Finally, the identification of the N&V sources, assessment of the causes for the deviations and the costs of the application of technological advances permitted to define the improvements to reach the targets.

An entire work-package was dedicated to review the main existing solutions for N&V abatement and to assess the improvements that can be gained applying the advances of propulsion, machinery, exhaust & ventilation and the application of new materials for the hull structure. A model experimental and numerical campaign has been carried out by several partners. In propulsion, positive results have been obtained by numerical optimization of conventional propellers, use of non-conventional propulsion like, CLT end-plate propellers, ducted propellers, podded propulsors, improved bow thrusters and water-jets.

A review of lightweight materials and of the modelling methods for ship vibrations was followed by presenting the state of the art in active and passive control strategies to reduce structure-borne and hydrodynamic N&V. Smart materials structures were also considered.

Reviewing the exhaust and ventilations solutions it has been found that this main ARN lacks specific regulations. There are solutions for active and passive control but they are usually not applied at design stage and then the corrective actions require elevated costs. To avoid this, the limitations, increasingly adopted by ports authorities, should be incorporated in the contractual specifications.

The purpose of the final task of work package 3 was to propose N&V limits based on the state of the art of the solutions and existing regulations. The method used was the solution matrix, permitting to apply a specific strategy to find an adequate solution for any case. The expected results and the work to be done have been defined for the evaluated solutions.

The capability of the numerical models to estimate the effectiveness of the N&V solutions was the main task of the fourth work package. Several ships of different types have been chosen for this exercise. Modern methods were applied by almost all partners. Studies of the human and marine fauna response to N&V were also included in the modelling.

The numerical prediction of the flow generated noise in such complex environment as the navigating ship is still a big challenge. New results have been reported by one of the partners (see [8]). For the time being most of the partners use empirical formulae or indirect approach.

In the case of noise propagation inside the ship the statistical energy analysis method was found accurate enough within 4dB and for the hull vibrations the use of FEM completely satisfactory. In both cases the specification of the sources, especially the propeller, still needs to be refined.

Finally the performance observed from the experiments and calculations was compared with the requirements for propellers, machinery, exhaust and ventilation and hull structure evaluating the most innovative solutions. Several conclusions have been drawn. Among them it is worth mentioning that a case study confirmed the primacy to consider together the natural frequencies of the hull plates with the propeller main excitation frequencies to avoid resonances.

N&V effects on humans and marine mammals were also treated. The human response to N&V was studied through questionnaires on comfort and performance. Appropriate statistical analysis of the data was done. Several recommendations were drawn distinguishing passengers from crew.

The assessment of the ship noise influence on the fauna in nearby area was performed using data of ships URN measurements and simulating cetacean presence. Admitting the insufficiency of data for the response of the marine fauna it was pointed out that because of the substantial differences in noise spectrum between the ships a single limit is not appropriate and categorization of the ships is recommended together with the specification of certain maritime regions of limitations.

The purpose of the last work-package was to summarize the technical conclusions and suggested solutions, to prepare a set of general and specific (for each category) guidelines and to propose a justified limit target levels (the "green label") in the three categories: N&V inside the ship, airborne noise and underwater generated noise. The balance between performance and feasibility had to be observed.

For N&V inside the ship the human response was taken into account together with measurements data from the data base. The criteria for the choice were: 90% passengers and crew satisfaction, at least 25% of the existing vessels to be able to reach the target and taking into account the 2011 IMO regulation. The limits in dB(A) (not presented here) are specified for all basic spaces of the ship. For instance, the noise limit of 50 dB(A) and vibration limit 1 mm/s were established for the passenger and crew cabins, being those limits 90 dB(A) and 2.5 mm/s in the machinery space where protection and limited stay are required.

For ARN the scope of the recommendation was limited to ships at quay (no cargo processing) and sailing along the coast, being the proposed limits at a distance of 25 m. from the ship: 75 dB(A) for the former and 65 dB(A) for the latter.

The lack of sufficient data for the impact of the noise on different marine species forced to set the URN requirements according to the technological limitations, extracted from the results of measurements and existing norms. For FRV the current ICES sound pressure level spectral curve is adopted and for the rest of commercial ships – a common limit, depending only on the speed condition, as shown in Figure 1 below. The transit limit corresponds to 85% MCR speed and the quiet – for 11 knots.

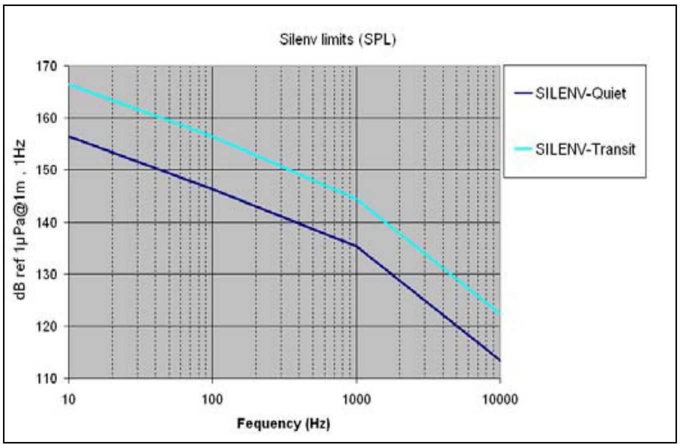

Figure 1. SILENV URN limits for commercial vessels

III. CEHIPAR'S CONTRIBUTION

A. *Solutions*

CEHIPAR has years of experience in the application of solutions to reduce N&V of hydrodynamic origin, maintaining good propulsive efficiency [5].

Three main strategies are used to reach these objectives:

- Optimization of the hull forms to gain efficiency and/or more homogeneous incident flow to the propeller (wake improvement).
- Design of conventional propellers to reduce cavitation with a consequent reduction of its N&V.
- Application of non-conventional propulsors, like ducted, podded or endplate (CLT) propellers.

The first approach has been treated in various publications and was not included in the works of SILENV project (see for example [4]). Innovative podded propeller solution is presented in [10] and ducted propellers applications – in the 2010 e-fishing symposium [6]. Two examples of the second approach and one of the third are described below.

1) Fishing research vessel

A design of the fixed pitch propeller of a 2000 kW FRV has been carried out to satisfy the requirements of the shipyard and using model scale towing tank tests data of the hull and a stock propeller. The design procedure includes the use of series, lifting line and validated lifting surface software for forces and cavitation prediction and the objective – minimize cavitation and pressure fluctuations within acceptable propulsive efficiency at given speed. An indication for the quality of the design was the comparison of the performance with that of the stock propeller after a complete set of tests with a manufactured model of the new propeller. A photo of the designed and fabricated in CEHIPAR (by NC milling machine) model propeller is shown on Figure 2. The propeller was tested then in the facilities of CEHIPAR separately (open water) and in behind (the hull) conditions.

Figure 2. FRV propeller model

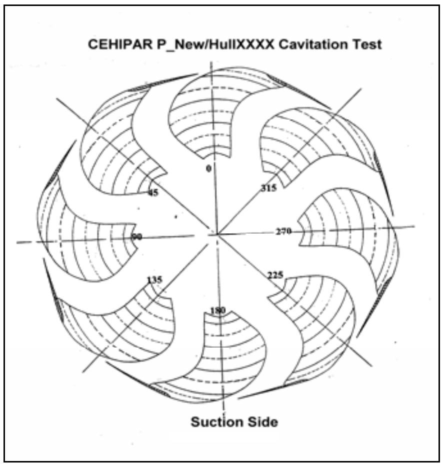

Figure 3. Cavitation diagram from observation of FRV_New propeller.

The diagram of cavitation observation test (Figure 3) in Cavitation Tunnel (CT) behind screens modelling the hull wake shows a lack of sheet or bubble cavitation. Only rarely avoidable stable tip vortex cavitation is present. The pressure side was free of cavitation.

Figures 4 and 5 compare the first harmonic of the maximum pressure pulses on the hull, also measured in CT, and the vibratory shaft forces (calculated) due to both propellers. A substantial reduction of the propeller excitation is observed.

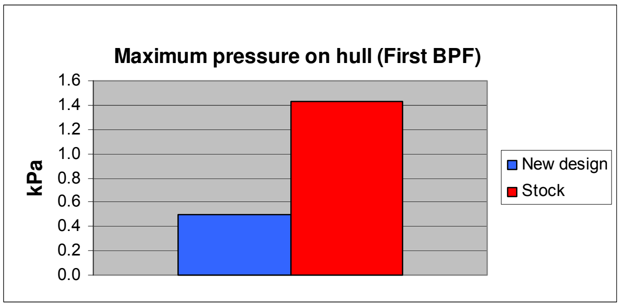

Figure 4. Maximum pressure pulses for the propellers of FRV

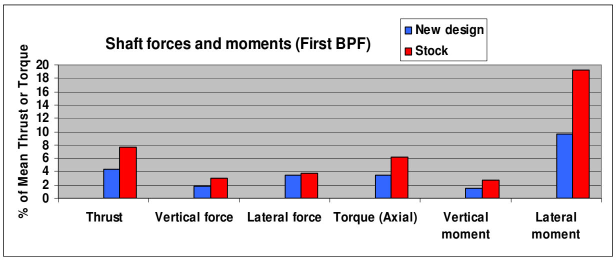

Figure 5. Calculated vibratory shaft forces for FRV.

Finally, the extrapolated for the full scale ship results of the self-propulsion tests carried out in Towing Tank show only small loss of the overall propulsive efficiency (Figure 6).

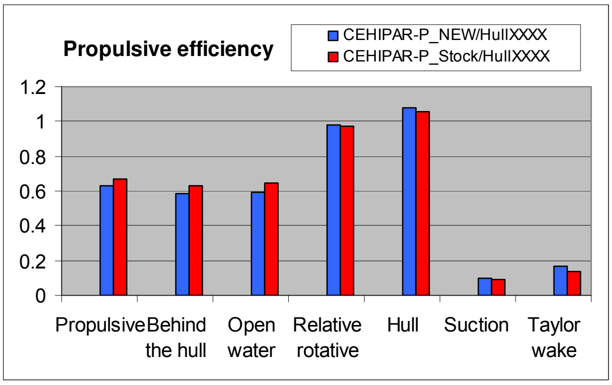

Figure 6. Components of the propulsive efficiency of FRV ship

2) *Fishing vessel*

This exercise consisted in designing an alternative low N&V propeller for a 5000 kW FV. Measurements and calculations for the stock propeller well adapted to the power-speed characteristics of the ship showed sheet and strong tip vortex cavitation on the suction side of the blades in the range of angles from 0º to 120º (not shown here). The objective was to design new propeller with blades of reduced, as much as possible, cavitation in order to gain in abatement of N&V.

The cavitation observation tests with the designed propeller shown in Figure 7 demonstrated practical elimination of the sheet cavitation on the suction side.

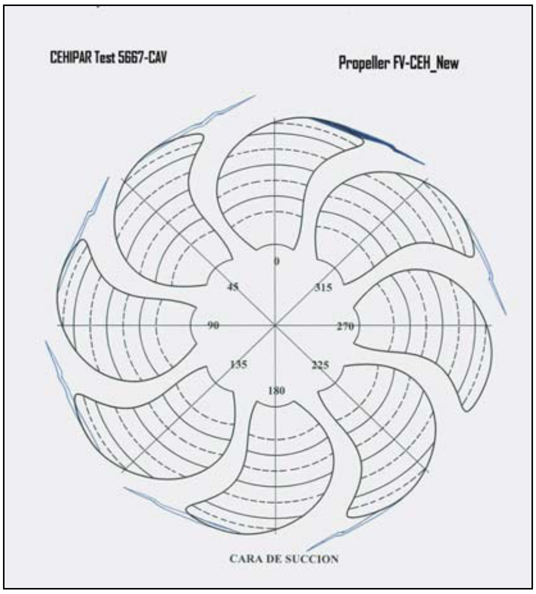

Figure 7. Cavitation diagram of suction side of propeller FV-CEH_new

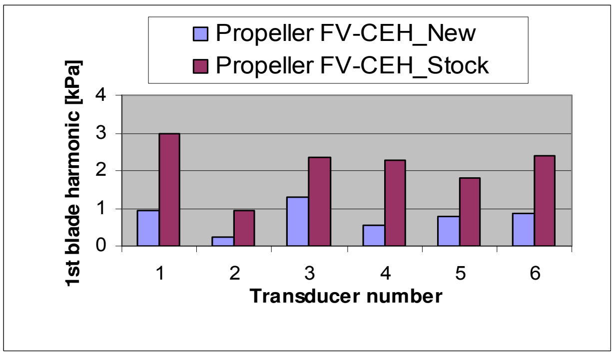

Figure 8. Comparative of pressure pulses on hull (first harmonic).

The pressure pulses consequently were reduced considerably as shown in Figure 8 that compares the new design versus the stock propeller as measured in the CT using 6 transducers on a flat plate above the propeller. All components of the vibratory forces, except the horizontal moment, were also reduced (not shown). In this case, the strong deviation of the blade geometry from the optimum to reduce suction side cavitation resulted in a decrease of the propulsive efficiency about 7%. Additionally, stable sheet cavitation appeared on the pressure side of the blades (Figure 9), which was not detected by calculations in the preliminary design stage. Its presence did not affect much the N&V behaviour of the propeller but should be considered from the erosion point of view. Obviously, the conclusion from this exercise indicates the necessity to control simultaneously all the parameters in the design process.

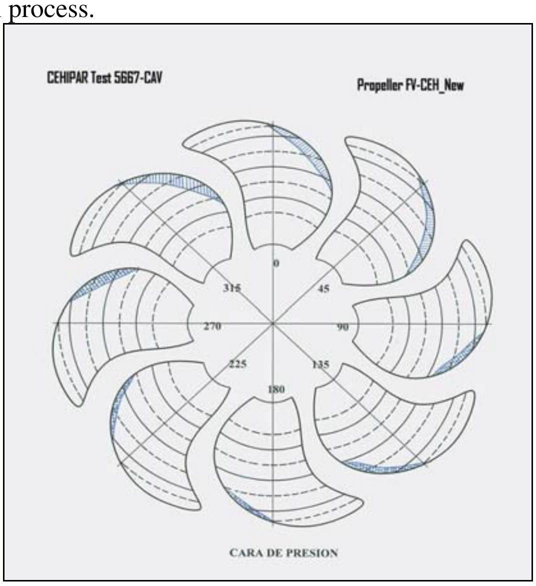

Figure 9. Cavitation diagram of blades pressure side.

3) *ROPAX ship*

A case of using non-conventional propulsor like the CLT end-plate propeller was carried out for a 14500 kW power per shaft twin screw ROPAX ship. Its conventional propellers were substituted, years ago, with controllable pitch CLT's (CLT1) and succeeded to reduce the severe vibrations and noise appearing during manoeuvring of the real ship at constant propeller revolutions and low pitch. The exercise in the present project consisted in designing (by SISTEMAR) and testing (by CEHIPAR) new CLT propeller (CLT2) with the aim to improve the performance of the actual one, especially at low pitch condition when not only higher tonal pressure pulses were observed, but also a considerable hump of broadband excitation (see [9]) solved with CLT1 propellers.

For this kind of propellers, having more pronounced scale effect, CEHIPAR/SISTEMAR apply a specific extrapolation procedure that has been continuously improved and validated with full scale and numerical results.

A photo of the new designed and manufactured CLT propeller model is shown in Figure 10 below.

Figure 10. CLT2 propeller model manufactured in CEHIPAR

The open-water test results of this model were extrapolated to full scale and used for simulating self-propulsion tests, using interaction data from tank tests performed with the conventional propeller. The comparison of the performance of the three propellers in Figure 11 revealed a small gain of efficiency obtained with the new design.

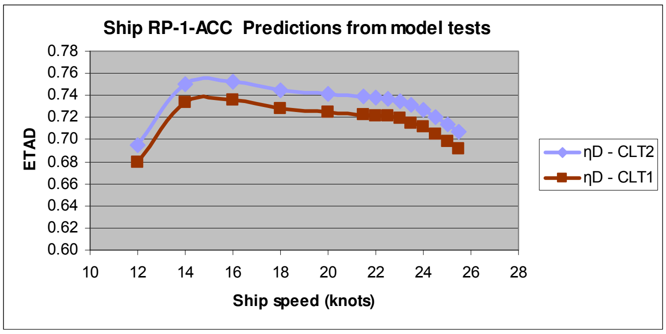

Figure 11. Comparative of propulsive efficiency

Figures 12 and 13 are from observation of the cavitation in the Cavitation Tunnel showing reduction of cavitation on the endplate for the new design at low pitch condition.

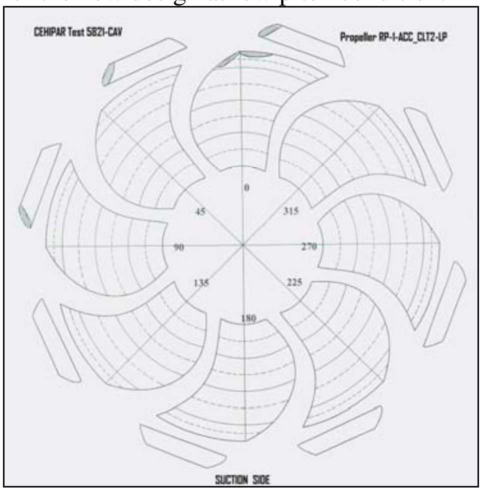

Figure 12. Cavitation diagram of blades suction side for CLT2 at low pitch.

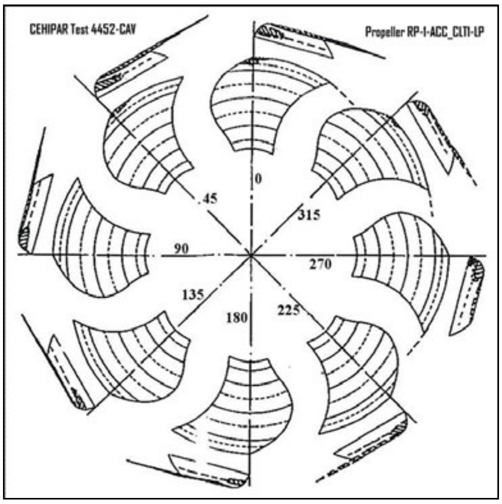

Figure 13. Cavitation diagram of blades suction side for CLT1 at low pitch

The consequence was lower pressure pulses on the hull. Figures 14 & 15 present the measured at 11 points and scaled for the ship first three pressure harmonics of the blade passing frequency (BPF) for CLT2 and CLT1. The new design still avoides the broadband hump in its spectrum at higher frequencies (Figure 16 – model scale values).

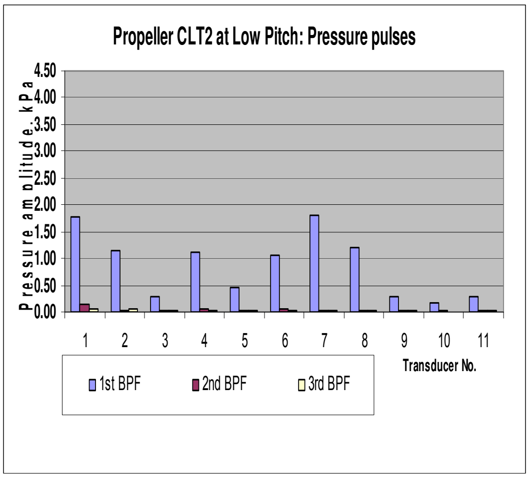

Figure 14. Pressure pulses on hull (3 harmonics)-Propeller CLT2_LP.

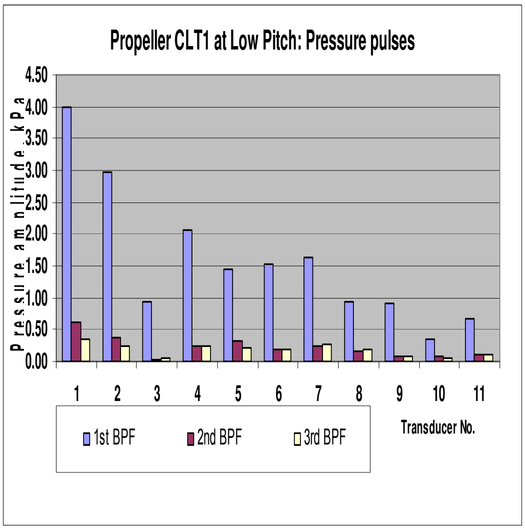

Figure 15. Pressure pulses on hull (3 harmonics)-Propeller CLT1_LP.

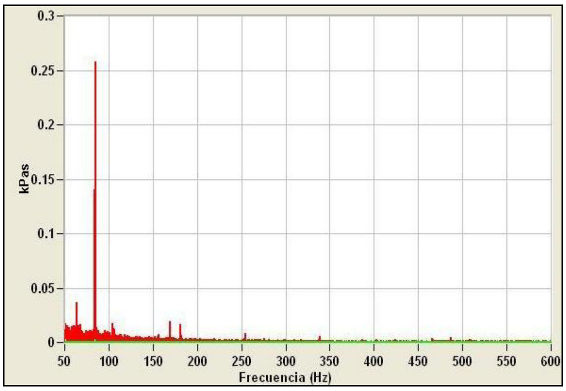

Figure 16. Model scale pressure spectrum of the 1st transducer of CLT2_LP

From the presented results it can be concluded that the new CLT design (CLT2) is superior to the previous one (CLT1) in cavitation, pressure pulses, succeeding even a little higher efficiency at wide range of speeds. Nevertheless, at design pitch, this propeller (CLT2) develops cavitation similar to CLT1 (not shown), so further improvement in cavitation should be looked for in the future.

B. *Modelisation and assessment*

CEHIPAR also contributed to the fourth work package dedicated to modelling and assessment.

Apart from the use of numerical models during the propeller design, RANSE type computations have been implemented for ducted and end-plate propellers. Details of the approach used are published in [7]. Notably, a contribution has been achieved in the complex problem of numerically evaluating the scale effect for CLT propellers.

CEHIPAR's was assigned the prediction of the periodical forces on the hull generated by the propellers for three ships, namely FRV-5-TSI of recent design, an old FRV-OLD and a 3000 kW, 123 m. length merchant ship M-1-TUV. The prediction has been obtained by integrating the pressures from numerical simulation of the flow. Only for the first case the existence of model experimental data for the pressures permitted to adjust the prediction to the experiment, keeping the numerical distribution over the stern, as it was obtained by computations with the full CAD geometry of the hull instead of flat plate.

Vibration excitation forces on the hull due the propeller are calculated integrating the pressure pulses (Fig.17) and taking also into account the shaft forces. The integrated pressure forces as amplitudes and phases (not shown) are presented in Tables 1 and the shaft forces: in Table 2.

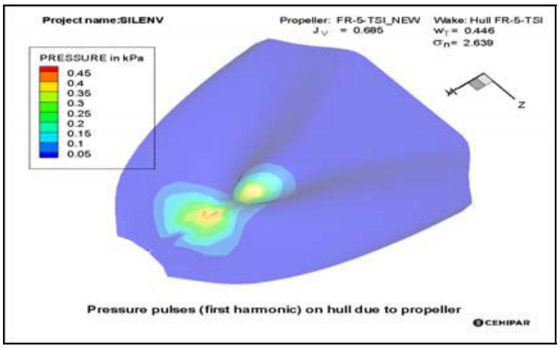

Figure 17. Calculated pressure contours due to propeller FRV-5-TSI_New.

TABLE 1: AMPLITUDES OF INTEGRATED PRESSURE FORCES

Pressure forces on hull	*1st BPF*	*2nd BPF*	*3rd BPF*
Axial force, kN	0.423	0.094	0.022
Horizontal force, kN	0.791	0.173	0.041
Vertical force, kN	2.03	0.280	0.064

TABLE 2: AMPLITUDES OF VIBRATORY SHAFT FORCES

Vibratory forces on shaft	1st BPF	2nd BPF	3rd BPF
Thrust, kN	10.84	5.33	5.06
Horizontal force, kN	1.96	0.55	1.30
Vertical force, kN	3.34	2.32	1.29
Torque, kN.m	3.94	2.18	2.08
Horizontal moment, kN.m	4.52	0.83	2.31
Vertical moment, kN.m	4.32	4.20	2.30

The force data was used by the corresponding partners to perform structural predictions, mostly using FEM and SEA and to obtain the vibration of the hull plates of the ship, especially at the stern. The numerical results show generally acceptable correlation with on-site measurements. There was a warning about possible underestimating of the predicted excitation forces in comparison with empirical formulae for one of the cases but no conclusive statement was issued because of the limitations of the study.

A case study of the correlation between structural and hydrodynamic results is published in [11].

IV. CONCLUSIONS

A holistic approach was applied to the complex problem of N&V generated by the marine vessels. The application of several state of the art solutions and its assessment permitted to formulate guidelines for the shipbuilding industry and the legislators. Many fields are still open for advancements, especially there is a lack of knowledge of the ships footprint, the prediction of propeller noise, the reaction of marine fauna, but it is clear that the existing solutions are able to assure sufficiently low N&V pollution without excessive costs if applied in the early stage of the ship design.

A summary of the project results is presented also in [1].

One of the conclusions of the project is that a full signature of the ship and the propeller are necessary in order to have a complete data for optimization. In this sense CEHIPAR is developing experimental procedures to measure the underwater radiated noise from propellers. First applications of this advancement will be incorporated in the actually going on European project AQUO.

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