Fifth International Symposium on Marine Propulsors
smp'17, Espoo, Finland, June 2017

Hydrodynamic design and model testing techniques for composite ship propellers

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ABSTRACT

For the designers of ship propellers, the use of composite materials instead of traditional bronze and stainless steel still has many unknowns. Potentially, by using composites, designers can meet the traditionally opposing objectives of maximising propulsive efficiency and minimising cavitation nuisance. However, the full potential of their application can only be appreciated when knowledge on the desired and practically achievable behaviour of these propellers is available. Designing and testing small-scale flexible propellers in laboratory conditions can be a first step to gain this knowledge, requiring accurate computational and experimental tools.

In this paper, the new hydrodynamic design opportunities are discussed that result from the low weight and possible flexibility of composite propellers. As an example, the case of a propeller for a research vessel is shown. Desired deformations of the propeller geometry are considered and their influences computed and discussed.

In the second part of the paper, the application of the digital image correlation (DIC) technique to measure flexible propellers operating in the wake field of a ship model is presented. This state of the art measurement technique can be used to validate the results of hydro-elastic calculation tools necessary in the design and analysis of flexible composite propellers.

Keywords

Flexible propellers, hydrodynamic design, model testing techniques.

1 INTRODUCTION

Advanced materials such as fibre reinforced composites and fibre metal laminates have become very common in the automotive and aerospace industries. Their low weight, superior fatigue properties and possible geometric flexibility are important drivers of the performance improvements seen there. For this reason it is obvious that these materials are also considered by the shipping industry.

Currently, composite ship propellers are mainly seen on smaller recreational craft and yachts. Larger ship applications are still rare, with some well-publicised examples such as the demonstrator propeller for the Triton Trimaran by QinetiQ in the UK, and other naval applications such as the German submarine propellers by HDW and the controllable pitch propeller blades of a Royal Netherlands Navy mine hunter by the Dutch company Airborne. In fact the introduction of composites to turbine rotor blades appears to be much more rapid in the tidal energy industry, see Davies (2013). However, interesting developments have recently been reported from Japan, where Nakashima propellers and classification society ClassNK developed a flexible composite main propeller replacement for the chemical tanker "Taiko-Maru". Significant power reductions as well as reductions of inboard noise and vibrations are claimed. Future developments have been announced for a ferry and a 60K DWT bulk carrier. Is this the beginning of acceptance of composites for larger size marine propellers?

At first glance, the advantages of composites for propeller blades are not so obvious. Fuel savings, increased comfort and increased handling performance are claimed, but often these claims are not very well substantiated nor are their hydrodynamic backgrounds explained. The definition of the success of an improvement in propeller design is not easy, see Huisman (2017), even for ordinary bronze propellers, in particular when combined with special energy saving devices, see Schuiling (2017). A lot of freedom exists in shaping a propeller blade and numerous parameters describe the qualities of a propeller design such as its engine adaptation, efficiency, cavitation related vibration excitation, underwater and inboard noise, acceleration and stopping capabilities and absence of cavitation erosion damage. Finding a compromise between these conflicting objectives is the main challenge in the design of conventional rigid propellers. The claim is that by using flexible composite propellers, designers can decouple these objectives and pursue maximum propulsive efficiency while simultaneously minimising cavitation nuisance.

The use of composite materials instead of traditional bronze and stainless steel still has many unknowns for the designers of ship propellers. Literature is scarce on how to design flexible propellers and most published research is focused at developing and validating methods to predict the complex hydro-elastic behaviour of flexible research propellers. It is assumed that the full potential of composite propellers can only be appreciated when knowledge on the desired and practically achievable behaviour of these propellers is available. Therefore, in the first part of this paper, we focus at the opportunities offered by composites in the hydrodynamic design of propellers. Designing flexible propellers requires design knowledge, validated tools and experience that can be gathered by testing model scale propellers in laboratory conditions. Therefore, in the second part of this paper the results of a pilot study are presented in which the digital image correlation (DIC) technique is applied to measure the small deformations of a flexible propeller in the wake field of a ship model.

2 NEW DESIGN OPPORTUNITIES

An everyday challenge for the designers of ship propellers is to design the geometry of propeller blades that have the highest possible efficiency with cavitation characteristics that are just good enough to avoid noise and vibration problems. In the following sections some new hydrodynamic design opportunities are discussed that result from the low weight and possible flexibility of composite propellers.

2.1 Diameter and Tip-hull Clearance

The diameter of a propeller and the clearance of the propeller tip with the hull plating are important parameters deciding on the energy losses incurred by an operating propeller, and thus on the consumption of fuel. In general it is advantageous to select a propeller (rigid or flexible) with the largest diameter and the slowest rotation rate possible. This preference follows from an assessment of the energy losses occurring by the propeller action, see Van Terwisga (2013). In the propeller design process a selection of the diameter, blade area, pitch and rotational speed is made so that the total of these energy losses are minimised.

In Figure 1 taken from Van Terwisga (2013) an overview is shown of the ratio of these different energy losses as function of the thrust loading coefficient C_T with some typical levels for some ship types. The diameter, which determines the area of the propeller and thereby its thrust loading coefficient C_T, has a major impact on the maximum achievable efficiency (ideal efficiency) of a propeller. Axial kinetic energy losses diminish when the thrust loading decreases. Thus selecting the diameter and area of the propeller as large as possible is an effective way to increase the propeller efficiency.

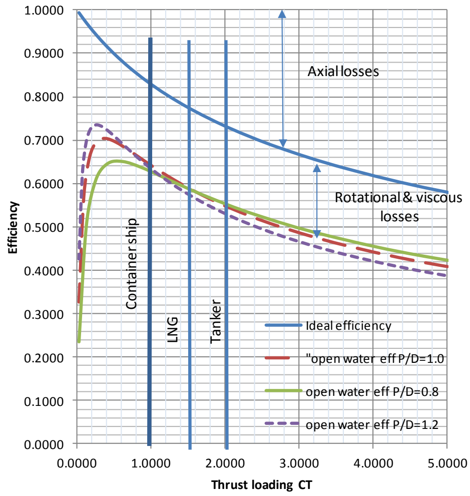

Figure 1: Propeller energy loss components and their relation with the propeller thrust loading coefficient.

In some cases, however, there are limits put to the maximum size of propellers, to prevent possible hull vibration problems or excessive inboard noise due to cavitation. In those cases opportunities lay here for the application of composite propellers.

It is discussed in many publications (Chen et al. (2006), Liu (2007)) that a coupling of the bending and twisting deformation modes can be achieved by proper orientation and stacking of the laminates in composite propeller blades. This property can be exploited to design propeller blades that reduce their blade pitch when passing the wake peak of the hull and thereby reduce the extent and dynamics of the cavitation when the blades are close to the hull. This design feature can have a substantial influence on the diameter selection and thus have prospects for a higher ideal efficiency. Therefore, flexible composite propellers potentially allow energy savings by increasing the diameter relative to these (restricted diameter) propellers.

Another consequence of reducing the propeller tip clearance without sacrificing comfort is an increased freedom in designing the hull lines. For merchant ships additional displacement can be added to the ship hull, which can have economical benefits. For mega-yachts more internal room can be made available, for instance for tender garages.

2.2 Tip Unloading

The radial blade loading distribution is an important characteristic of a propeller design. This distribution derives from the selected radial variations of the pitch, camber and chord length of the blade sections. Classical theories such as that of Van Manen and Van Lammeren (1955), describe criteria for optimum radial circulation distributions to minimise induced resistance. Usually the circumferentially averaged, radially varying inflow field is considered, leading to an ‘averaged’ optimal loading distribution.

The radial loading distribution, and in particular its variation in the tip region is very important for the design of low noise propellers, see Stanier (1995). The local gradient of the circulation distribution along the propeller blade determines the strength of the local vorticity that is shed in the downstream blade wake. Reduction of the circulation gradient by changing the local pitch, camber and chord distributions is used to reduce the strength of the tip vortex and associated cavitation noise and hull pressure fluctuations. However, the application of tip unloading has a significant efficiency penalty of up to 5 per cent, for fully unloaded, metallic propellers designed for vessels with radiated noise or comfort requirements.

When incorporating the mentioned structural pitch unloading response in composite propeller blades, a number of useful features emerge that can be exploited in the propeller design:

- The cavitation margins for both pressure side and suction side cavitation increase when the cavitation. The increased margins result from a reduction of the angle of attack and can be exploited to further reduce (suction side) cavitation, or they can be used to increase the efficiency of the propeller by reducing the length of the sectional chords and thus the blade area.
- The reduced angle of attack variations will result in an increase of the profile section efficiency. The flow towards the profile sections can be designed closer to their ideal angle of attack.
- Besides a reduction of the pitch of the propeller blade tip, for low noise propellers the reduction of the circulation gradient is also achieved by increasing the length of the tip chord. This effective design choice might not be needed for flexible propellers with appropriate tip deformation.
- The composite propeller blades can also be conveniently designed to have their near optimum radial loading distribution at low loading conditions. This is particularly advantageous for ships that consume most fuel in part load conditions.

The combined effect of potentially increased diameter, reduced blade area and more favourable variation of the radial loading distribution is expected to have an efficiency improvement that is better than only the influence of the tip loading alone.

2.3. Propeller Blade Thickness and Weight

Also the low weight and superior fatigue properties of composites bring new opportunities in the propeller design. The blades of conventional Ni-AL bronze propellers are usually designed as thin as possible to keep material costs low. Propeller weight is an important parameter for propeller manufacturers when competing with others for orders. Therefore the earlier discussed compromise between efficiency and cavitation characteristics is also influenced by the factor ‘weight’.

For composite propellers weight savings between 50 to 75 per cent are reported compared to their bronze equivalents. Use can be made of this weight saving to reduce the weight and cost of the propeller drive train.

In Hadler (1982) the results of a study are reported on the application of hollow bronze blades and hubs to construct very large diameter, low RPM propellers. Also fibre reinforced composite material was already considered in this study. Taking advantage of the superior fatigue characteristics of composites, the thickness of the propeller blades can be reduced to increase efficiency. An example could be the blade root area of controllable pitch propeller blades, which are usually quite sturdy and sensitive for developing cavitation.

Composite propeller blades can potentially also be made much thicker without the propeller weight becoming excessive. In particular for vessels with challenging requirements for low vibrations and underwater noise signature, the cavitation free operational range of propellers can be extended by increasing the thickness of the blade sections, in particular at the leading edge and tip. As an illustration in Figure 2 it is shown how the cavitation free range (bucket) increases of a blade section with increasing thickness ratio t/c. If the rotation rate of the propeller is chosen sufficiently low to prevent mid-chord bubble cavitation, an increase of the blade thickness can thus be used to widen the cavitation bucket of the b

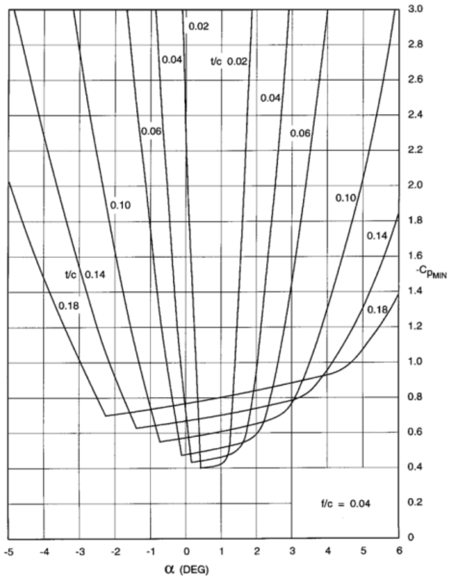

Figure 2: Cavitation bucket ($-C_{pmin}$ vs. angle of attack α) versus maximum profile thickness ratio t/c for a 2D blade section family.

2.4 In Service Propeller Blade Loads

In addition to the shaft rate variations of the angle of attack in calm water related to the viscous wake of the appended hull, additional variations occur in operational service conditions. These are related to:

- A mean change in propeller loading due to the added resistance in wind and waves.
- A steady drift angle of the hull induced by the mean wind and wave drift forces.

- Dynamic low-frequency variations in the inflow due to course keeping and steering, induced by wind gusting and wave grouping in an irregular wave train.
- Wave-encounter-frequency variations in the inflow induced by the incident waves and the ship response, also due to vortex shedding from upstream elements like bilge keels.
- High, short-duration impulsive loads due to ventilation in the cases when the propeller approaches the surface too closely.
- The loads during transient manoeuvres (like a crash stop).

The accelerations of the hull at the location of the propeller, including slamming induced vibrations, are an additional source of propeller blade loading.

In the contemporary structural design of propellers the above "service" factors are "covered" by a large safety factor on the computed forces in a steady flow. It seems obvious that the practical application of flexible propellers requires a more "first-principles" verification of the performance and structural design (ultimate loads, fatigue) in service conditions.

2.5 Engine Matching, Safety and EEDI

The matching of the propeller power absorption with the characteristics of the drive train is an essential topic in the design of ship propellers. Rigid metallic propellers, driven by diesel engines are designed with so-called light running margins, see Figure 3. This means that the propeller is not designed to absorb the available specified maximum continuous rated power (SMCR) at the nominal shaft speed (indicated by the red engine layout curve), but at a slightly higher rotational speed allowed by the overspeed margin of the diesel engine (green light running curve). Notice that for rigid propellers this 'propeller law' curve is a third power of the rotation rate ($c{\cdot}N^3$).

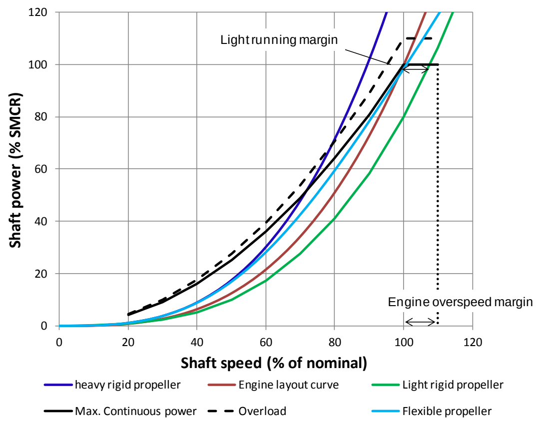

Figure 3: Schematic diesel engine diagram with illustration of light running for rigid and flexible propellers.

In operational conditions with the ship experiencing an added resistance, the power demand of the propeller increases and the propeller is said to run more heavily (dark blue curve). In cases when the light running margin has not been adequately designed, the heavy running curve of a rigid propeller can prematurely exceed the limits of the engine. In that case the very unsafe situation of an engine stall can occur.

With the future tightening of the Energy Efficiency Design Index (EEDI) regulations, worries are that the new generation of ships will have insufficient power installed to safely operate in adverse weather conditions. Therefore, propulsion system manufacturers are advocating the increase of light running margins, see Bryndym (2015). For rigid propellers this approach can also solve issues with slow acceleration and long times to pass potential barred speed ranges (resonance areas).

Due to its pitch deflection, flexible composite propellers will not follow an N^3 curve but will gradually start to deviate from it with increasing power (and thrust). The light running margin of a flexible propeller is therefore not constant but depending on the level of overloading of the propeller. The heavy running curve (light blue) in Figure 3 illustrates this behaviour for a flexible propeller. During sailing in heavy weather, or certainly in cases when the ship is towing at low ship speeds (near bollard pull), the light running effect is significantly higher than in high speed trial conditions. Although this advantage is quite clear, knowledge and information is lacking on how big these advantages on fuel consumption, manoeuvring capabilities and safety really are. It is therefore suggested that composite propellers be further investigated in view of EEDI and its demand for lean propulsion.

3 EXAMPLE

Here the case is presented of the propeller design for research vessels that are typically designed with low underwater noise requirements such as the DNV Silent-A/S/F/R/E rules. These rules specify limits to underwater noise in dedicated frequency ranges, specified speed profiles and sea states. These requirements are usually fulfilled by designing the propeller blade for the absence of sheet and vortex type cavitation. Low noise design techniques for conventional metallic propellers for these kinds of vessels involve some distinctive design features focused at delaying the cavitation inception, see Zondervan (2016).

In particular for research vessels it is of interest to extend the cavitation free range to specified Sea State (4) conditions, or conditions in which the ship is towing survey systems. Usually the focus here is the delay of inception of tip vortex cavitation. To see the opportunities of a flexible composite propeller it is investigated how the blade loading is varying. In Figure 4, the variation of the blade force during one revolution is shown for a typical fixed pitch propeller operating in the pronounced wake of a single screw hull. The forces have been computed using MARIN's BEM code PROCAL, see Bosschers et al. (2017).

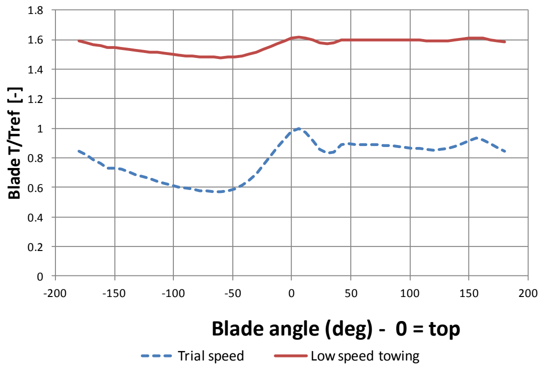

Figure 4: Thrust variation for a research vessel (max speed and towing).

As shown in Figure 4, for conditions in which the ship is sailing at trial speed, the blade force reacts to the variations of the axial and tangential velocities in the wake field. Peaks in the blade thrust are seen when the blade passes the axial wake peak in the 12 o'clock position. At other blade angles the thrust variation is driven by the tangential velocity component, moving with and against the rotation of the blade. The red curve indicates a condition when the propeller absorbs the same maximum engine power at a low speed. In this case, the mean blade force is almost double the value at the trial speed, but circumferential variations are much smaller because the inflow angle of the propeller blades is dominated by the rotational speed of the propeller blade. Given this rather small variation a first order estimate based on uniform flow calculations is made.

For a composite propeller design with flexible blades, several possible pitch deformation distributions can be considered for the low speed towing condition. Starting from an assumed rigid propeller design three pitch distributions are shown in Figure 5. Distribution 2 and 3 are linearly scaled deformation distributions taken from published measurements such as Chen et al. (2006). Distribution 1 assumes a hybrid solution with a rigid inner part and a more flexible tip area.

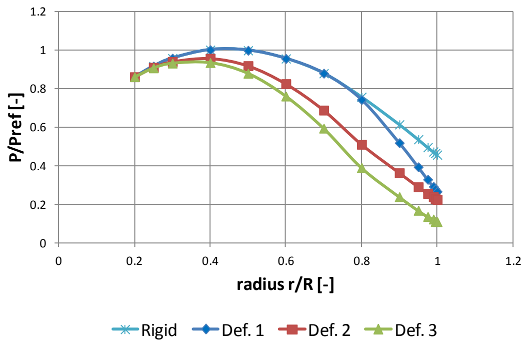

Figure 5: Radial pitch deformation variants.

Using the ETV tip vortex cavitation model implemented in PROCAL (see Bosschers (2017) an estimate has been made of the influence of the different (rigid) deformation distributions on the tip vortex inception (TVI) characteristics. In Figure 6 a computed cavitation inception diagram is shown with tip vortex cavitation inception bucket computed for the rigid propeller and the inception points computed for the composite propeller variants, all for equal absorbed power. Also shown are the operational curves for the rigid propeller and the working points for the trial and towing conditions. The result of the pitch deformations is that the loading of the propeller blades will shift radially inward and the gradients of the circulation distribution at the blade tip will decrease. The pitch reduction will result in a light running of the propeller and therefore the flexible composite propeller will run at a much higher rotation rate. The thrust coefficient K_T and the cavitation number σ_n, see equation 1, contains the rotational speed to the 2[nd] power in the denominator.

$$\sigma_n = \frac{p_0 - p_v - \rho g h}{\frac{1}{2}\rho n^2 D^2} \qquad (1)$$

All TCI points for the different propeller variants are inception points in Figure 6, lying on different inception curves. Also shown are the operating points for the pulling condition, indicated by the hollow markers. From the graph it can be concluded that only for the distribution 3 deformation, the operating point lies inside the (green) tip vortex cavitation bucket. This simple example illustrates how improvements in cavitation free operating range can be achieved.

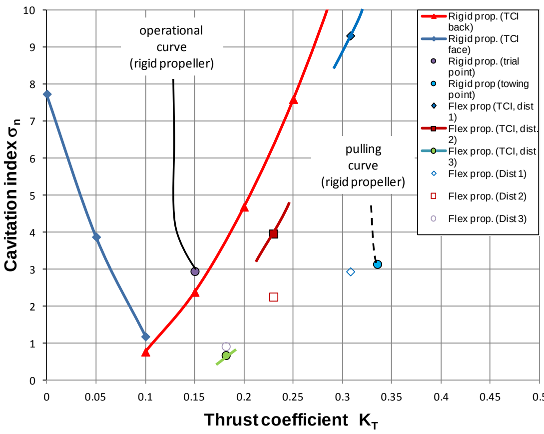

Figure 6: Tip vortex cavitation inception bucket and tip vortex inception points of the variants.

To determine the pitch deformation distributions such as the ones shown in Figure 5 in model experiments in a towing tank, it is necessary to be able to measure minute deviations of the pitch angle (e.g. 0.1 degrees). This requires an experimental technique to measure the small differences (in the order of 0.01 mm) in deformation between the leading and trailing edge of the composite propeller blades. In the next chapter the development of an experimental technique is described that has the potential to measure for the first time the dynamic deformations of flexible propeller in the wake field of a ship model.

4 MEASUREMENT OF PROPELLER DEFORMATIONS

MARIN has in recent years developed and applied a method for measuring geometry deformations through Digital Image Correlation. This technique can be used in multiple applications, including the deformation measurement of flexible propellers.

Recently, MARIN performed a pilot study to investigate if this measurement technique can be applied in the towing tank in behind ship model condition. The main advantage is that we can design and validate the technique of flexible propellers in a controlled environment in which realistic operational conditions can be simulated.

4.1 Digital Image Correlation Measurement Technique

Digital Image Correlation (DIC) is a full-field image analysis method able to measure the displacements and deformations of objects in three-dimensional space. The method tracks the gray value pattern in small regions of the images called subsets. If all displacements are taking place in a plane, only one camera can be used to accurately track the subsets. If displacements take place in three-dimensional space, at least two cameras must be used. The measurement principle is based on the stereoscopic principle of a test setup with two cameras. Reference is made to Sutton, Orteu and Schreier (2009) for more information on this subject.

The surface of the measured object must present a random speckle pattern with no preferred orientation (isotropic) and have a high contrast. The size of the features in the pattern should be large enough to distinguish them as distinct features. If the material does not present naturally a usable speckle pattern, it must be applied through printing or painting. Figure 7 shows an example of two different types of speckle patterns: printed and spray painted.

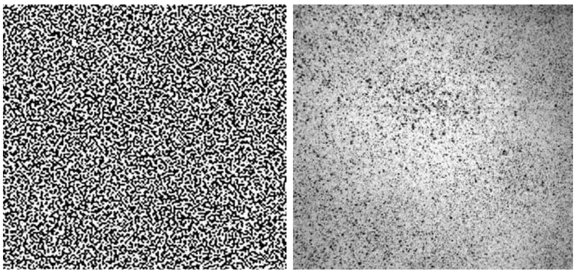

Figure 7: Speckle patterns. Left: Artificial speckle pattern for printing. Right: Speckle pattern created with spray paint. (Van de Bunt and Lafeber 2011).

DIC is an established measurement technique within MARIN. Van de Bunt et al. (2011) describe the successful application of this technique for three cases: the high-speed strain measurement of the foam structure of an LNG containment system subjected to wave impacts, the deformation measurement of a flexible ship model due to mechanical excitations and the deformation measurement of a composite propeller in the Cavitation Tunnel of MARIN. The latter was performed in 2009 and was the first application of this measurement technique in water at MARIN.

Maljaars et al. (2017) present the results of a validation study of a steady BEM-FEM coupled simulation with experiments on a model scale composite propeller in uniform flow. The experimental data were obtained in the Cavitation Tunnel of MARIN through DIC by using an improved version of the test setup presented by Van den Bunt and Lafeber (2011). The assessment of measurement accuracy showed that the DIC technique provided deformation data with an accuracy of 0.02 mm. This result shows the effectiveness of this technique aimed to measure the deformations of flexible propeller blades. In the near future similar validation studies will be carried out involving propeller blade deformation data gathered with DIC in non-uniform flow in the Cavitation Tunnel and on full scale on a sailing vessel.

At MARIN, the most recent application of DIC for deflection measurement of a flexible propeller is in ‘behind ship’ model conditions. The principal aim of these tests was to prove the feasibility of this measurement technique in behind ship condition. The test setup and an overview of the results are presented in the following sections of this paper.

4.2 Test Set-Up

The following sub-sections detail the test facility chosen for the experiments and the general test set-up.

4.2.1 Test facility

The measurements of flexible propeller deflection in ‘behind ship’ model conditions were performed in 2016 in the Depressurised Wave Basin (DWB) of MARIN in the city of Ede, The Netherlands. This test facility was built in the first half of the 1970’s and known until recently as the Depressurised Towing Tank (DTT) or Vacuum Tank. The facility was renamed to the DWB after recently being modernised and fitted with wave generators. In this unique facility, cavitation experiments can be performed with propeller models that experience unsteady inflow due to the wave influence and wave induced ship motions, see Figure 8.

Figure 8: Ship model in waves in Depressurised Wave Basin (DWB).

4.2.2 Instrumentation set-up

The test set-up consisted of a custom-made camera housing placed behind the model, with a length of approximately 1 m and a width of 0.5 m, containing two synchronised high-speed cameras set to acquire images at a frequency of 4800 Hz with a resolution of 1280 x 1024 pixels and continuous LED illumination. The bow of this housing had a triangular shape to allow the positioning of a flat transparent window required for the installation of the stereo-cameras system. The window was placed completely below the still water level. The positioning of housing was chosen to avoid interaction with the propeller while maintaining an optimal view on the pressure side of the propeller. The set-up is shown in Figure 9.

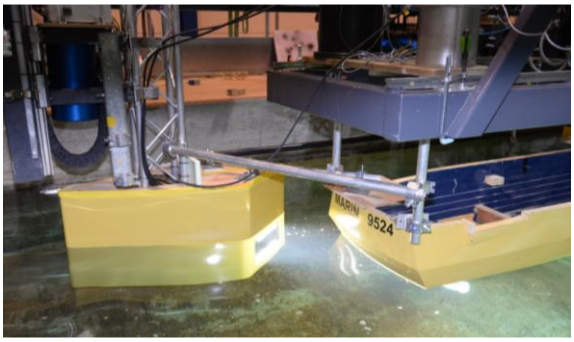

Figure 9: The test set-up including camera housing.

4.2.3 The flexible propeller

A five blades flexible dummy propeller was installed at portside on the model of a twin-screw ship configuration with open shafts. The propeller was 3D printed in an isotropic ABS thermoplastic material. This dummy propeller model was fitted with a thickness distribution with the sole purpose to achieve significant deflection of the blades. This means that at this stage no advanced bending-twisting coupling was pursued. A picture of the propeller including its speckled pattern is visible in Figure 10.

Figure 10: The flexible propeller model including the speckled pattern.

4.3 Overview of the Analysis and Results

Several tests were carried out in the towing tank including (among others): bollard pull runs (zero speed), free sailing tests and runs with fixed thrust or RPM. The obtained stereographic image data was of very high quality with high contrast and no visible motion blur even at the highest RPMs.

The blade deflections were computed through DIC by comparing the 3D shapes of the propeller under loading condition and a reference undeformed propeller shape. The results were further post-processed and a correction was applied to account for rigid body motions induced by vibrations, deformations of the shaft and relative motions between the model and the camera housing.

The results showed deflections up to 13.6 mm at the blade tip for a run with fixed RPM aimed to generate a high loading on the propeller. Figure 11 shows the results of the bollard pull runs: the picture on the left is the unloaded propeller and the other pictures are respectively at intermediate and maximum RPM. The maximum recorded blade deflection in the latter case is 7.6 mm.

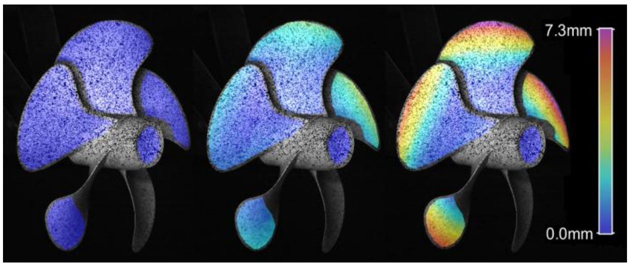

Figure 11: Measured propeller deflection at increasing RPM for bollard pull condition.

4.3.1 Assessment of measurement accuracy

An estimate of the measurement accuracy was determined by imposing a fixed 5 mm rigid body motion on the propeller along its axis using a spacer ring. This rigid body motion was measured by the camera system, see Figure 12. On the largest area of the blades surface the absolute measurement error was less than 0.15 mm. On a few spots, the error was 0.4 mm to 0.6 mm. The erratic shape of these areas with higher errors shows that very likely this is resulting from geometrical imperfections of the Plexiglas window which are impossible to account for in the current calibration procedure. This indicates the importance of using optical path of very high quality since this directly affects the measurement accuracy. It must be noted that the measurement accuracy is an absolute value: it does not vary with the magnitude of the deflections or the propeller rotation rate.

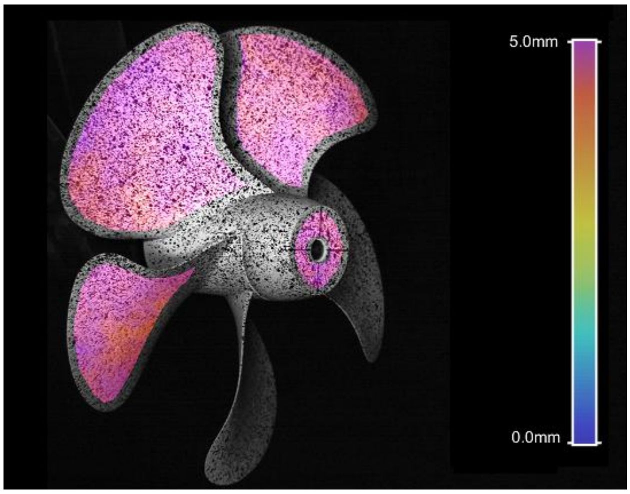

Figure 12: Axial 5 mm rigid body shift of the propeller as measured with DIC.

5 CONCLUSIONS

This paper tries to contribute to the development and market introduction of propellers made of composite material to large ships. Several points are addressed with respect to the design and testing of adaptive composite propellers.

- Since the use of composite materials has still many unknowns for the designers of ship propellers it is recommended to investigate the potential of these composite propellers, first on model scale.
- It is suggested that composite propellers might play a role in view of further tightening of EEDI and the demand for lean propulsion.
- Several propeller design strategies are discussed that could bring both fuel saving as well as reduced noise and vibration on ship and radiated underwater noise.
- Digital Image Correlation is an established measurement technique within MARIN and it has been successfully applied in several applications including deflection measurements of flexible propellers at model scale in the MARIN Cavitation Tunnel and towing tanks.
- In particular, deflection measurements of a flexible propeller in 'behind ship' model conditions were successfully conducted providing reliable data for validation studies.
- An absolute measurement error of less than 0.15 mm has been achieved on most of the blades surface. On some spots the measurement error was higher due to imperfections of the Plexiglas window. This highlights the importance of using a high quality optical path since this directly affects the measurement accuracy.
- Improvements in the test setup, especially regarding the quality of the Plexiglas observation window are expected to bring the measurement accuracy closer to the values experienced during the tests in the MARIN Cavitation Tunnel (0.02 mm, see Maljaars *and al.* 2017). This would allow successful measurement of anticipated pitch angle deformations of low noise propellers.

ACKNOWLEDGEMENT

The authors like to thank the Defence Material Organisation of the Netherlands for providing the opportunity publish the results of the pilot study.

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DISCUSSION

Question from Luca Savio

What is the baseline of the camera system? Have you considered the problem of coordinate transformation from camera system to propeller reference system.

Author's closure

The baseline of the camera system was set at approximately 15 cm. In this case, the transformation between camera and propeller reference system was defined by using the lines drawn on the flat area on the propeller hub, after correcting for rigid body displacements.