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Hydro-elastic Analysis of Flexible Propellers: An Overview

Pieter J. Maljaars[1], Mirek L. Kaminski[2]

[1,2] Ship Hydrodynamics and Structures Department, Delft University of Technology, Delft, The Netherlands

ABSTRACT

Especially the last ten years, a growing list of papers has been published on the hydro-elastic analysis of flexible (composite) propellers, showing that we are dealing with a challenging research area. Recent studies have illustrated the benefits related to the concept of flexible propellers, therefore it can be expected that the number of publications will continually grow. At a certain point it can be helpful to evaluate where we are and in which direction we have to go. Therefore, this paper gives an overview of the past research on the hydro-elastic analysis of flexible propellers. The paper shows that the majority of the presented methods for flexible propellers are limited to steady inflow conditions. Validation experiments are hardly ever conducted. Instead a lot of effort is spent on optimization problems and numerical studies which demonstrate the potential benefits of flexible composite propellers. This paper is written with the intention to review research conducted in the past and give recommendations for future research.

Keywords

Fluid-structure interaction, hydro-elasticity, composite propeller.

1 INTRODUCTION

Especially the last decade many papers have been published about the hydro-elastic analysis of flexible (composite) propellers. This flow of publications still goes on, illustrated by the four papers from 2014 which are referenced in this publication. More and more authors publish on this topic. However, mostly all the authors have published not more than one or two papers about hydro-elastic analysis of flexible propellers and have limited themselves to steady flow conditions. On the other hand, it should be noted that probably not all the research performed on flexible propellers has been published. The large number of papers published on the hydro-elastic analysis of composite ship propellers the last few years, is explained in the following.

First of all, the use of composites as propeller material has a lot of intrinsic benefits like reduced corrosion, significant weight reduction, lower electric-magnetic signature, reduced vibration and improved damping properties. However, the deformations of the propellers cannot be ignored in the hydrodynamic calculations as is usually done for conventional propellers, meaning that hydro-elastic computations have to be performed. The increased computing power has opened possibilities to perform these fluid-structure interaction computations (FSI) of deformable propellers in an acceptable time-frame, even on a personal computer.

Secondly, the deformations of flexible propellers can offer additional benefits like improved efficiency, higher cavitation inception speeds and reduced acoustic signature. The conceptual idea behind these benefits, is to use the flexibility of the propeller blades to create a propeller which passively adapts the pitch of the blades to hydrodynamic load variations. With the increased fuel prices and the foreseen tightening of international legislation concerning emissions of CO_2, NO_x, particulate matters and underwater radiated noise, companies are attracted to new methods of saving fuel and reducing ship propeller noise signature.

An important note is that the research on hydro-elastic analysis of ship propellers was initiated in the 80s in order to include the deformations of (highly skewed) bronze propellers into the hydrodynamic calculations and has therefore nothing to do with the use of composites as propeller material. The applied models and coupling procedures presented in that research are however useful for composite propellers as well. Therefore, the most important papers from this period are also included in this overview.

The first paper on the hydro-elastic analysis of composite ship propellers, referenced in this paper is from 2004 by Lin and Lin. Since 2004 many papers have been published. Therefore, after more than ten years of extensive research it is time to review where stand now. In that sense this paper is written, without pretending to be complete. The purpose of this paper is to show the state of the art of the research on the hydro-elastic analysis of flexible composite propellers. Different strategies and methods are compared. It is furthermore hoped that this paper helps to give direction to further research.

2 CONTENT

In sections 3 to 7 the paper reviews the most relevant publications with respect to different aspects of the hydro-elastic analysis of flexible propellers. First of all, the structural modelling of propeller blades is discussed in section 3. That section reviews the referenced papers with respect to the question in which way the structural modelling of propeller blades has to be performed.

Section 4 compares the different hydrodynamic modelling techniques. Important issues for the hydro-elastic analysis of flexible propellers are the accuracy and the computational cost of the applied hydrodynamic approach. The referenced papers are reviewed with respect to these issues, in order to find out which approach has been demonstrated to be the best.

Section 5 is completely devoted to the FSI coupling related aspects. First, two different coupling approaches are discussed, the question related to this section is how to set up the FSI calculation of flexible propellers.

The paragraph on steady and unsteady coupling focuses on the additional complexity of unsteady flexible propeller calculations compared to the steady calculation and whether the sensitivity of the time-dependent terms have been investigated by parametric studies in the past. Sensitivity analyses of the time-dependent variables in the hydro-elastic analysis of flexible propeller calculations will provide important knowledge about which time-variant terms may be taken time-invariant without violating the accuracy of the calculation scheme in order to reduce computational cost.

Non-identical meshes are often applied for the fluid and structural model in FSI calculations, meaning that a transformation routine has to be applied. Section 5.3 zooms in on two different transformation methods. The referenced papers are reviewed with respect to applied transformation schemes. A question that comes to mind is whether the referenced papers have shown which transformation approach has been demonstrated to be preferable.

Section 5 ends with a paragraph on the modelling of cavitation in the FSI calculation of flexible propellers. Papers are reviewed with respect to the modelling of cavitation for flexible propellers and the knowledge on the cavitation behaviour of flexible propellers, in order to show the state of the art of this research area.

Section 6 presents the most important results obtained from numerical studies on flexible propellers and is subdivided in two parts. The first part will focus on the optimisations performed on flexible propellers. In this part different papers which have presented an optimisation study on flexible propellers are summarized. It is discussed whether these optimisation studies did include all the design constraints or not. The important question is to what extent the optimisation studies have proven the advertised benefits of flexible propellers.

The second paragraph of section 6 presents the most important results of flexible propeller case studies apart from the optimisation studies which are discussed already in section 6.1. Again, one should read this paragraph by keeping in mind that it is intended to show to what extent these studies have demonstrated the proclaimed improvements of flexible propellers.

Section 7 answers the questions as to the current status of experimental research on flexible propellers. Finally, in section 8 a concluding answer on the formulated questions as stated above is given. From these answers the relevant challenges that are still open are formulated in order to give recommendations for future research.

3 STRUCTURAL MODELLING

According to Young (2007a), the most extensively used model for analysing the strength of propeller blades is the modified cantilever beam model as proposed by Taylor (1933). Since then this method is further developed by many researchers over the years (Rosingh (1937), Romson (1952), Morgan (1954), Burrill (1959) and Schoenherr, (1963)), resulting in formulations where effects of rake, skew and centrifugal force are included. The cantilever beam model has proved to be an effective way of calculating the maximum bending stresses near the root of propeller blades and therefore has been widely used in propeller strength calculations over many years. However, the method has some intrinsic disadvantages. For instance, the method cannot predict the overall deformation pattern of a blade, and poor stress results are obtained when this method is applied to determine the stress distribution along the chord instead of at the point of maximum thickness.

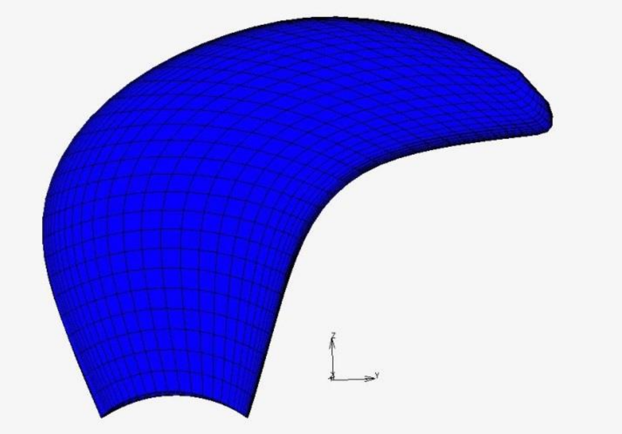

Figure 1: Solid FEM model of a propeller blade.

In order to overcome these fundamental problems, shell theories were developed to improve blade stress predictions (Cohen 1955, Conolly, 1961). However, with the increased computational power, the research on propeller strength calculations has shifted to methods based on finite element modelling. This step can be assessed as an essential one for the development of hydro-elastic designed propellers. Finite element modelling has opened possibilities to predict accurately the deformations of propeller blades under all kinds of pressure distributions. In that respect all the FSI computations including hydro-elastic effects in propeller calculations, are based on a structural modelling by the finite element method (FEM).

With regard to the FEM modelling of propeller blades two different approaches can be distinguished; namely a solid or a shell element approach.

A description of the propeller geometry and stiffness by a solid element FEM model is used in the coupling as presented by Young (2007a), Ducoin (2009), Ghassemi et al. (2012), He et al. (2012), Sun and Xiong (2012), Taketani et al. (2013) and Maljaars and Dekker (2014). A typical propeller blade, modelled by solid elements is depicted in figure 1.

A shell element FEM model is applied in the coupling as presented by Lin and Lin (1996), Georgiev and Ikehata (1998), Blasques et al. (2010), Lee and Lin (2010), Mulcahy et al. (2010) and Lee et al. (2014). Comparative studies between solid element models and shell element models for propeller modelling are presented by Young (2008) and Blasques et al. (2010). The last one prefers a shell element model, since the displacement fields predicted by a solid and shell element model are sufficiently identical but shell elements require a shorter computation time. The study presented by Young (2008) reveals a benefit of using solid elements instead of shell elements. This contradicting conclusion from these two studies can be explained by the fact that Blasques et al. (2010) makes an assessment based on displacements and Young (2008) on stresses. The impact of the higher computational cost of solid elements over shell elements is small for FSI calculations on flexible propellers, since the computation time for the fluid domain usually surpasses that of the FEM calculations. Therefore, solid elements for the FSI coupling of propeller blades are recommended, since the structural response is modelled more accurately than with shell elements, although it does not necessarily provide more insight in propeller structural behaviour.

4 HYDRODYNAMIC MODELLING

Three different approaches are mainly used in hydrodynamic calculations for flexible propellers, namely Computational Fluid Dynamics (CFD), Boundary Element Methods (BEM) and a Vortex Lattice Methods (VLM). A detailed description of these approaches is beyond the scope of this paper and can be found in for instance Wendt (2009), Anderson (2001) and Katz and Plotkin (2001).

With a CFD approach is meant that the Navier-Stokes equations are numerically solved. A CFD modelling is used in the flexible propeller FSI computations of Ducoin (2009), Mulcahy et al. (2010), He et al. (2012), Taketani et al. (2013) and Solomon Raj and Ravinder Reddy (2014).

The second approach assumes the flow to be inviscid, irrotational and often incompressible. This implies that the velocity field can be obtained from the velocity potential which can be expressed as a solution of the Laplace equation. In a post-processing step the pressures can be directly calculated from the Bernoulli equation. A BEM (or panel method) is a numerical approach to obtain the potential function which obeys the Laplace equation by solving an integral equation. In this method, panels cover the surface of the body, (an example of such a BEM model is depicted in figure 2), each panel representing an elementary potential flow function with an unknown source strength. The strengths of the elementary potential flow functions are calculated under certain boundary conditions on body-, wake- and cavity-surfaces. Potential-based panel methods are applied in the hydro-elastic propeller analysis of Kuo and Vorus (1985), Georgiev and Ikehata (1998), Young (2007a), Blasques et al. (2010), Ghassemi et al. (2012), Sun and Xiong (2012), Lee et al. (2014) and Maljaars and Dekker (2014).

A VLM calculates a solution to the Laplace equation by solving an integral equation as well. The difference between a BEM and a VLM is that in the last approach only the mean camber surface is covered by singularity elements instead of the complete 3-D propeller surface as in a BEM. The VLM as developed by the Massachusetts Institute of Technology (MIT) (Kerwin and Lee (1978) and Greeley and Kerwin (1982)) is used for the propeller hydro-elastic analysis method as developed by Lin and Lin (1996) and Lee and Lin (2010). The hydro-elastic coupling developed by Atkinson and Glover (1998) is based on a VLM as well.

As far as the author knows no comparative studies between CFD, BEM and VLM methods for the FSI analysis of flexible propellers are presented in literature. However, based on qualitative aspects the following advantages and disadvantages of the different methods can be listed. The higher accuracy is the main advantage of a CFD method. The main drawback of a CFD computation is the relative high computational cost and expensive grid generation. One of the reasons for the higher computational cost of CFD compared with BEM or VLM is that the CFD solver generally requires a relatively fine 3-D mesh. Moreover the CFD grid is usually finer than the mesh required for the FEM solver. As a result an additional routine has to transform the pressures and displacements between the two meshes.

A BEM is the most often applied numerical method in computing the hydrodynamic performance of marine propellers. Its strength, but at the same time its weakness, is the simplified fluid model. The potential flow assumptions, reduces the non-linear Navier-Stokes equations to a Laplace equation for the velocity potential. Due to the potential flow assumptions phenomena as separation of the flow, boundary layer build up and vorticity dynamics cannot be captured by a BEM, resulting in less accuracy than a CFD method. Nevertheless, BEMs have proven to be accurate methods for determining the flow around propellers operating in uniform and non-uniform wakefields. As was stated above, panel methods are based on solving an integral equation. These integral equations provide the value of the potential in an arbitrary point of the flow domain in terms of monopole and dipole sources on the boundaries. Therefore, the problem is reduced to determining the value of these quantities on the boundaries. A BEM is based on this feature, by solving the potential at only the boundaries of the computational domain. Therefore, a BEM enables one to solve a 3-D problem by solving a 2-D problem, resulting in the relative low computational cost of the BEM compared to CFD. Apart from that, the second computational time gain of a BEM is because of solving a linear set of equations instead of the non-linear equations as in CFD.

A disadvantage of a VLM is the lower accuracy compared to a BEM. An advantage of a VLM is that it is relatively fast, an unsteady propeller analysis takes about one minute instead of ten minutes with a BEM. Another disadvantage of a VLM is that only the mean camber surface is modelled instead of the real 3-D propeller. A VLM can therefore partly include the influence of geometry deformations in the FSI, an important feature for flexible propellers.

It can be concluded that a BEM is the most appropriate method for propeller calculations including deformations. A BEM is relatively fast and has proven to be an efficient and accurate method for steady and unsteady propeller calculations.

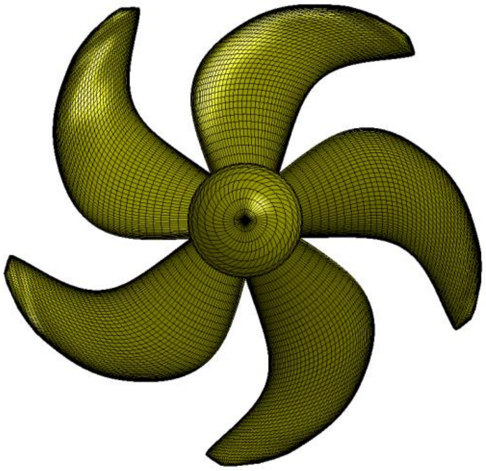

Figure 2: BEM model of a highly skewed propeller.

5 FLUID-STRUCTURE INTERACTION

5.1 Different approaches

Basically two approaches can be considered in fluid-structure interaction computations. The partitioned approach is based on two completely uncoupled problems, where the interaction between the fluid and structural solver is maintained by transferring the body boundary interface conditions between the separate solvers. Except Lin and Lin (1996) and He et al. (2012) all referenced papers presenting a hydro-elastic coupling have applied this approach. Although Lee et al. (2014) showed the coupled system of equations, it turns out they used a partitioned approach as well, since iterations are applied between a fluid and structural solver.

In the monolithical approach the hydrodynamic system of equations, structural system of equations and coupling matrices are determined and combined in one system of equations, resulting in a non-linear strongly coupled problem. The system of equations is iteratively solved by for instance a Newton-Raphson approach. This approach is applied by Lin and Lin (1996) to the steady analysis of flexible propellers. In that paper some details about the monolithical coupling approach are presented; the coupling matrix was derived from the steady Bernoulli equation, where the hydrostatic pressures were written in terms of unknown vortex strengths. He et al. (2012) applied a monolithical approach as well, but no details are provided. The main advantage of the monolithical approach is that the fluid and structural problem are simultaneously solved, meaning that the numerical error due to a time lag between the imposed boundary interface conditions and the actual interface conditions is avoided. Therefore this approach may converge the fastest. However, a smaller computation time cannot be automatically expected. For a monolithical approach, the fluid and structural problem should be of equal size as a direct consequence of the method, meaning that identical meshes have to be used for the fluid and structural problem. This means that the required mesh size should be based on the mesh size to obtain a converged solution with both solvers. Normally the fluid solver requires a finer mesh than the structural solver. In that case, too fine a mesh is used for the structural problem, increasing the total computation time. Another important drawback of this method is that uncoupled existing validated fluid and structural solvers cannot be used.

5.2 Steady and unsteady couplings

By an unsteady hydro-elastic coupling for propeller calculations is meant a coupling which can predict the deformations and performance of flexible propellers in unsteady flow. A few authors have published about developed unsteady hydro-elastic couplings, see for instance Young (2007a), He et al. (2012) and Lee et al.

(2014), the remainder of the couplings being limited to steady flows. Since most of the hydro-elastic couplings for propeller analysis are based on a BEM formulation, this section will focus on the complexity of unsteady hydro-elastic propeller calculations when a BEM is applied.

In that case the propeller and wake surface are covered by monopole and dipole sources. Influence coefficients are determined, where the entries of the monopole and dipole influence coefficients matrices are defined as the induced velocities at a control point from a unit monopole and dipole source strength at another point, respectively. By imposing the Kutta condition and the no penetration boundary condition the potential field can be calculated. In case of a rigid propeller operating in an unsteady flow, a propeller revolution is subdivided in a certain number of time-steps, where each time-step reflects a different azimuthing angle. By solving the numerical problem for all angles sequentially a solution for the entire unsteady flow field is obtained. From this short description one may think that a quasi-steady approach is applied for unsteady flows, however, the actual concept is more complicated. At each time step, in the calculation the previously obtained wake strengths, represented by wake panels in the slipstream, are included in the analyses. Results of the work of Vaz (2005) illustrates that these history effects are not insignificant for rigid propellers. As a rule of thumb Vaz (2005) defined that the minimum required revolutions to obtain a converged solution, should be equal to the number of propeller blades plus two. Including these history effects in the hydro-elastic analysis is one of the complicating factors of the analysis of flexible propellers in unsteady flows.

The second complicating factor is that in case of a vibrating blade the effects of blade vibration on the pressures has to be included in the analysis. Young (2007a) and He et al. (2012) decomposed the total pressure field into a pressure due to rigid blades rotating in a non-uniform wake and a pressure due to the blade vibrations. Subsequently, the vibration-induced pressures are written in terms of added mass and hydrodynamic damping and moved to the equations of motion for the propeller. An advantage of this method is that the vibration induced pressures are directly included in the structural analysis, resulting in a faster convergence. However, determination of the added mass and hydrodynamic damping matrices appears to be based on many assumptions. Elaborating this subject is beyond the scope of this paper. Suffice it to say that, for instance, the influence of the wake on the added mass and hydrodynamic damping seems completely neglected, meaning that the blade vibrations itself will not introduce any change in circulation about the propeller. This assumption sounds reasonable since the changes in circulation due to propeller vibrations may be small, however, as far as the author knows, no results are presented in literature in order to evaluate this assumption.

A precise, but computationally more intensive method would be to include the vibrating velocities of the propeller blade as a component of the inflow velocity in the BEM calculation. In that case the vibration velocities are treated as a body boundary interface condition as well. An interesting study would be to compare these two methods to each other in order evaluate the correctness of the approach in which the pressure field is decomposed.

Perhaps one of the most complicating factors is that an unsteady BEM formulation has to be developed which can accurately predict the performance of a rigid propeller in non-uniform wakefields before it can be applied for flexible propellers. The work done by MIT in 90s (see for instance Lee, (1987), Hsin (1990) and Fine (1992)) and by the Maritime Research Institute Netherlands (MARIN) (see for instance Vaz (2005), Vaz and Bosschers (2005), Vaz et al. (2005)) on BEMs illustrates that.

Finally, developing a hydro-elastic coupling applicable for steady and unsteady flows is a complicated task. Perhaps in the first place for the reason that up to now o, no results are available from literature about the importance and sensitivity of the different time-dependent variables involved in the hydro-elastic analysis of flexible propellers. For instance, the influence of the wake geometry displacements due to deformations and vibrations of the propeller are completely unclear. The easiest is to ignore them, by assuming that the wake geometry deformations have an insignificantly small influence on the flow around the propeller. Such assumptions and many others should be investigated and shared with other researchers, since more fundamental knowledge about self-pitching propellers is required in order to develop hydro-elastic couplings for unsteady propeller calculations.

5.3 Transformation over body boundary interface

In case of an FSI coupling based on a partitioned approach, fluid forces have to be transferred to the structure and structural displacement, velocities and accelerations have to be transferred in opposite direction. In order to avoid an interpolation scheme, identical grids can be used in the fluid and structural solver. Lin and Lin (1996), Young (2007a), Ghassemi et al. (2012) and Maljaars and Dekker (2014), used this approach for the FSI coupling of flexible propellers. The ability to use the same meshes is a benefit of a BEM FEM coupled approach as showed by Maljaars and Dekker (2014) that both solvers require identical mesh densities .

In de Boer et al. (2007) a review of coupling methods for non-matching meshes is presented. The global conservation of energy over the interface is formulated in this paper as the most important criteria to evaluate methods which can deal with information transfer between non-matching meshes. With global conservation of energy over the interface is meant that the work performed by the loads are retained after interpolation. If energy is exactly preserved the interpolation is of the conservative type. Another method is a consistent way of interpolation. In a consistent interpolation scheme constant values are interpolated exactly, which is not the case for a conservative interpolation. Non-identical meshes are applied in the couplings as presented by Lee and Lin (2010), Mulcahy et al. (2010), Sun and Xiong (2012), Taketani et al. (2013) and Solomon Raj and Ravinder Reddy (2014), but no details about the interpolation schemes are presented in these papers. Ducoin et al. (2009) presented that a conservative coupling approach was used. Blasques et al. (2010) particularize that the pressure value at each node of the structural model is determined by 3-D linear interpolation of the pressure calculated at the control points of the hydrodynamic model, which means that a consistent coupling approach is applied. Lee et al. (2014) applied an inverse distance weighting algorithm for the information sharing between the fluid and structural solver, which means a consistent coupling approach is used.

5.4 Cavitation

An important potential benefit of flexible propellers is that they may have increased cavitation inception speeds, due to unloading of the tip as result of the de-pitching behaviour of the blade in loaded conditions. Improved cavitation properties are claimed by Solomon Raj and Ravinder Reddy (2014). Chen et al. (2006) concluded from a cavitation tunnel experiment that flexible propellers can have a reduced tip vortex cavity owing to tip unloading.

Young (2007a) has presented a fluid-structure interaction coupling for flexible propellers operating in steady and unsteady, subcavitating and cavitating flows, Young (2008) shows some numerically and experimentally obtained results for cavitating flexible propellers (see also figure 3). The predicted cavitation patterns agrees with experimental observations. The BEM applied by Maljaars and Dekker (2014) for the steady FSI coupling, can calculate sheet cavitation extents as well. However, the results presented by Maljaars and Dekker (2014) are only for subcavitating conditions. It can be concluded that the knowledge on cavitation behaviour of flexible propellers is very limited up to now. Without any doubt cavitation is also a function of the deformations of the propeller, in case of a strong dependency the calculation of the cavitation extents has to be included in the iterating loop between the fluid and structural solver, resulting in much longer computation times. An important research question is to what extent cavitation can be taken outside the iterative calculation. Another important research question is if the cavities on the propeller blade will remain stable in case of a transient blade vibration.

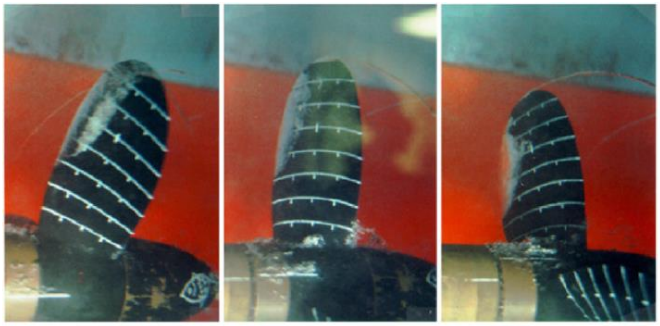

Figure 3: Unsteady cavitation patterns on a model scale propeller (From Young (2007a)).

6 NUMERICAL STUDIES

6.1 Optimizations

A lot of papers present an FSI coupling for flexible composite propeller blades combined with an optimisation procedure. Most of the optimisations have as objective to increase efficiency at off-design conditions, like Pluciński et al. (2007), Lin et al. (2009), Blasques et al (2010), Lee and Lin (2010), Mulcahy et al. (2010). Except Mulcahy et al. (2010) all these authors used genetic algorithms as optimisation procedure for composite propellers. Genetic algorithms can easily deal with discrete design domains which is the case if fibre orientation angles can only take a fixed set of values due to manufacturing constraints.

Blasques et al. (2010) used two different fibre orientation approaches, namely a straight fibre path approach and a curved fibre path approach. In the latter approach a parameterization of the ply orientation angles is used based on the result of Parnas et al. (2003). In the curved fibre path approach the fibres are oriented along curved paths, which will result in a larger design space compared to the straight fibre path approach. Therefore, it does make sense, as Blasques et al. (2010) found, that the largest reduction in fuel consumption was found with the curved fibre path approach. Lee and Lin (2010) optimise the stacking sequence of a composite propeller by a genetic algorithm with local improvement, they used the method as proposed by Lin and Lee (2004). A genetic algorithm with local improvement is used by Pluciński et al. (2007) as well, Young et al. (2010) extended this optimisation procedure from a deterministic type to a probabilistic optimisation and shows that uncertainties in material stiffness parameters have a marginal effect on the hydro-elastic behaviour of flexible propellers. That is due to the optimization of the bending-twisting coupling that produces a system which is more sensitive to variations in ply angle and advance coefficients than to expected variations in material stiffness parameters. From an engineering point of view an interesting paper on the optimisation of composite propellers is the paper presented by Mulcahy et al. (2010).

This paper presents an optimisation procedure in which the hydrodynamic calculation is not included in the optimisation loop, which reduces the required computation time, but higher efficiency increases for off-design conditions would be obtained when an optimisation with the coupled CFD-FEM solver was applied.

The optimisations as described above, are focussing on the efficiency of flexible propellers and performed without attention to critical loads, fatigue and sometimes production constraints. Secondly, the optimisations are all based on a fixed propeller geometry, assuming that the geometry of the rigid propeller blade is optimal for the flexible composite propeller as well. Most probably that will be not the case, since for instance the thickness of composite blades can be simply adjusted without violating the weight and strength constraints which is not possible for rigid blades. In that respect the reader is referred to the paper of Chen et al. (2006) who designed some flexible composite propellers from rigid blade geometries and found that with the rigid blade geometry the potential advantages of flexible propellers were not fully explored. Therefore a new flexible propeller blade design was proposed with increased skew and reduced thickness.

6.2 Flexible propeller case studies

The main part of all the papers published on the hydro-elastic analysis of flexible propellers are focussing on case studies. Case studies are useful in a sense that they can illustrate some concepts and produce novel hypotheses which can be used for later testing, however, the main disadvantage of case studies is that results cannot be generalised. With respect to the structural strength of flexible composite propellers one can conclude that the case studies on this topic solely focus on ultimate strength, whereas fatigue strength of flexible composite propellers has been excluded so far from the analyses.

Blasques et al. (2010) assessed the strength of an optimized lay-up design for a fixed pitch, 0.305m diameter composite marine propeller with high skew, using the two dimensional version of the Tsai-Wu strength index. In order to distinguish between the contribution of the different failure modes, they used the Maximum Stress Failure Criterion as well, in parallel with Tsai-Wu strength index. It turns out that the most strength critical regions are the leading and trailing edge parts close to the hub.

The same critical regions were found by Lin et al. (2004). They used the Hashin failure criteria, this failure criteria considers separately the different failure modes, like fibre tension and compression, matrix tension and compression and delamination in contradiction to the Tsai-Wu strength index. In this paper the strength and failure modes of a composite propeller with different stacking sequences is analysed under various loading conditions. The paper presents the failure modes and where the failure will occur. It turns out that the critical failure mode is delamination occurring at tip, leading and trailing edge.

Another critical failure mode was found by Kiasat et al. (2010). The composite surface piercing propeller having two-layer carbon fabric-epoxy blades filled with a core material failed under the compressive stresses induced by the hydrodynamic pressure due to buckling of the backside of the composite blade. From these papers it can be concluded that the strength of composite propeller blades should be assessed by FEM software. Idealized models as presented in the section on structural modelling, cannot capture the failure modes of composite propellers.

The hydro-elastic reponse of flexible propellers is the subject of many case studies as well. First of all most of the papers on the hydro-elastic response of flexible propellers present their results in non-dimensional quantities, like thrust, torque and advance coefficient. That suggests that only one open-water diagram characterises the performance of a flexible propeller. However, in case of a flexible propeller one can construct as many open-water diagrams as loading conditions, since the flexible propeller will constantly change its geometry. Presenting results without noticing what is stated above, can lead to the seemingly contradictory conclusions between Ghassemi et al. (2012) and Maljaars and Dekker (2014) on the one hand and Lin and Lin (1996) and Lin et al. (2010) on the other hand. In the latter two papers it is concluded that for a moderately skewed propeller the influence of the flexibility of the blades was found especially in the low advance coefficient regions. This conclusion is in contradiction with the conclusions drawn by Ghassemi et al. (2012) and Maljaars and Dekker (2014). These papers show the results of studies into the effect of the skew angle on the performance of a flexible marine propeller and found similar results, meaning that the skew angle has a very pronounced effect on the performance of flexible propellers. Moreover the results showed that the largest influence of the flexibility occurs at the highest influence coefficients, this can also be concluded from figure 4 and 5 as presented by Motley et al. (2009). Maljaars and Dekker (2014) give as explanation for this behaviour the moving of the net hydrodynamic force over the propeller surface. The thrust at small advance coefficients is generated more towards the leading edge of the propeller and moves towards the trailing edge when the advance coefficient increases. The movement of the thrust load causes, especially in case of highly skewed propellers, a larger de-pitching moment. The contradicting conclusions with respect to the influence of blade flexibility at various advance coefficients can be explained as follows: Lin and Lin (1996) and Lin et al. (2010) performed calculations at various advance coefficients were the rotational rate of the propeller was kept constant. It seems that they did not normalize the thrust and torque at various advance coefficients, resulting in the highest hydrodynamic loading at low advance coefficients and consequently the largest influence of the flexibility of the blade was recorded at the low advance coefficients. That the performance of a flexible propeller cannot simply be expressed as a function of advance coefficients due to differences in dimensional load, which will induce different blade deformations and hence change the hydrodynamic performance, is also explained by Young and Motley (2009) and Motley et al. (2009). Especially the last paper provides a lot of insight in the hydro-elastic behaviour of cavitating flexible composite propellers (see also figure 4 and 5). For instance it is shown that the efficiency increase of flexible propellers in steady and unsteady flows has similar magnitude. This can be explained by the fact that wakefield used for the unsteady computations, does not have a severe wake peak. The results show that highest increase in efficiency (in the order of 10%) is obtained for the highest advance coefficient of 0.9, the efficiency increase for advance coefficients 0.5 and 0.8 which are the two calculated advance coefficients around the design advance coefficient of 0.66 are in the order of 1-2%.

As found by Blasques et al. (2010), as a result of an optimisation calculation the optimal configuration for efficiency was a propeller blade with a flexible tip and a stiff body closer to the hub. Young (2007b) concludes from the presented results that pure bending deformations without twisting has negligible influence on the propeller performance and efficiency. On the other hand, Young et al. (2010) concluded that the efficiency of a propeller showed to be the most sensitive to variations in advance coefficient and fibre orientation angle in that order.

Such as for the optimisation studies as shown above, the numerical studies on flexible propellers are mainly oriented towards the efficiency of flexible propellers as well. However, there is a large dispersion in proclaimed efficiency enhancement by different authors. Chen et al. (2006) came up with an efficiency improvement up to 5% at the design condition in an unsteady flow. Mulcahy (2010) concluded that the efficiency gain of a flexible propeller operating at design condition in ship wake is less than 1%. On the other hand, efficiency improvements are higher at off-design conditions. However, up to now, there are no results published that demonstrate the actual efficiency improvement of flexible blades on full scale.

Blade flexibility can be applied also to improve vibration and cavitation behaviour. A paper focussing on the numerical study of blade vibrations of flexible composite propellers is presented by He et al. (2012). The calculations were performed for propellers with tiny blade vibrations. A coupled CFD-FEM procedure is applied, but considering such small vibrations might be performed without accounting for the blade deformations in the flow calculation. On the other hand, the paper demonstrates that the stacking scheme has an important influence on the vibratory loads.

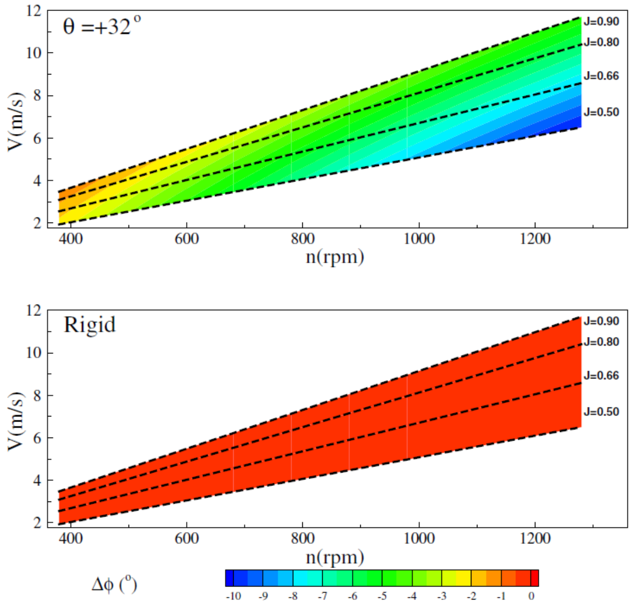

Figure 4: Contours of change in tip pitch angle for a flexible (top) and rigid (bottom) propeller in a uniform flow (From Motley et al. (2009).

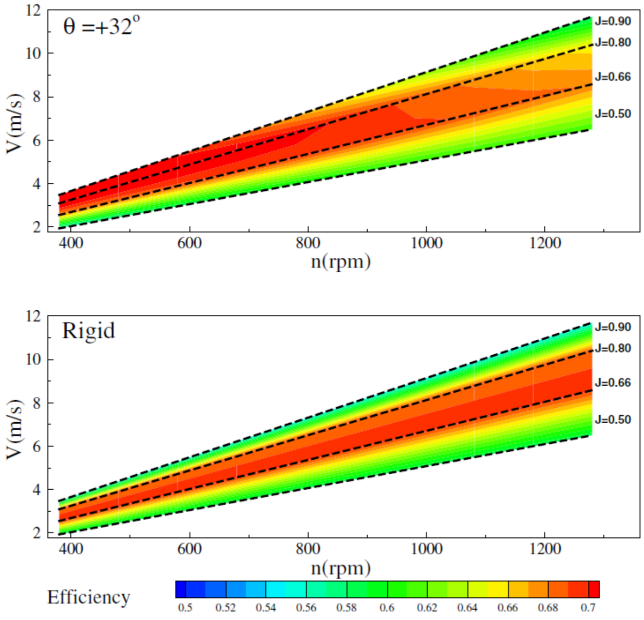

Figure 5: Efficiency for the flexible (top) and rigid (bottom) propeller in a uniform flow (From Motley et al. (2009).

It can be concluded that the case studies presented on flexible propellers provide a lot of insight into the behaviour of this type of propellers and clearly demonstrate the potential abilities of them. By noticing the advertised improved efficiency, vibration properties and cavitation behaviour of flexible propellers from these studies, it should be kept in mind that critical loads, fatigue and production constraints are mainly not considered in the improved designs, perhaps sometimes resulting in too optimistic conclusions.

7 EXPERIMENTAL STUDIES

From the last sentences of the previous section it can be concluded that there is a clear need for experimentally based evidence with respect to the improved properties of flexible composite propellers. A second reason for more experimental data is related to the fact that the majority of the hydro-elastic couplings for propeller analysis are not validated. The BEM-FEM coupling as presented by Young (2007a) can be seen as one of the best validated couplings for flexible propeller computations. A strong point of the coupling as presented by Young (2007a), is that the applied BEM software is extensively validated in the past for cavitating, non-cavitating, fully and partially submerged propellers. An overview of the BEM validation studies is presented in Young and Kinnas (2003). In that respect no BEM validation studies or references to such studies are given in the papers on couplings as presented by Blasques et al. (2010), Ghassemi et al. (2012), Sun and Xiong (2012) and Lee et al. (2014). The VLM code applied by Lee and Lin (2010) is validated by Greeley and Kerwin (1982). Therefore, it is important to note that a validation study of an FSI coupling starts by a validation study on the fluid and structural solver separately. A FEM validation study for the coupling as presented in the papers of Young, can be found in Young (2007a) and Young (2008). A validation study for the complete BEM-FEM coupling is presented in Young (2008), computed and experimental obtained propeller performance curves are compared to each other and a limited validation of the deformation predictions is presented. Moreover, the validation study is limited to uniform wake fields. Lee et al. (2014) used the results of Young (2008) as validation for their steady FSI coupling, especially at high advance coefficients a large difference between experimental and numerical obtained results can be detected. Measurements for a non-uniform wakefield have been conducted by Chen et al. (2006). Their results are used by Lee et al. (2014) to validate the developed unsteady hydro-elastic coupling, but it can be concluded that the validation data is too limited to show the reliability of the proposed method. Since Chen et al. (2006) performed measurements on a 610mm diameter carbon fiber reinforced plastic propeller in a uniform as well as a four cycle non-uniform wake. The pitch change of the propeller was measured at two locations using a video camera. Measured and predicted pitch changes were compared showing that the magnitude of the pitch reductions are under predicted, however, the trends are predicted well. To the best of the author’s knowledge Chen et al. (2006) are the only ones who performed deformation measurements on flexible propellers in a non-uniform flow. A more advanced deformation measurement technique is presented in the paper of Maljaars and Dekker (2014). However, their digital image correlation technique was only applied to measure the tip displacements and axial deformations of the midchord points of a propeller operating in a uniform flow, the model scale propeller is depicted in figure 6. Maljaars and Dekker (2014) used the experimental data as obtained by the cavitation tunnel experiment in order to validate the developed BEM-FEM coupling. It was concluded that the developed coupling can predict the qualitative response of a flexible propeller correctly. However, to quantify the accuracy of the coupling code, similar experiments have to be performed after improving the presented test setup. On the other hand, the digital image correlation technique has proven to be a promising technique for further experimental research on deformable propellers. Another paper which presented experimental results on flexible propellers operating in a uniform flow is the paper from Lin et al. (2009). They have measured the performance and the deformation of a model scale propeller in a cavitation tunnel. Deflections are measured by a kind of image correlation technique. Pictures of the blade were taken and superimposed. The displacements were determined by counting the pixels between deflected and undeflected points. No details about the accuracy of this method have been presented. Taketani et al. (2013) did several cavitation tunnel experiments as well. Three propellers made of isotropic material were tested in a steady flow. Thrust and torque were measured, tip deformations were determined by taking pictures and measuring the displacements. The results were compared to predicted thrust, torque and tip displacement values by a CFD-FEM coupling. For larger deformations the analysis proved relatively inaccurate in estimating the propeller behaviour.

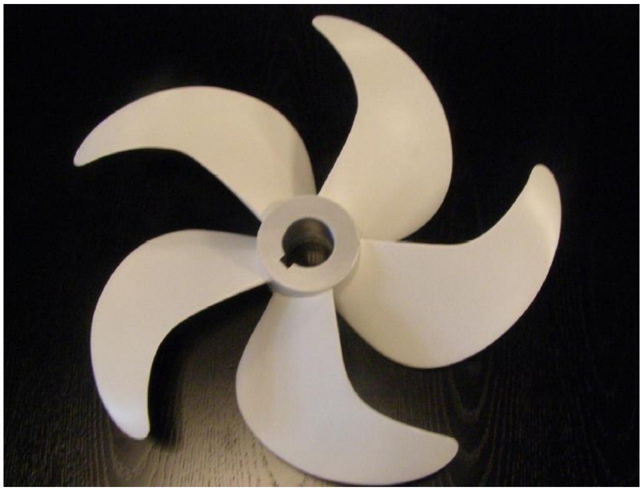

Figure 6: Composite model scale propeller. (Courtesy of Airborne Composites B.V.).

Young (2008) measured the deformations of the propeller by a laser tracking technique. According to the author the accuracy of this technique was too low to accurately predict the changes in pitch deformation of the stiffest propeller. Based on the presented results one can conclude that these pitch deformations should be in the order of one degree, which is a large error, when noticing that the pitch deformation for flexible propellers should probably not be larger than five degrees. All of this illustrates that measuring the deformations of rotating propellers, even in a steady flow, is a complicated task, where nobody up to now has clearly demonstrated how to do that in an accurate way. The method that Solomon Raj and Ravinder Reddy (2014) have used to validate their coupled CFD-FEM coupling, seems to be effective in order to exclude any deformations measurements. Solomon Raj and Ravinder Reddy (2014) performed a cavitation tunnel experiment and measured only the thrust and torque coefficient and conclude from one experiment that the numerical method was successfully validated. However, it should be first demonstrated that thrust and torque are effective parameters to assess the accuracy of the numerical method. This means that the inaccuracy of the fluid solver should be at least an order smaller than the procentual difference in thrust and torque between a flexible propeller and its rigid counterpart. In the papers of Lin and Lin (1996), Georgiev, and Ikehata (1998), Lin et al. (2009) and Sun and Xiong (2012) the deformations of the propellers seems to be tiny, such that the criteria as stated above is (probably) not fulfilled. Nevertheless, it is concluded in some of these papers that the hydro-elastic coupling is demonstrably validated only based on measured and computed pressure distributions and thrust torque values.

An interesting paper on experimental research on composite ship propellers is the paper presented by Taketani et al. (2013). In this study three propellers of 0.25m diameter made of isotropic material are tested in a cavitation tunnel experiment. The propellers were made of materials with respectively a Youngs modulus of 70GPA, 51GPa and 1.240 GPA. The propeller made of aluminium (70GPa) is classified as being rigid. The propeller performances as measured in the cavitation tunnel indicate that there is an optimal level of deformation since the propeller with the lowest stiffness displays the largest deformation but also has the lowest propeller efficiency, while the propeller with a stiffness of 51GPA shows an increased efficiency compared to the rigid propeller for small advance coefficients. On these propellers cavitation test were performed as well. For this experiment the propellers were measured in an unsteady flow. Pictures shows that the flexibility of the blade reduces the cavity extents of the propeller. This is also indicated by the amplitude of the fluctuating pressure, as measured by a pressure sensor arranged above the propeller. The propeller with reduced sheet cavitation has also a smaller fluctuating pressure amplitude.

This overview on the experimental research on flexible composite propellers shows that most of the experimental investigations are limited to uniform wakefields. Limited results are presented on the deformation measurements of flexible propellers. An accurate recording of propeller deformations in terms of twist and bending deformations, might result in effective data for the validation of hydro-elastic couplings. However, the limited results presented on deformations of flexible propellers, illustrates the complexity of these measurements.

8 CONCLUSIONS AND RECOMMENDATIONS

From section 3 it can be concluded that a FEM modelling with solid elements is recommended for the FSI coupling of flexible propellers. In section 4 different hydrodynamic modelling techniques are discussed. From a qualitative assessment a BEM method might be qualified as the most appropriate for propeller calculations including deformations. On the other hand, no comparative studies between different hydrodynamic modelling approaches for the FSI analysis of flexible propellers have been presented in literature. Therefore, an important addition to the current investigations would be such a comparative study in which also the implication of neglecting the fluid viscosity in the hydrodynamic modelling should be assessed.

With respect to the partitioned and the monolithical coupling approach for FSI calculations, it can be concluded that the partitioned approach provides the best flexibility, because with this approach one is not restricted to a particular fluid or structural solver or mesh size. Moreover, this method can be applied to propellers with large deformations which is not the case for a monolithical approach.

From section 5.2 it can be concluded that the majority of the hydro-elastic couplings is limited to uniform wakefields. A few authors have published about developed unsteady hydro-elastic couplings. The complexity of the unsteady hydro-elastic computations is explained in this section. In section 2 the question was formulated whether papers have been published on the sensitivity of the time-dependent variables in the hydro-elastic analysis of flexible propeller calculations, since this knowledge is essential for developing an accurate and computational cost competitive unsteady hydro-elastic coupling. It can be concluded that none of such studies have been presented in literature up to now. Therefore, an important addition to the current publications would be a study in which the importance of the time-dependent variables will be investigated and concluded which variables can be taken time-invariant without violating the accuracy of the method.

Several papers have presented studies in which an identical mesh in fluid and structural solver is applied, which is possible for a BEM-FEM coupling, since both solvers require almost an identical mesh density. On the other hand, most of the papers in which non-identical meshes are applied do not present any details about the interpolation scheme. In future research conservative and consistent transformation approaches in propeller FSI calculations have to be compared in order to make a founded choice for one of these methods.

It can be concluded from section 5.4 that the knowledge on the cavitation behaviour of flexible propellers is very limited up to now. Experiments have confirmed that flexible propellers can have reduced cavitation, but whether the cavities on a propeller blade will remain stable in case of transient blade vibrations is an important research question for the future. Knowledge about the modelling of cavitation in the FSI coupling of flexible propellers is limited as well. There is one author who has presented an FSI coupling for flexible propellers operating in steady and unsteady, subcavitating and cavitating flows. An important question related to the modelling of cavitation in flexible propellers is whether or not the calculation of the cavity extents has to be included in the iteration loop between the fluid and structural solver. It is recommended to conduct these numerical studies in order to provide an answer to this question.

It can be concluded from section 6.1 that the conducted optimisation studies are all focussing on the efficiency of flexible propellers instead of other possible design objectives like high cavitation inception speeds or reduced acoustic signature. Moreover, these optimisations are performed without attention for critical loads, fatigue and sometimes for production constraints as well, probably resulting in too optimistic conclusions. Secondly, all the optimisations concentrate on optimizing the stiffness properties of propellers with a constrained geometry. Larger improvements might be obtained when this would not have been the case. Therefore, future optimisation studies should focus on other design objectives instead of efficiency only and have to take the geometry of the propeller as optimisation variable as well. More knowledge about the strength and fatigue of composite propellers is required in order to include strength and fatigue constraints into the optimisation studies.

Similar conclusions can be drawn when reviewing flexible propeller case studies performed in the past. It can be concluded that fatigue strength of flexible composite propellers has been hardly analysed in the past, although it might be (one of) the most important design constraints. Therefore, investigating the fatigue strength of flexible composite propellers can be formulated as an essential research topic for the future. As for the optimisation studies, the majority of the flexible propeller case studies focus on propeller efficiency, resulting in a lot of publications demonstrating the potential abilities of flexible propellers

with respect to fuel saving but fewer papers showing the advertised improved vibration, cavitation and noise properties of them. Therefore, more numerical studies on vibration, cavitation and noise properties of flexible propellers are recommended. Secondly, a challenge for future research will be to demonstrate the benefits of flexible propellers on full-scale, starting for instance by showing the actual efficiency improvements of flexible blades, since numerical studies show a large spread in claimed efficiency increases.

Section 7 summarizes the experimental research performed on flexible propellers. It can be concluded that few validation data is available, resulting in limited validated hydro-elastic couplings. It can be concluded that thrust and torque values are often used as validation data, however, it can be argued that propeller deformations might be more effective parameters for the validation of the hydro-elastic couplings, since, usually the deformations are small, resulting in small thrust and torque variations, while these variations may have the same order of magnitude as the accuracy of the measuring technique or the accuracy of the flow solver. An accurate recording of the propeller deformations in uniform and non-uniform flows will provide possibilities for validation purposes. But it can be concluded that up to now, there is nobody who has clearly demonstrated to measure the deformations of flexible propellers, even in a steady flow, in an accurate way. Therefore, the first challenge is to develop a measuring set-up which can accurately record the deformations of flexible propellers. An even greater challenge will be to measure the deformations of a flexible propeller in an unsteady flow. These type of experiments are required to obtain validation data for unsteady hydro-elastic FSI couplings.

An overview of the research on hydro-elastic analysis of flexible (composite) propellers is presented in this paper. At present we are more or less ten years on the way, where previous researches have shown to be effective in a sense that they have illustrated the potential benefits of these new generation of propellers, attracting more and more researchers to publish about this interesting topic. As has been shown, there is still a lot of research work to be done in the future.

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DISCUSSION

Question from Luca Savio

Which experimental technique have you planned to apply for the experimental validation of future work?

Authors’ Closure

In short the following experimental set-up will be applied: measurements will be done in a cavitation tunnel, thrust and torque will be measured on the shaft. Deformations of the blade will be measured by a digital image correlation technique.