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WAVE-CURRENT INTERACTIONS IN MARINE CURRENT TURBINES

N. Barltrop[1], A. Grant[2], K. S. Varyani[1], X. P. Pham[1]

Abstract

The influence of waves on the dynamic properties of bending moments at the root of blades of tidal stream vertical axis rotors is reported. Blade theory for wind turbine is combined with linear wavw theory and used to analyse this influence. Experiments were carried out to validate the simulation and the comparison shows the usefulness of the theory in predicting thef bending moments. It can be concluded that in steep waves, due to high non-linearities, linear theory may under-estimate the dynamic behaviour of bending moments. However, in long waves, linear theory works very well.. Bending moments at roots of rotor blades fluctuate with significant amplitudes which willy be important for design of tidal stream rotosr.

KEYWORDS: Tidal stream, current turbine, wave-current interaction, linear blade theory.

1. Introduction

Horizontal-axis wind turbines have achieved a dominant position in the market, and for tidal streams, the arguments in their favour are even more compelling [2,7,8]. Vertical-axis rotors are subject to cyclic loads even in uniform flow, and in tidal streams these may threaten structural integrity in all but small machines. For horizontal-axis machines, relatively low levels of turbulence minimise stochastic structural loads, but deterministic cyclic loading (from velocity shear and yaw error effects) may be comparatively large. Reversing gravity loads, which are very important for horizontal-axis wind turbines, should be much less important because buoyancy can be used to balance the weight. The effect of waves is likely to be important. Cavitation will probably be insignificant unless the rated current speed approaches 2m/sec. (DO YOU HAVE A SPECIFIC REFERENCE e.g. 3?)

It is desirable to locate rotors near the free surface to make maximum use of the available cross-sectional area and to intercept the highest stream velocities. The effect of waves will therefore be an important consideration in determining limits for device location and rotor operational envelopes. A substantial body of knowledge on wave loading already exists, but not in this context. There is an urgent need for further research to determine the response and practical limitations posed by the associated phenomena.

The main objectives of this study were firstly to assess the limits imposed by waves on the performance of tidal stream rotors, to investigate ways in which these limits might be relaxed by refinements of rotor design and the control of operating conditions, and to confirm that the concept is structurally and mechanically possible. In this paper, the authors specifically look into the dynamic property of bending moments acting about the roots of tidal stream rotors. Experiments are carried out and data are used to validate simulation results based on a mathematical model, i.e. linear wave and blade element theory. It is noticed that in long waves, linear blade theory predicts very well the dynamic response of these bending moments. However, in steep waves, due to the presence of high non-linearities, linear wave theory under-estimate these responses.

2. Theory

2.1. Torque, Thrust and Bending Moments Induced by Stream Flow without Waves

The torque, thrust and bending moments induced by stream flow are calculated based on linear blade theory as presented in [1]. In the sea, tidal stream rotors are also under the influence of waves. The effects are briefed in section 2.2.

[1] Department of Naval Architecture and Marine Engineering, Universities of Glasgow and Strathclyde, Scotland, UK.
[2] Department of Mechanical Engineering, University of Strathclyde, Scotland, UK.

2.2 The Impacts of Waves on the Rotor Performance

The possible problems waves can cause to tidal stream water turbine are mainly embodied in change of flow velocity field around the rotor and pressure field as well. The former change will affect dynamical circumstances of the rotor. The later and former may trigger or depress the occurrence of cavitation.

The effect of waves on the rotor depends on magnitude and direction of flow velocity that is induced by waves. Wave velocity u will increase U_∞ if they are in the same direction or decrease U_∞ if they are not in the same direction. Wave velocity w will change the flow incidence angle and hence modify the lift and drag forces. The waves impacts on the rotor are periodical if the waves are regular waves. The wave effects on the rotor are also reduced when the rotor is positioned at greater water depth because the wave kinematics decrease with depth.

The waves effect on the rotor can be ignored if waves flow is small compared with tidal currents. The waves are important if the waves flow speeds are a significant proportion of or are greater than those of the tidal current This generally happens in extreme weather.

3. Rotor design and manufacture

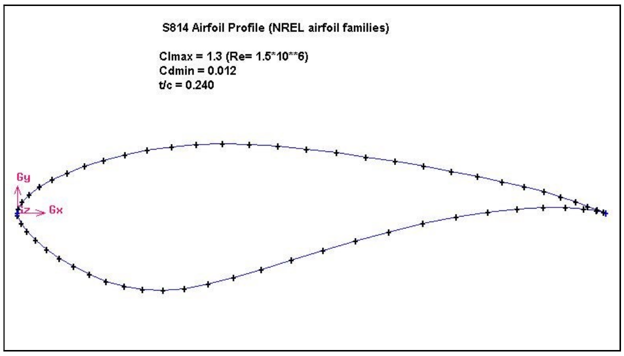
For the project, three rotor designs were produced, with progressive refinement based on results of testing. The largest practical rotor diameter was used to minimise scale effects.

The first model rotor was essentially a wind turbine configuration, with a slight increase in blade chord and thickness for structural strength. The aerofoil profile (NREL S814) was chosen for its good performance at low Reynolds numbers, and its tolerance of surface imperfections. The rotor has three blades, and an overall diameter of 350 mm. At the root, the blades taper down to a circular section, to facilitate the fitting of strain gauges.

The second rotor also uses 3 blades. Its diameter is increased to 400 mm to increase torque and thrust, and blade chord is increased in an attempt to combat the cavitation observed on the first rotor. The same aerofoil profile is used, but the configuration at the blade root is changed: the blades merges into the hub without taper, and strain gauges are not fitted. However, blade angles can be adjusted over a range of about 15 degrees.

In the third rotor, an attempt is made to produce a lightly loaded, high-solidity turbine with good resistance to cavitation and the effects of marine growth. The blade number, diameter and hub design are the same as for the second rotor. However, a higher-lift aerofoil is used (NREL WA3-02) and blade chord is further increased.

In this paper, analysis focuses on the first model rotor. The S814 is one of the series developed by NREL, USA for wind turbines. One particularly important characteristic of the S814 is the minimal sensitivity of its maximum lift coefficient to roughness effects, a critical property for stall-regulated wind turbines. The aerofoil has a very low drag coefficient and is also not sensitive to change of angle of attack at around stalling angle. The profile shape is illustrated in Figure 1a; specific technical features of the NREL S814 are detailed in [9]. The length of the blade used for rotor 1 was 150 mm with maximum chord of 44 mm. Nominal chord length at the tip was 20 mm, but the tip was rounded to reduce shed vortices. Chord and pitch distributions are shown in Figure 1b; an increase of about 5° from the nominal pitch angle was found to give best performance.



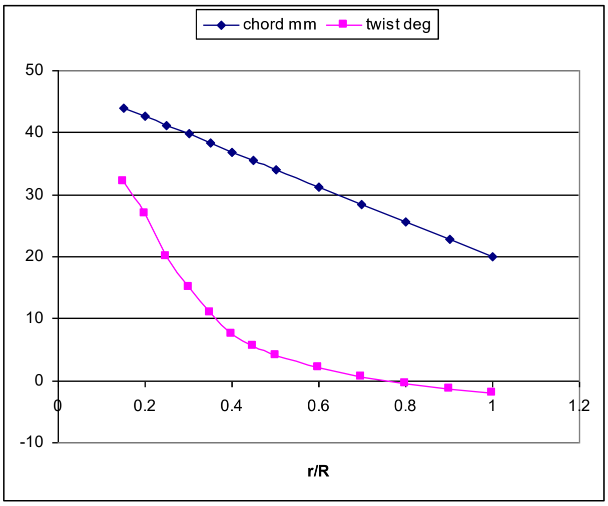


Figure 1a (above): Sectional profile of NREL S814 blade.

Figure 1b (right): Chord and pitch distribution along blade.

4. Experiment

Rotor performance (shaft torque, axial thrust and blade bending moments) was investigated in the Universities of Glasgow and Strathclyde 77 x 4.6 x 2.4m deep wave/towing tank. A two dimensional aerofoil section 'boat' made of glass fibre (Figure 2a) was used to house the motor, gearing and torque and thrust transducers (Figure 2b). The rotor was supported in front of the boat which itself was cantilevered down from the towing tank carriage.

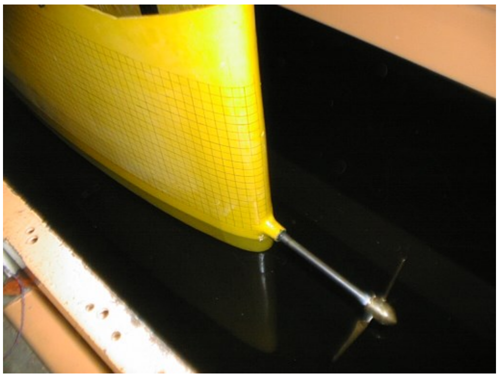


Figure 2a: Overall arrangement for the Glasgow tests

Figure 2b: Assembled thrust and torque transducers.

Strain gauges were used for the measurement of bending moments about the root of the blade in the case of rotor I. The strain gauges were made water tight using M-Line J-Coat. The shaft to which the rotor is attached was hollow. The cables of the strain gauges were accommodated through the inside of the shaft and the signals were transferred through slip rings. Provision was made for amplifying the signals before passing them through the sliprings but slipring tests and the final results demonstrated remarkably good performance without the need for amplifiers on the rotating shaft. The shaft was supported by linear bearings to allow rotation and axial movement. To allow precise speed control a motor/generator with gearbox and tachometer was used with closed loop control. The motor/generator could provide power (at low current speeds) or absorb power (at the higher current speeds). The shaft extended in front of the boat bow sufficiently for minimal interference between the boat and the rotor. A grease box prevented the entry of water around the shaft. The boat was clamped and bolted by steel beams to a rail mounted moving carriage over the tank. The carriage moved the boat along the tank at steady speed to simulate tidal currents. A flap type wave generator produced waves of a known wavelength and period. These are of course encountered at a higher frequency than the generated wave frequency when the rotor is moving towards the waves. (Note that, within the limitations of potential flow theory the model was a precise Froude scaled representation of the real case of a fixed rotor encountering waves of the generated length on the current).

Experiments were carried out to test the performance of the tidal stream rotors for different conditions. The most important parameters were the dynamic properties of the rotor under different wave-heights, wave frequencies and current speeds. Only the first rotor was strain gauged because the requirements for high stresses in the root under the towing test conditions were not compatible with the need to load the rotor more highly to obtain a high Reynolds number in the cavitation tests. The experiments covered a range of towing speeds (0.0 – 1.6 m/s), wave heights and frequencies, and depths of immersion. The aims were to investigate the magnitude and variation of thrust, torque and bending moment at the root of the blade in the case of rotor I and thrust, torque and rpm in the case of rotor II. The results were then compared with calculations. This paper presents the dynamic property of bending moments acting about the roots of blades of rotor I in waves of 150 mm height (model scale) and two frequencies, i.e. 0.5 Hz and 1.0 Hz.

5. Validation

5.1 Long waves of 150 mm height and 0.5 Hz frequency

Figures 3a,b and 3c,d show dynamic properties of bending moments about roots of rotor blades in waves of 0.5Hz frequency and 150mm height at current speeds of 0.3m/s and 1.0m/s (at model scale), respectively. The maximum wave slope is approximately 8 degrees. As can be seen, in long waves, blade element with linear wave theory can predict the dynamic response of both out-of-plane and in-plane bending moments.

5.2. Steep waves of 150 mm height and 1.0 Hz frequency

Figures 4a,b and 4c,d show the dynamic properties of bending moments about roots of rotor blades in steep waves of 1.0Hz frequency and 150mm height at current speeds of 0.3m/s and 1.0m/s, respectively. The maximum wave slope is approximately 29.5 degrees. It can be seen that blade element with linear wave theory can predict relatively well the fluctuation of in-plane bending moment (My) both in low and high current speed ranges. However, for out-of-plane bending moment, the fluctuation predicted is less than that measured. This highlights the significance of high non-linearities associated with steep waves. Figures 4a and 4c show that the amplitude of bending moment variation recorded during the test is of order of two times that predicted.

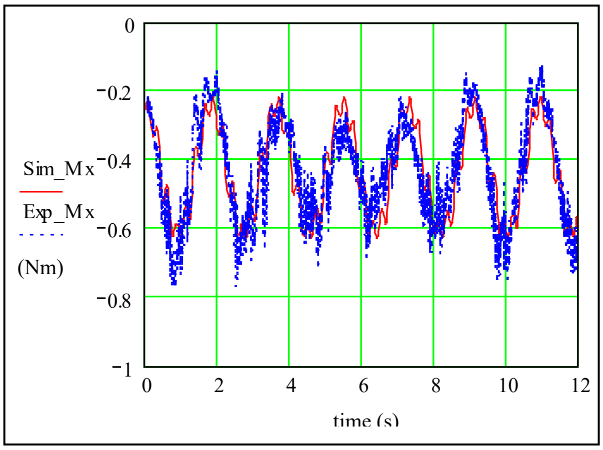


Figure 3a: Out of-plane bending moment in waves of 150 mm height and 0.5 Hz frequency and current speed of 0.3 m/s at model scale.

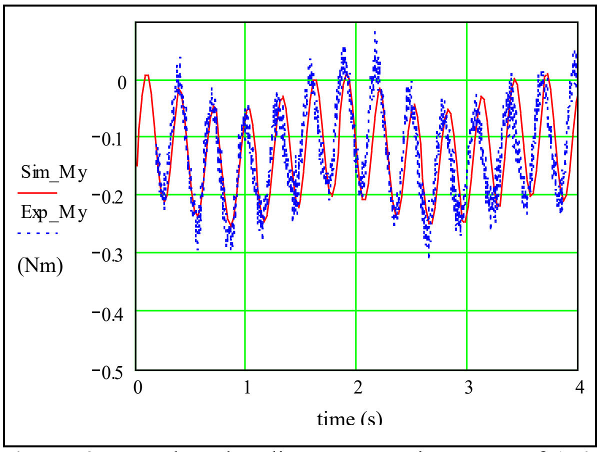


Figure 3b: In-plane bending moment in waves of 150 mm height and 0.5 Hz frequency and current speed of 0.3 m/s at model scale.

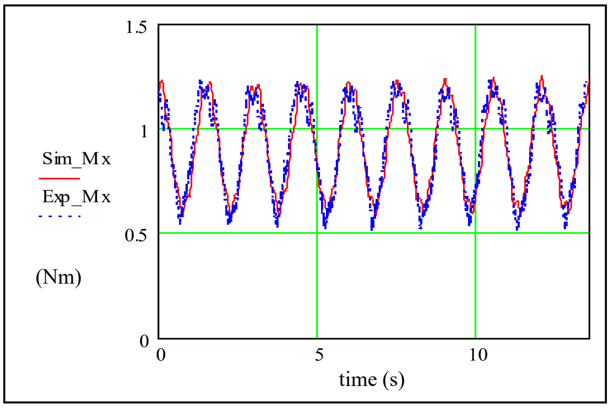


Figure 3c: Out of-plane bending moment in waves of 150 mm height and 0.5 Hz frequency and current speed of 1.0 m/s at model scale.

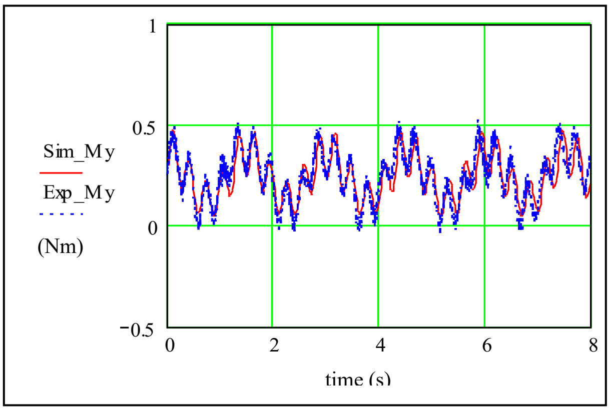


Figure 3d: In-plane bending moment in waves of 150 mm height and 0.5 Hz frequency and current speed of 1.0 m/s at model scale.

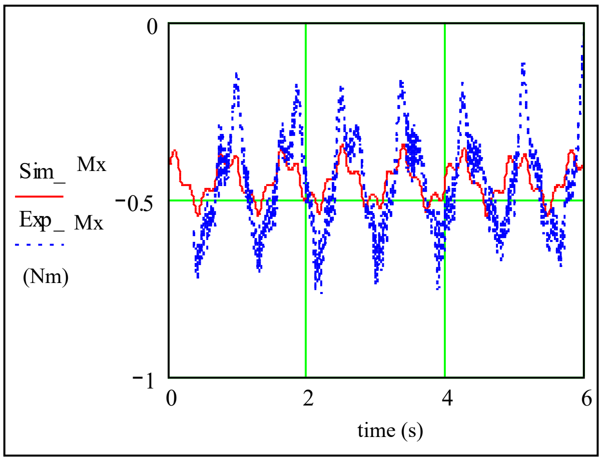


Figure 4a: Out of-plane bending moment in waves of 150 mm height and 1.0 Hz frequency and current speed of 0.3 m/s at model scale.

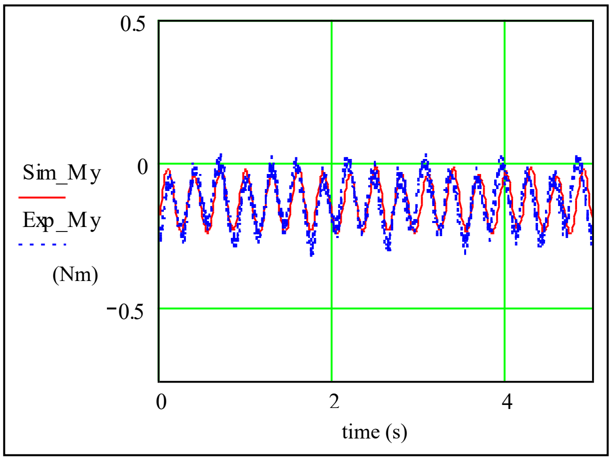


Figure 4b: In plane bending moment in waves of 150 mm height and 1.0 Hz frequency and current speed of 0.3 m/s at model scale.

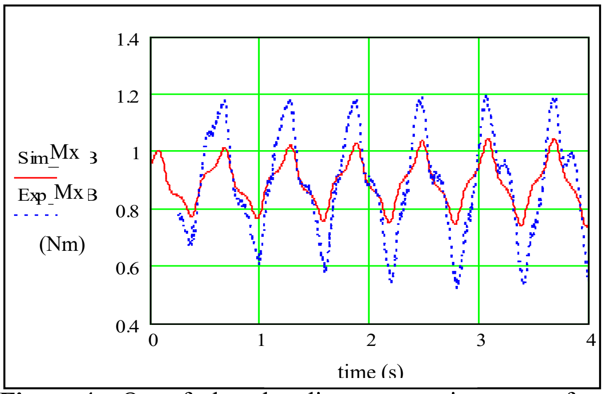


Figure 4c: Out of-plane bending moment in waves of 150 mm height and 1.0 Hz frequency and current speed of 1.0 m/s at model scale.

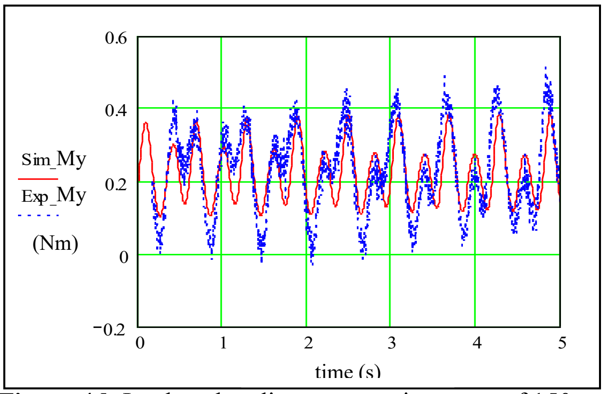


Figure 4d: In plane bending moment in waves of 150 mm height and 1.0 Hz frequency and current speed of 1.0 m/s at model scale.

5.3 General discussion

A general observation on the dynamic characteristics of bending moments at the root of a rotor blade is that it sees that the main oscillation at the encountered wave frequency. The rotor frequency shows in the smaller superimposed oscillation in the in-plane bending moment and is mainly the self-weight effect. The numerical model is clearly giving reasonable results especially in the middle of the short segment of time history where the numerical wave has been synchronised with the measured wave (Figure 4b). (It is interesting that in these relatively steep waves the difference between the linear wave length and the non-linear wave length results in a loss of synchronisation between rotor position and wave phase in just a few wave cycles. This is significant when comparing predictions with measurements but is not important for design.)

6. Case study using linear blade simulation model

6.1 Effects of flow incidence angle

Of theoretical interest is the effect of the vertical component of wave particle velocity which mainly affects the flow incidence angle onto the aerofoil (Figure 5). The numerical calculations show a small effect at the main peaks of the wave loads (because these correspond to peaks in the horizontal velocity where the vertical wave velocity is zero). Also numerically it has been possible to consider cases where wave and current are in different directions. Figure 6 shows firstly a case with the current and wave normal to the rotor plane and secondly a case with the wave direction at 45 degrees to the rotor plane. The highest total and fluctuating wave loads occur with the wave propagating normal to the rotor plane.

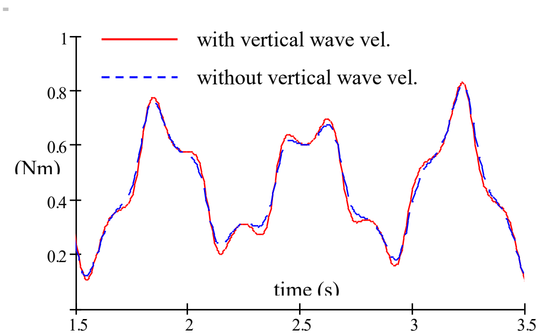


Figure 5. Out of plane bending moment with and without vertical wave velocity.

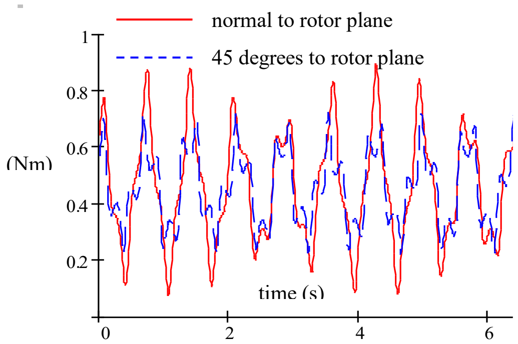


Figure 6. Out of plane bending moment corresponding to wave normal to rotor plane and wave at 45 degrees to rotor plane.

6.2 Effects of waves on bending moments

Figure 7a,b show the influence of waves on out-of-plane and in-plane bending moments, respectively. It appears that within practical wave frequency range, steeper waves impose less bending moments in both directions about the roots of rotor blade. In steady water condition, out-of-plane bending moment is steady but in-plane bending moment varies harmonically with frequency of rotor due to the gravity bending moment component. The amplitude of out-of-plane bending moment fluctuation is more than halved as wave frequency increases from 0.5Hz to 1.0Hz. In steep waves, Figure 7b shows that the fluctuation of bending moment (My) is mainly due to the gravity component as the in-plane bending moment in steep waves is more or less equivalent to that in steady water condition. The fluctuation of My is significant in long waves as seen in Figure 7b.

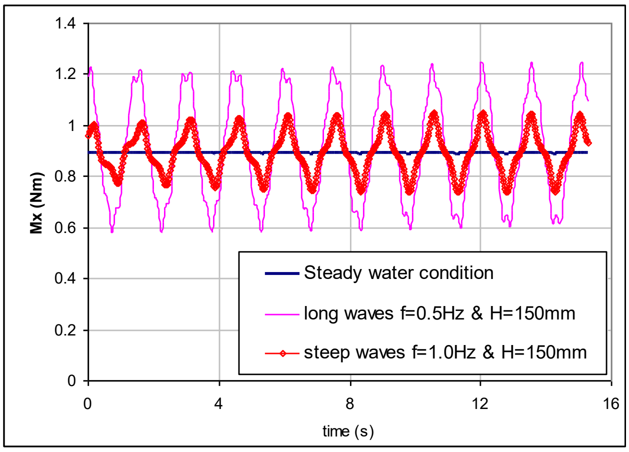


Figure 7a. Out-of-plane bending moment in different conditions.

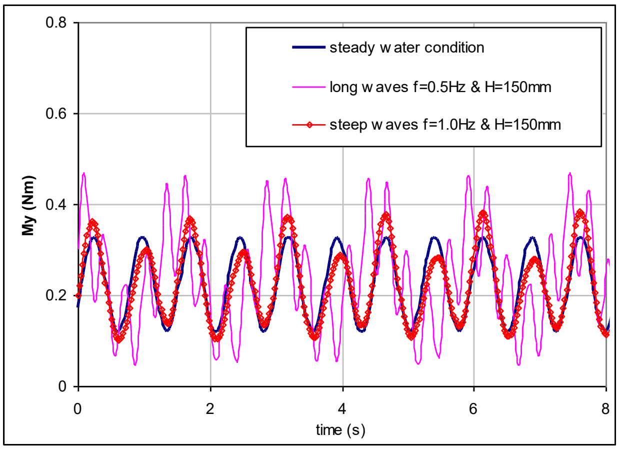


Figure 7b. In-plane bending moment in different conditions.

6.3 Full-scale case study

Figure 8 presents simulation results of bending moments acting on a hypothetic full-scale rotor of 20m diameter rotating at 7 rpm in waves of 3.0m height and 10.0s period on top of current speed of 2.0m/s. The tip-speed-ratio is then equivalent to 3.6, which corresponds to the current speed of 1.0m/s at model scale. The water depth is set at 40.0m and the clearance between still water surface and highest point of blade tip is 10.0m. The hub radius of the rotor is 1.4m and root radius is 0.3m. As the result, the mean thrust acting on the rotor is 0.124MN and mean torque is 0.142MNm. The corresponding mean power generated is 0.104MW. As can be seen in Figure 8, the variation of bending moments acting about the root of rotor blades is very significant. The range of fluctuation of out-of-plane bending moment is approximately 0.78MNm about the mean value of 0.38MNm. The in-plane bending moment, is smaller but its dynamic property is equally significant with range of fluctuation approximately 0.24MNm about the mean of about 0.1MNm.

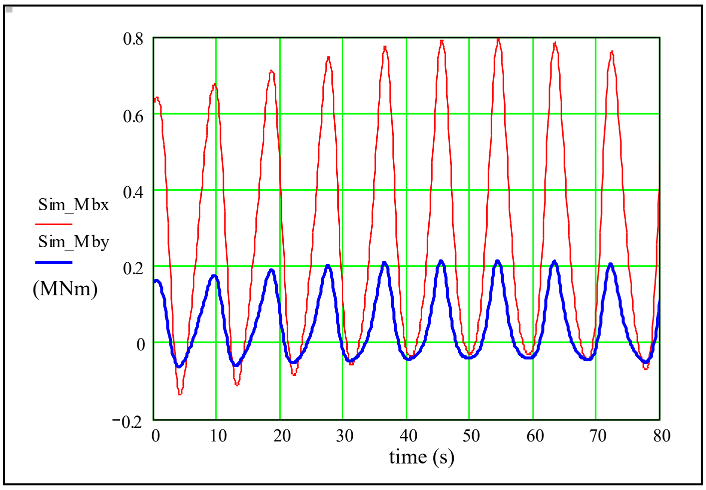


Figure 8. Bending moments about root of blades of a hypothetic full-scale rotor.

7. Conclusion

The paper has briefly introduced linear blade theory which includes wave effects in analysing dynamic properties of bending moments acting at roots of rotor blades of a tidal stream rotor. Experiments were also described in the validation of simulation results. Based on what has been obtained, the following conclusions are drawn:

- In-plane and out-of-plane bending moments both fluctuate significantly and this is worse in steep waves. In long wave condition, the fluctuation of these bending moments can be predicted well by linear wave thory with blade element theory. However, in steep waves, due possibly to high non-linearities involved, the out-of-plane bending moment fluctuates significantly more than that predicted (by about two times in this case).
- Waves approaching along the normal to the rotor plane lead to the largest bending moments on the blades.
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