Prediction of unsteady propeller performance in an inhomogeneous wake

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ABSTRACT

Accurate prediction of unsteady propeller loads for propellers operating in non-uniform flow (i.e. the wake of a ship hull) is vital for assessing the suitability of candidate propellers in the context of noise and onboard vibration. This requires an assessment of the flow around the hull, the response of the propeller to the incident flow, and the propeller interactions with the flow field and other appendages/surfaces. This paper examines a subset of these by evaluating the suitability of several computational codes for assessing the unsteady response of a model propeller to wake inhomogeneity. The motivation for this work is to better understand the trade-off between accuracy and computational cost. This understanding allows for a more robust investigation of the design parameter space. Unsteady thrust and torque predictions from the Boundary Element Method (BEM) code PROCAL and Unsteady-RANS solver Star-CCM+ are compared with a prediction from the unsteady lifting surface theory code PUF-2 and experimental measurements carried out at the David Taylor Research Centre (DTRC). To reproduce the experimental conditions with Unsteady Reynolds Averaged-Navier Stokes (URANS), a consistent methodology for representing the wake field is introduced. It is found that the BEM method can provide predictions with accuracy close to that of the URANS calculations for low frequency harmonics.

1 INTRODUCTION

Marine propellers often operate in unsteady spatially non-uniform flow, which is formed by merging the turbulent boundary layer and the wake from the hull of a ship (Knox et al. 2016). Due to the periodic nature of propeller rotation, the blades encounter a non-uniform flow that develops unsteady periodic loads. These periodic loads result in thrust and torque harmonics at the frequencies where the inflow wake harmonics match multiples of the number of blades and its consecutives (±1).

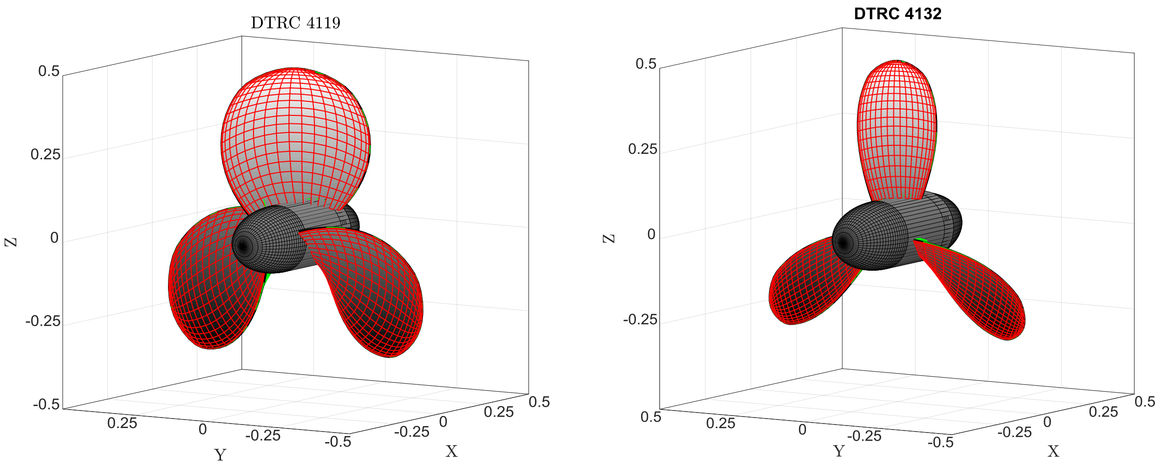
Many studies have been carried out to investigate the unsteady response of a propeller to the harmonic composition of non-uniform wake fields. Boswell and Miller (1968) applied multiple lifting-line techniques to quantify the unsteady blade loads due to the wake harmonics. They also carried out experimental measurements with wire-mesh wake screens to ensure that the propeller inflow contained the desired harmonic content. Pfister (1971) applied an analogous experimental technique to generate the fundamental blade-rate harmonic and measured unsteady propeller loads. To investigate the propeller response to higher wake harmonics, Jessup (1990) tested the same series of propellers in wakes containing strong harmonics which were multiples of the number of blades. The non-uniform inflow was generated by wake screens with discrete numbers of segments. It was observed that the amplitude of high order wake harmonics were subjected to significant decay downstream from the wake screens. A special correction was required in the numerical model to adequately account for the decay between the measurement plane and the propeller location. These three references provide comprehensive experimental measurements that can be used as a benchmark for validation of any numerical methods for prediction of propeller unsteady loads. Suitable methods, in order of increasing fidelity and computational cost, include: the lifting-line theory; the boundary element method (BEM); Unsteady Reynolds Averaged-Navier Stokes (URANS) and Large Eddy Simulation. The critical condition for consistency of this validation is the equivalence of the wake field, including its harmonic composition, that is used in these numerical frameworks.

This objective of this paper is to examine the suitability of unsteady thrust and torque predictions from the BEM code PROCAL (version 2.329, developed by the Cooperative Research Ships organization) and URANS solver

Star-CCM+ (version 12.04.010) by comparing them with a prediction from the unsteady lifting surface theory code PUF-2 and experimental measurements carried out at the David Taylor Research Centre (DTRC). To reproduce the experimental conditions with URANS, a consistent methodology for representing the wake field is introduced. This methodology includes the ability to generate both the primary and high-order wake harmonics within a non-uniform inflow. The modelling technique is implemented in both BEM and URANS computations and applied to the benchmark DTRC series propeller. The harmonic components in the computed unsteady loads are analysed and compared against experimental measurements from literature.

2 DAVID TAYLOR RESEARCH CENTRE SERIES PROPELLER

The propeller models adopted in the current work were developed in the David Taylor Research Centre, USA. The geometries are tabulated in Kerwin (1976) and are given in Figure 1. Propellers 4119 and 4132 have expanded area ratios of 0.6 and 0.3 respectively. The radius (R) of the two models are both 0.153 m. The propeller blades are made from modified NACA 66 sections with zero skew and rake.



(a) (b)

Figure 1. Three dimensional representations of DTRC propellers (a) 4119 and (b) 4132

3 COMPUTATIONAL METHOD

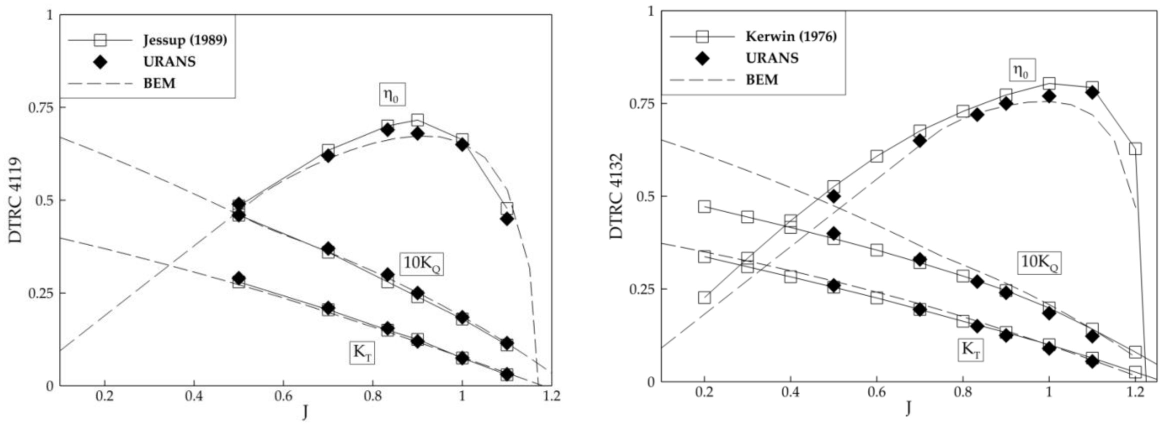
Two computational methods are employed to investigate the hydrodynamic performance of the propellers shown in Figure 1: the inviscid BEM method with viscosity corrections and the fully viscous URANS method. The effects of cavitation are not considered in the current work.

The BEM solver PROCAL is adopted to predict propeller hydrodynamic performance. Applying Green's second theorem, the numerical domain is solved by introducing boundary conditions and the equation for the potential on surface of the propeller. The propeller geometry is modelled by defining the chord length, thickness and camber at different sections along the propeller blade. A total number of 10200 panels are defined and generated in the presented simulations. The inhomogenous inflow velocities are defined separately based on a cylindrical coordinate system, and are treated as time-independent variables throughout individual computation. More detailed theoretical explanation on viscous corrections and grid discretisation techniques can be found in Bosschers and Peddle (2014).

The URANS computations in this study are performed using commercial solver Star-CCM+. The code uses a finite volume discretisation to solve for the single phase incompressible flow coupled with the conservation of continuity. The pressure-velocity coupling is calculated using a PIMPLE algorithm. The closure of the URANS equations is achieved using the k-ω Shear-Stress Transport turbulence model on the basis of the description by Menter (1994) and Wilcox (2008). The numerical domain comprises approximately 15,000,000 unstructured polyhedral grids with refinements on the propeller blades and in its vicinity. The propeller is placed at a distance of 1.30R behind the inlet boundary of the numerical domain. A sliding interface is created between the far-field region and the propeller region for modelling the propeller rotation. The inhomogenous flow is modelled by time-independent spatial velocity vectors in the fluid domain and its inlet boundaries. The prescribed flow field is based on a Cartesian coordinate system, which is converted from the wake field data file within the PROCAL output directory.

4 OPEN-WATER PROPELLER PERFORMANCE

The open-water performance of the DTRC 4119 and 4132 models are evaluated through BEM and URANS computations in this section. The results are given in Figure 2 where comparisons are made against the results from literature. In general, very good correlation (average comparison error of around 5%) is found on the steady thrust, torque and efficiency between numerical and experimental data, particularly for the DTRC 4119 model. For the DTRC 4132 model, URANS computation seems to produce more accurate results, especially for the torque coefficients. For the URANS and BEM predictions the average comparison errors are approximately 8% and 20% respectively. Considering computational efficiency, BEM can be regarded as a feasible substitute when rapid solutions are required.



(a) (b)

Figure 2. Comparison of computed open-water thrust, torque and efficiency against experimental data (a) 4119 and (b) 4132

5 PERFORMANCE OF DTRC 4132 IN NON-UNIFORM WAKE FLOW

The unsteady response of the DTRC 4132 propeller model in non-uniform wake flow is investigated through BEM and URANS computations in this section. The rotation speed of the propeller is predefined as 10 RPS. The corresponding advance coefficient is 0.83, assuming a mean inflow speed of 2.53 m/s. Comparisons between the two series of computational results and experimental data from Jessup (1990) are presented in Sections 5.1 and 5.2.

5.1 Synthesising the steady inhomogeneous wake

The steady non-uniform axial wake field $V_x(\theta_w)$, at a particular radial position, incident on the propeller model is synthesised using the following expression for a Fourier series:

$$V_x(\theta_w)/V_s = \sum_{N=1}^{15}(A\cos N\theta_w + B\sin N\theta_w) \tag{1}$$

where N is the harmonic number, V_s is the volume mean velocity or advancing speed and θ_w is the angle in reference to the propeller axis. The values of coefficient A and B are available from Jessup (1990) and vary for different wake screens adopted in their experiment. It is important to highlight that the measured wake field is at a distance of 0.432R forward of propeller plane.

In the present work, the wake fields generated after the three-cycle, six-cycle, nine-cycle and twelve-cycle wake screens are shown. These synthesised velocity fields are given at different blade positions in Figure 3 and are used as input to the BEM and URANS computations. r/R is the radial location normalised to the radius of the propeller. The frequency content of the normalized volumetric mean wake for the various wake screens are shown in Figure 4. It should be noted that the magnitude of these have been scaled by a factor of 500. The largest wake harmonic in each case is correlated to the number of segments/cycles in the wake screen.

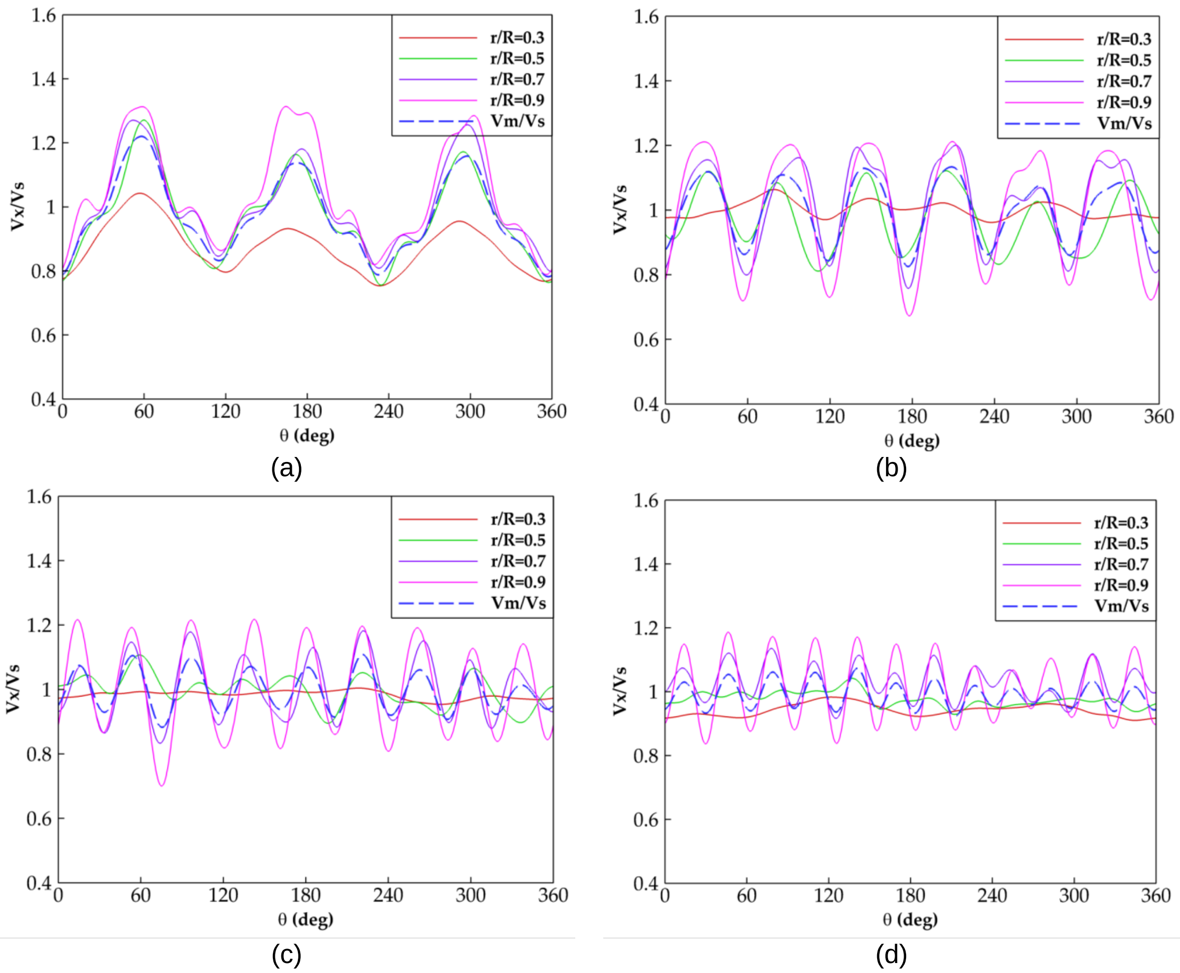


Figure 3. Synthesised wake profiles after (a) three-cycle wake screen, (b) six-cycle wake screen, (c) nine-cycle wake screen, and (d) twelve-cycle wake screen

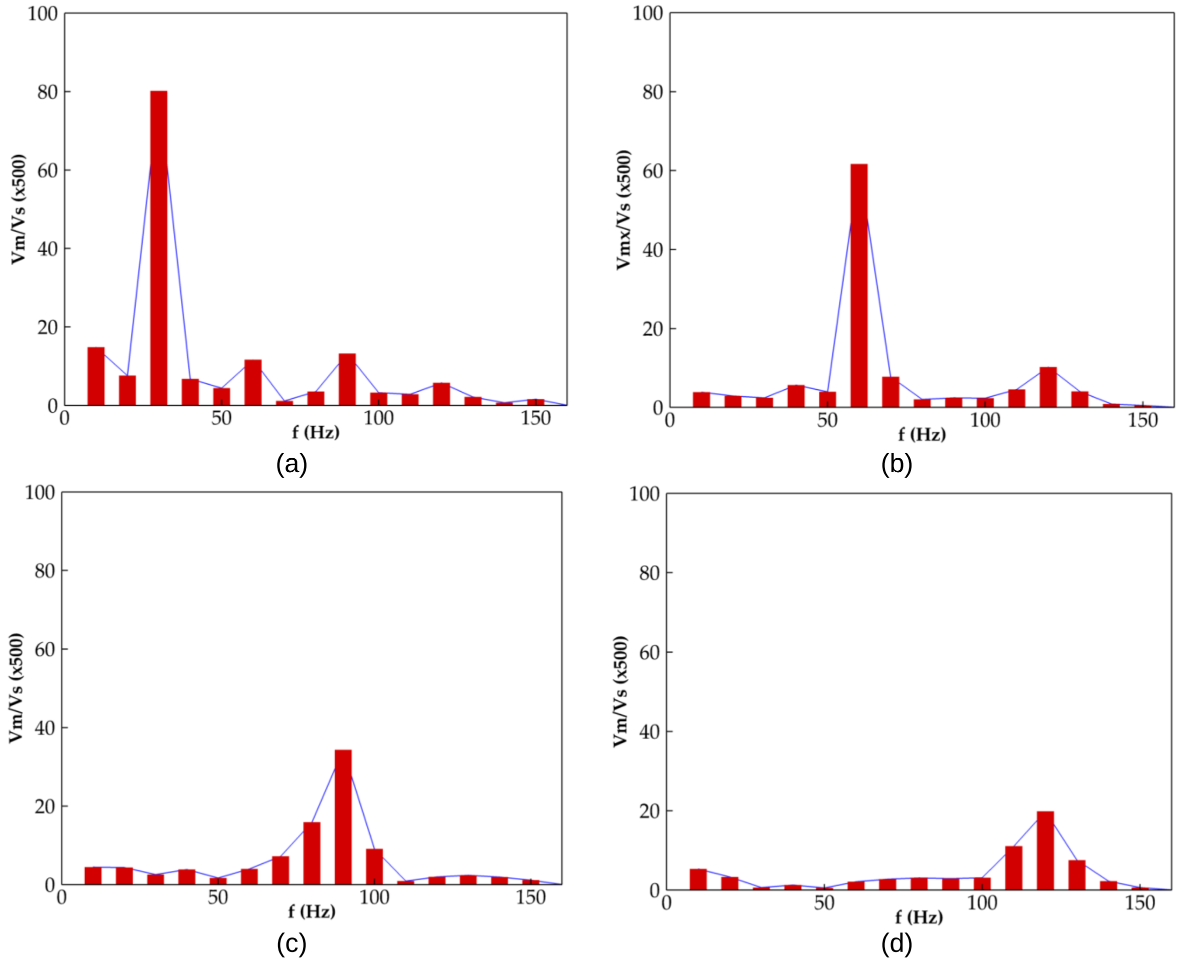


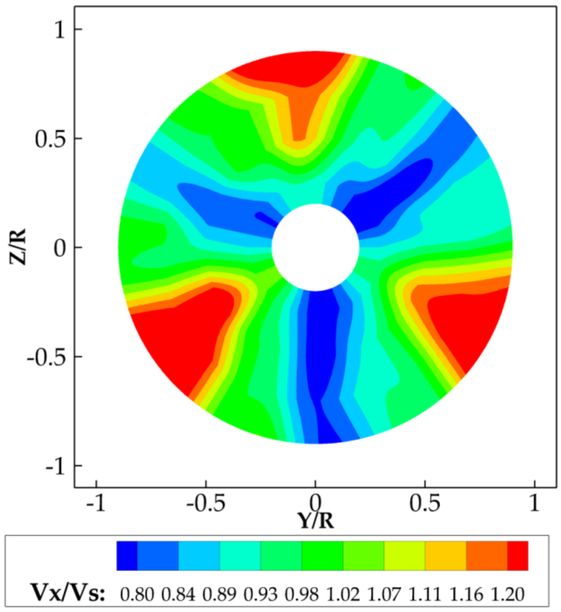
Figure 4. Frequency content of the volumetric mean wake field after (a) three-cycle wake screen, (b) six-cycle wake screen, (c) nine-cycle wake screen, and (d) twelve-cycle wake screen sampled by the rotating propeller.

5.2 BEM and URANS predictions of DTRC 4132 unsteady thrust

Implementing the above mentioned synthesised wake model in the BEM and URANS solvers, a comparison is first made of the wake field at the propeller plane produced by the three-cycle wake screen. It should be noted that the wake decay from the flow measuring plane (0.432R) to the propeller plane (0R) is not considered. According to Jessup (1990)'s laser dropper velocimetry measurements, this difference is around 2.2% of V_s and is constant over the blade radius. The consequence of not including wake decay in our computations is discussed in a later section.

Figure 5 shows the comparison of the 2D wake plane implemented in the BEM and URANS models. Visually, these two wake fields look very similar. The frequency content of the two wake fields, sampled by the rotating propeller, is also very similar (Figure 6). The harmonic content of the wakes are given in Table 1. It can be seen that the three-cycle wake screen produced a strong third order, which would have improved the signal-to-noise for the measurement at the blade-passing frequency. The BEM was found to accurately represent the synthesised wake field. For the URANS computation, reduction of the magnitude of high order harmonics (above 60 Hz or 6^{th} order) is observed. This is considered as a result of numerical dissipation due to the low-order discretization scheme adopted.

Having established an adequate approach to replicate the wake fields in the BEM and URANS computations, the predictions for the unsteady thrust and torque coefficients for the DTRC 4132 model are calculated and are presented in Figure 7 for one revolution of the blades. The BEM predictions are 7.45% and 6.33% greater than the URANS results for mean thrust and torque respectively. Figure 8 presents a comparison of after propeller wake field between URANS and BEM. The BEM captures the vortices generated by the propeller using prescribed vertical helices. However, it fails to capture the variation of velocity field due to propeller rotation. On the other hand, the URANS method is better in resolving the vortical structure after the propeller with better fidelity.



(a)

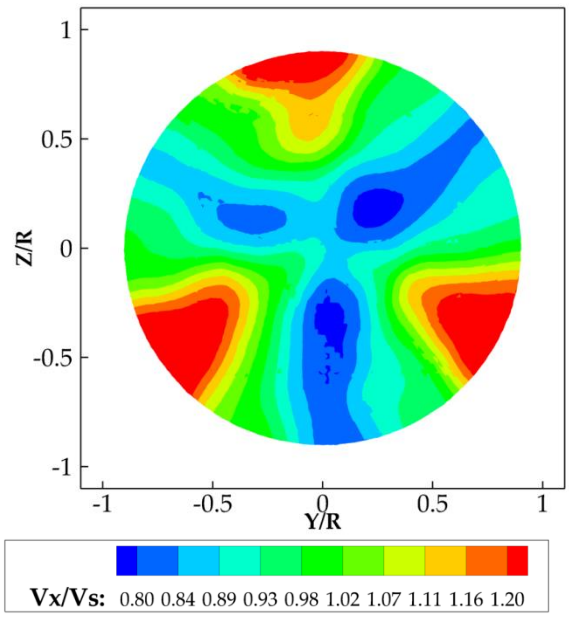


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Figure 5. Synthesised inhomogeneous wake field after the three-cycle wake screen in (a) BEM (b) URANS

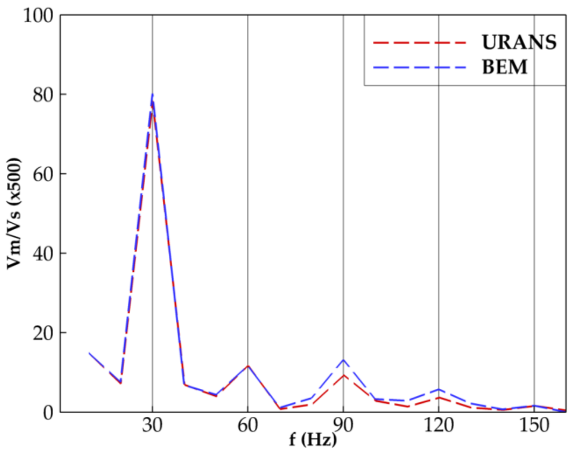
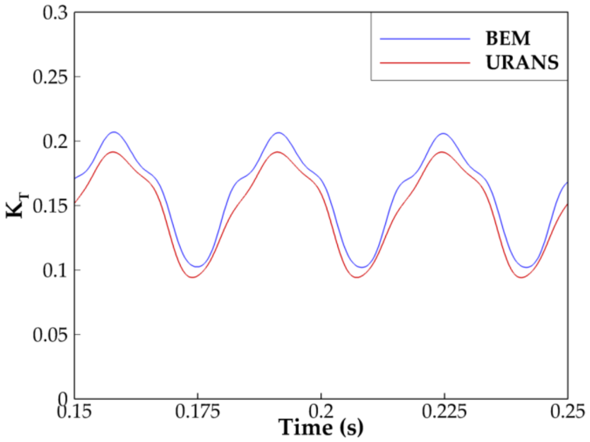


Figure 6. Frequency content of the propeller wake from the BEM and URANS computations for the three-cycle wake screen condition



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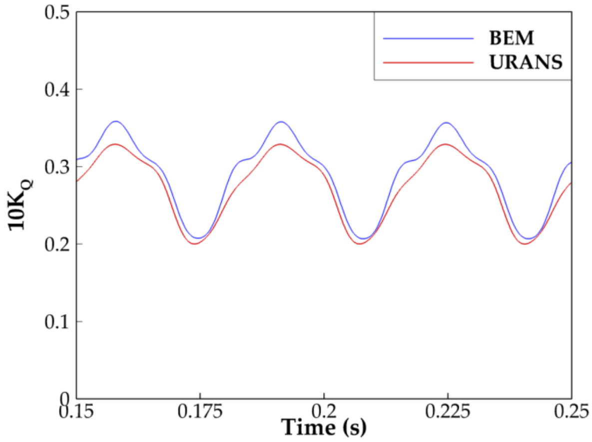


(b)

Figure 7. Unsteady (a) thrust and (b) torque coefficient prediction by BEM and URANS method for the three-cycle wake screen condition

Table 1. Quantitative comparison of harmonic contents modelled in BEM and URANS excluding wake decay

Harmonics order	**Frequency (Hz)**	**Harmonics Amplitudes (x500) m/s**	
		Input and BEM (PROCAL)	**URANS (Star-CCM+)**
1	10	14.87	14.89
2	20	7.61	7.20
3	30	80.19	78.31
4	40	6.80	6.88
5	50	4.41	4.01
6	60	11.68	11.74
7	70	1.13	0.75
8	80	3.53	1.94
9	90	13.21	9.32
10	100	3.29	2.86
11	110	2.87	1.43
12	120	5.75	3.69
13	130	2.18	1.14
14	140	0.70	0.58
15	150	1.63	1.61

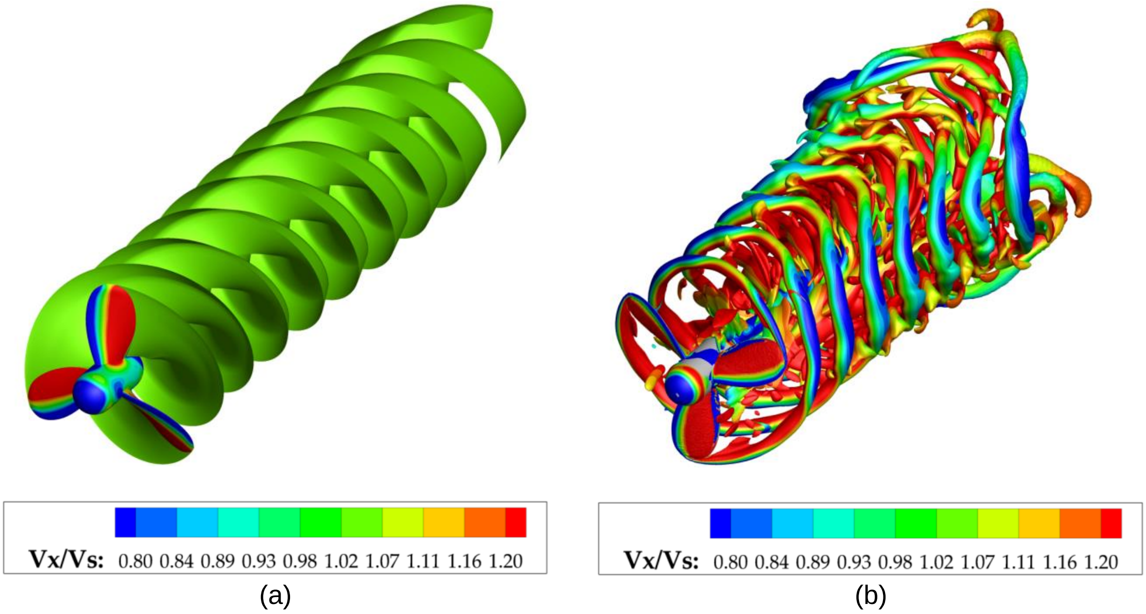
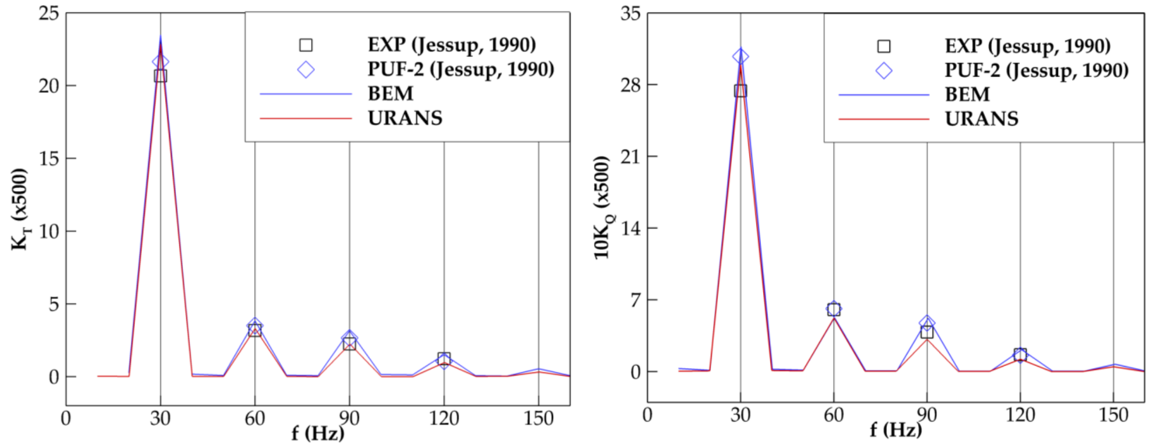


Figure 8. Velocity contour on the propeller blades and vertical structures from (a) BEM and (b) URANS for the three-cycle wake screen condition

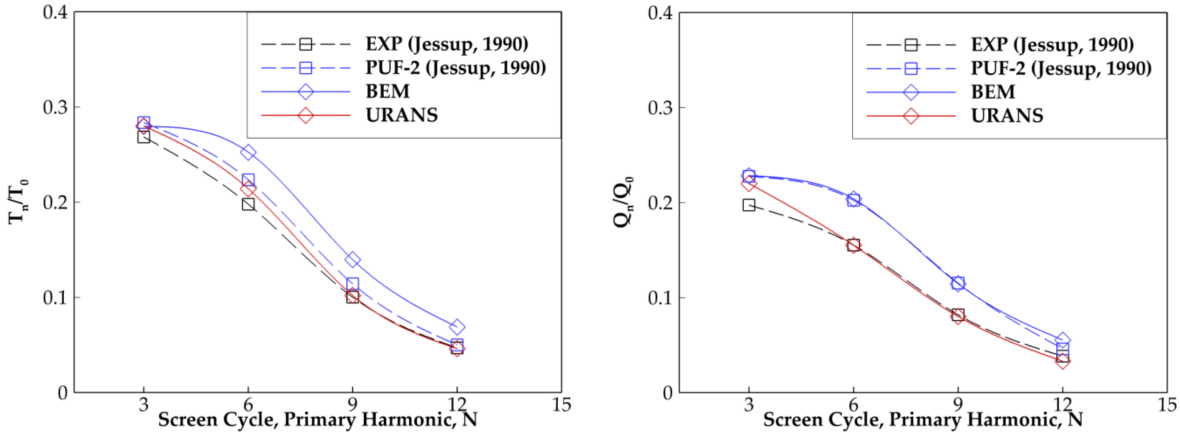
The harmonic content of the predictions of the unsteady thrust and torque coefficients for the three-cycle wake screen condition are shown in Figure 9. Large responses are observed at harmonics of the blade-passing frequency. Comparisons of the harmonic responses are made among BEM, URANS and results from literature in Figure 9. The average comparison error against experimental data is around 20.0% and 15.0% for the BEM and URANS computations respectively. In general, the correlations are satisfactory, especially for the BEM simulations considering they are much less computationally intensive where the computational time can be over 100 times less than that of the presented URANS cases. On the other hand, the URANS computations underestimate the magnitude of high order harmonic contents (above 60 Hz or 6^{th} order). This is likely due to numerical dissipation of wake velocities in the inflow as previously explained.

Apart from the three-cycle wake screen case, computations are also carried out for DTRC 4132 after the six-cycle, nine-cycle and twelve-cycle wake screens. The non-dimensionlised primary harmonics of the unsteady thrust and torque are presented in Figure 10. The general correlations among BEM, URANS and the results from the literature are reasonable, the comparison errors are tabulated in Table 2. The URANS computations predict the primary harmonics of the propeller responses with excellent accuracy when compared against the experimental results. The presented PROCAL simulations over-predict the primary harmonics. This is most likely due to the absence of modelling wake decay and the propeller influence on the incoming nominal wake. Referring to Jessup (1990), this could lead to 12.0% or more over-estimation of the wake harmonic magnitudes at the propeller plane. The reduced accuracy is balanced against the reduced computational cost.



(a) (b)

Figure 9. Harmonics within the BEM and URANS computed unsteady (a) thrust and (b) torque of DTRC 4132 for the three-cycle wake screen condition



(a) (b)

Figure 10. Comparison between primary (a) thrust and (b) torque harmonics captured for DTRC 4132 after different wake screens

Table 2. Quantitate comparison of thrust and torque primary harmonics after different wake screens

T_n/T_0 Primary Harmonic	EXP	PUF	PROCAL	E(%)	URANS	E(%)
3	0.268	0.284	0.280	4.10%	0.280	4.10%
6	0.198	0.223	0.252	27.6%	0.214	7.60%
9	0.100	0.114	0.140	39.5%	0.102	1.90%
12	0.047	0.050	0.069	47.0%	0.046	-1.70%
Q_n/Q_0 Primary Harmonic	EXP	PUF	PROCAL	E(%)	URANS	E(%)
3	0.197	0.228	0.228	15.7%	0.220	10.3%
6	0.155	0.202	0.204	31.4%	0.155	-
9	0.082	0.115	0.114	39.9%	0.080	-2.30%
12	0.038	0.046	0.055	44.1%	0.033	-16.1 %

6 CONCLUSIONS

The present work focuses on unsteady thrust and torque calculations adopting BEM and URANS methods. The numerical framework has been tested and validated against experimental measurements of a model propeller at the David Taylor Research Centre. The computed results provide a good agreement with experimental data. This agreement demonstrates the feasibility of the proposed numerical procedure (using both BEM and URANS methods) for evaluating unsteady propeller performance. Discrepancy in high order wake harmonics observed in the URANS computation is most likely caused by the low order grid discretisation scheme adopted in the simulations. In comparison to the BEM, the URANS computations are able to capture higher flow resolution, especially behind the propeller. In general, the BEM method is suitable for rapid prediction of propeller openwater and unsteady performance. In contrast, the URANS method can capture the viscous effects and more detailed flow physics at a higher computational cost.

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