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Abstract—**This paper describes a recent study to investigate the applicability of a horizontal-axis wind turbine (HAWT) structural dynamics and unsteady aerodynamics analysis program (FAST and AeroDyn respectively) to modeling the forces on marine hydrokinetic (MHK) turbines. This paper summarizes the added mass model that has been added to AeroDyn. The added mass model only includes flow acceleration perpendicular to the rotor disc, and ignores added mass forces caused by blade deflection. A model of the National Renewable Energy Laboratory's (NREL) Unsteady Aerodynamics Experiment (UAE) Phase VI wind turbine was analyzed using FAST and AeroDyn with sea water conditions and the new added mass model. The results of this analysis exhibited a 3.6% change in thrust for a rapid pitch case and a slight change in amplitude and phase of thrust for a case with 30° of yaw.**

Keywords-added mass; unsteady; wind turbine; water turbine; marine hydrokinetic, AeroDyn, FAST

I. INTRODUCTION

Marine hydrokinetic (MHK) turbines have the potential to capture the energy in waves, tides, ocean currents, rivers and streams. MHK turbine design and analysis requires accurate modeling of the fluid dynamic and structural dynamic forces on the rotor blades. The more accurately these forces can be modeled, the more efficiently MHK turbines can be designed. More efficient MHK turbine designs help to reduce the cost of marine energy and make it more competitive with other forms of energy production. Recent studies of MHK devices [1-4] mainly focus on quasi-unsteady modeling techniques. Accurately modeling the unsteady effect of the rotor fluid dynamics is still a challenge.

The National Renewable Energy Laboratory (NREL) is conducting several studies of MHK turbines using different methods. For example, Lawson et al. [5] used RANS to model the unsteady effect of the turbine. Churchfield et al. [6] used a hybrid approach combining the LES-actuator line to study an MHK turbine array. Although these approaches presented reasonable results, the computational costs were too high. NREL is currently investigating a more cost-effective way to simulate MHK turbines.

Because MHK turbines are very similar to wind turbines, researchers at NREL decided to modify the lab's wind code, FAST, to study MHK turbines. FAST has been used to model the structural dynamics of wind turbines for many years. In FAST, AeroDyn is used to model unsteady aerodynamic effects via the General Dynamic Wake (GDW) theory. The two programs work together to provide full unsteady aerodynamic and structural dynamic analysis capabilities for wind turbines. To model the unsteady fluid dynamics of horizontal-axis MHK turbines, the research presented in this paper focuses on the implementation of an added mass model in AeroDyn.

An added mass force is created when the mass of fluid surrounding a body is accelerated. This force is not used for large bodies moving relatively quickly in air, such as a wind turbine. The added mass force needs to be added to the fluid dynamics models for MHK turbine blades because water is approximately 700 times more dense than air. This paper includes descriptions of the added mass effect, the GDW theory used in AeroDyn, and how this theory was modified to model the added mass effect for MHK turbines. The paper also describes how the added mass effect influences MHK rotor blade forces.

II. GENERAL DYNAMIC WAKE THEORY OVERVIEW

AeroDyn uses the GDW theory to model the time-dependent relationship between changes in the rotor forces and corresponding changes in the rotor induced velocity distribution. The GDW theory used in AeroDyn was developed by Suzuki and Hanson for wind turbine analysis by modifying the Pitt and Peters model developed for helicopters in forward flight [7,8]. Suzuki showed that empirically based correction factors could be applied to the GDW model for wind turbine applications [9].

For this research, the GDW model was used to find the flow field accelerations necessary to compute the added mass forces. The GDW model does not account for added mass forces; hence the need for a separate added mass model.

The development of the GDW model for wind turbines is based on the work by Suzuki [10]. An overview of the theory and implementation of this model in AeroDyn can be found in the AeroDyn Theory Manual [11].

III. Added mass model with GDW

This section describes the implementation of the added mass model in AeroDyn. The acceleration can be divided into two parts: the acceleration of the flow and the acceleration of the body (turbine blade for this application). Only the acceleration of the flow was considered in this study, as the acceleration of the blade would need to be passed from the structural dynamic analysis program FAST to the fluid dynamic analysis program AeroDyn. Passing data on blade accelerations from FAST to AeroDyn was beyond the scope of this research, because such an operation would cause numerical stability issues resulting from the interaction between the two programs.

The acceleration of the flow was computed from the time rate of change of the axial induction factor, which was computed from the GDW solution found by AeroDyn. The body and flow accelerations were multiplied by the added mass of a blade element to compute the added mass force of that element. The added mass was assumed to equal the mass of a cylinder of fluid with the diameter equal to the average chord length of each blade element, times the radial span of each blade element. This study only examines the effect of the acceleration of the axial flow through the rotor disc.

The added mass force is distinct from the forces computed in the GDW or the Blade Element Momentum (BEM) theories. These theories are based on solving for the balance of force and pressure for GDW and momentum for BEM at a steady flow condition. The GDW theory has a term called apparent mass that is used to capture the time dependent change in force and pressure on a rotor caused by the dynamic response of the rotor wake. The apparent mass term in GDW theory does not account for the force required to accelerate the fluid from one time step to the next, which is the added mass force. As mentioned earlier, this force is typically very low for wind turbines, but can be significant for water turbines.

Derivation of Added Mass Force Equation

The following derivation assumes an incompressible fluid with density ρ, no surface or wave interaction, and constant wind/water flow speed (although the flow through the rotor disc may change). Equation 1 shows the kinetic energy of the axial flow through the disc [8].

$$T = \frac{\rho}{2}\int_V (u-W)(u-W)dV \qquad (1)$$

Where V is entire domain or volume of fluid, W is the axial component of wind speed, or far-field fluid velocity, and u is the axial component of fluid velocity (which is a function of location in the volume). If the flow is such that when the local mean flow speed (U) changes, the fluid velocity at each point in the fluid (u) changes in direct proportion to U, then (1) can be changed to (2). In (2), I represents the integral of the change in local velocity relative to the local mean flow speed (U). This assumption is valid for potential flow, but may be violated for stall dominated and vortex shedding flows [8].

$$T = \frac{\rho * I}{2} * U^2 \;\; where \;\; I = \int_V \frac{(u-W)}{U}\frac{(u-W)}{U}dV \qquad (2)$$

Force can be related to the time rate of change of the kinetic energy and to the time rate of change of velocity (acceleration):

$$F = -\frac{1}{U}\frac{dT}{dt} = -\rho\, I\frac{d}{dt}(U-W) \qquad (3)$$

A new added mass term (m_a) can be used to replace the "$\rho * I$" term. If the wind speed is assumed constant, it can be removed from the equation, because the time rate of change of W would go to zero. If the wind speed is accelerating, then a different solution is necessary, which can be found in [8]. The work summarized in this paper assumed constant wind speed. An added mass model that accounts for accelerating wind speed will be examined in a future study. The resulting equation that assumes constant wind speed can be seen in (4).

$$F_a = -m_a\left(\frac{dU}{dt}\right) \qquad (4)$$

Where F_a is the added mass force. For the application of a horizontal-axis MHK turbine, U is the flow speed through the rotor disc, so it will be replaced by a term U_d. The wind speed and flow through the rotor disc can be related by the axial induction factor (A), as shown in (5).

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$$A = 1 - \frac{U_d}{U_\infty} \quad \text{or} \quad U_d = U_\infty(1 - A) \qquad (5)$$

$$F_a = -m_a\left(\frac{dU}{dt}\right) = m_a\left(\frac{dA}{dt}\right) \qquad (6)$$

Where U is the flow through the rotor disc and is assumed to be constant across the disc. The flow-field acceleration was found by numerically differentiating the axial induction factor, resulting in (7).

$$\frac{dA}{dt} = (A - A_{PreviousTimestep})/\Delta t \qquad (7)$$

The added mass (m_a) was assumed to be that for a flat plate of infinite span, which is the equivalent mass of the area of a cylinder with its diameter equal to the length of the flat plate, in this case set equal to the airfoil chord length [8].

$$m_a = \pi * R^2 * \rho * length\_cylinder \qquad (8)$$

Where R is the radius of the cylinder or half-length of a flat plate. Using chord length, (8) is equivalent to:

$$m_a = \frac{1}{4}\pi * C^2 * \rho * length\_cylinder \qquad (9)$$

Once F_a has been calculated, it is added to the component of force normal to the rotor disc, because the flow acceleration (da/dt) is assumed to be normal to the rotor disc.

IV. Water Turbine Model Description

A model of the NREL unsteady aerodynamics experiment (UAE) phase VI wind turbine was analyzed using FAST and AeroDyn with sea water conditions and the new added mass model. The FAST Cert Test (Certification Test) is an automated procedure that runs a series of simulations using different turbine models that operate with various features enabled under a variety of wind conditions. This automated certification procedure can be used to compare the effects of alterations to FAST, including the effects of new fluid dynamic models [12]. The FAST input file used in the research for this paper is based on Test 10 of the FAST Cert Test cases, which is the UAE VI upwind turbine test case [12-14]. For more information about versions of FAST and AeroDyn, see the Appendix of this paper.

The UAE wind turbine rotor was selected for analysis because there is already a significant amount of data available for this turbine. This test case does not represent an optimum water turbine, but rather a wind turbine operating in water. The original blade planform and airfoils of the UAE Test 10 case were used in the present model, which are labeled "Mod_S809" in the Cert Test files.

The rotational speed of the water turbine test case was reduced from 71.9 RPM for the original wind turbine model to 21.9 rotations per minute (RPM). The rotational speed was reduced to account for the lower flow speed of the water turbine; this adjustment approximately maintains the range of tip speed ratios. The density and kinematic viscosity of sea water was used in the water turbine model, which is changed in the "Test10_*.ipt" AeroDyn aerodynamic parameters input file.

Sea water conditions:

density: 1030.0 (kg/m^3)

kinematic viscosity: 1.17e-6 (m^2/s)speed of sound: 1500 (m/s)

- Flow speeds in the range of 1 m/s to 8 m/s
- Axisymmetric inflow (aka equil. inflow)
- Rigid tower and blades
- No teeter
- No generator model
- No dynamic stall modeling

V. Results

The water turbine was analyzed using the water turbine version of AeroDyn to illustrate the effect of the added mass model. The results from two cases are presented: a step pitch change and a rotor operating in yaw.

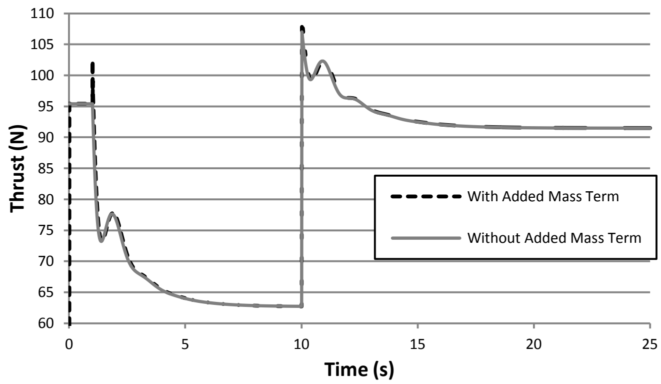

Fig. 1. Thrust force of the rotor versus time. At 10 seconds the rotor blade was rapidly pitched, causing a dynamic response. The initial transience before 5 seconds is due to initialization of the model and is not physical.

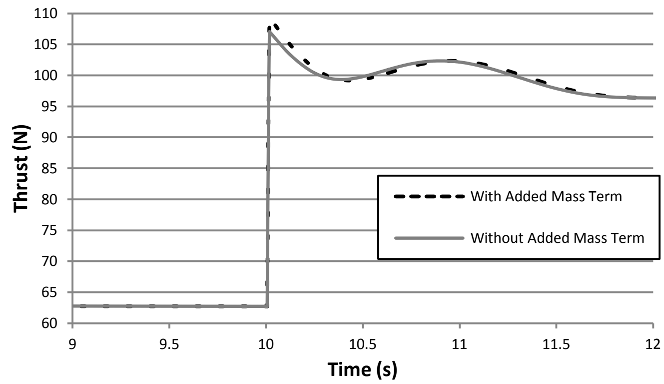

Fig. 2. Thrust force of the rotor versus time.

The first case is a step pitch change at 10 seconds from a blade root pitch of 4.815° to 0.815° over a time of 0.012 seconds (3 time steps).

Results for the step pitch change case are shown in figures 1 and 2. Figure 1 shows the time history of rotor thrust for this unsteady analysis. The general dynamic wake model was initiated at 1 second, resulting in initial transient forces that are not physical. These initial transient forces typically dissipate within 5 seconds for wind turbine models; however, this figure illustrates that 5 seconds is insufficient to reach a steady state solution for the water turbine analysis. A longer settling time of 10 seconds was used for all cases in this paper.

Figure 3 shows the percentage change in thrust due to the added mass model, relative to the final value of thrust 25 seconds into the simulation. This figure illustrates that the added mass model increases the load on the rotor blade by 4.1% for the case of a step change in blade root pitch. The increase in blade pitch results in a decrease of thrust on the rotor, hence the negative values in Fig. 3 which indicate a relative increase in loads on the blade as compared to the analysis without the added mass model. The 4% change in blade thrust load due to the added mass model could have a noteworthy impact on MHK rotor blade structural design, as this load increment will impact the fatigue load on the blade, which determines the operational lifetime of the blade.

Figure 4 shows the initial spike in angle of attack (AOA) caused by the rapid pitch change. The initial change in AOA equals the pitch change and then slowly decreases toward the steady-state solution. The initial spike in AOA is because the shed and trailing vorticity in the wake has not had time to respond to the change in circulation caused by the increase in AOA. Fig. 5 shows the response of the axial induction factor to the step pitch change. The time rate of change of the axial induction factor is also shown, which is used to compute the added mass force. Table 1 shows the results of the time-step with the maximum difference caused by added thrust.

The second case that was analyzed was the model water turbine operating with a yaw of 30° and with constant velocity and blade root pitch. Fig. 6 shows the response of the angle of attack to the changing inflow angle due to the rotor yaw angle. Note that the values before 5 seconds are due to the GDW model initialization.

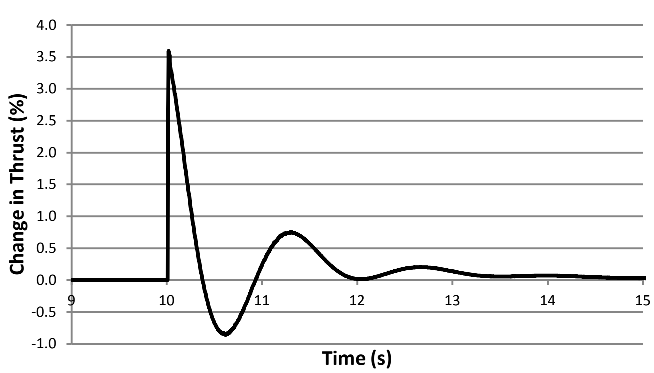

Fig. 3. Percentage change in thrust due to the added mass model. Thrust values were divided by the final thrust value at 25 seconds. The spike at 10 seconds shows the maximum change in thrust due to the model for this rapid pitch change case.

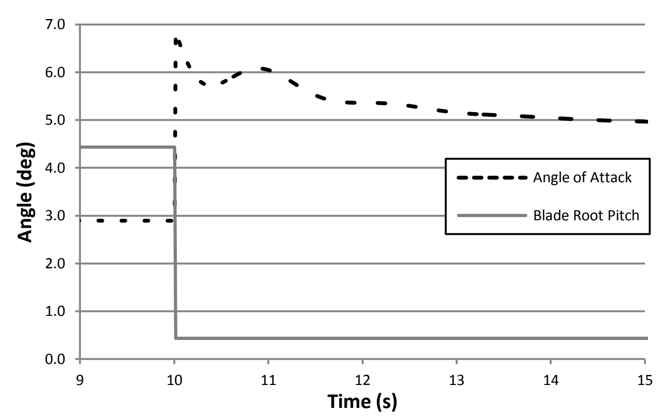

Fig. 4. Angle of attack response to a rapid pitch change. At 10 seconds the rotor blade was rapidly pitched by -4° over 0.012 seconds.

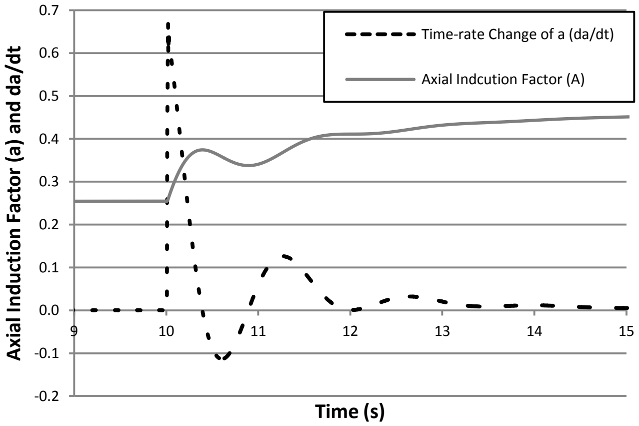

Fig. 5. Axial induction factor and the time rate of change of axial induction factor verse time for the pitch change case.

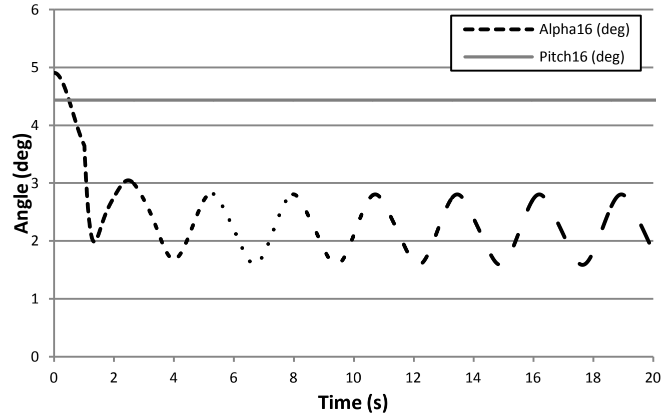

Fig. 6. Angle of attack response of a yawed rotor.

TABLE I. EFFECT OF ADDED MASS MODEL ON PITCH CASE

Time (s)	Thrust no_AM (N)	Thrust w/AM (N)	Delta Thrust (N)	Delta Thrust %	
10.02	106.89		109.19	2.3	3.59

Fig. 7 shows the change in axial induction factor with time. As with the angle of attack, the oscillatory response is due to the changing local flow angle caused by the yaw angle. The time rate of change of the axial induction factor is also shown in Fig. 7. The peaks in the time rate of change of axial induction factor will cause the highest values in the added mass force.

Fig. 8 shows the thrust force response with time, with and without the added mass model. With the added mass model turned on, the amplitude of the thrust force decreases by 3.9% and the phase to shift by 6.37°.

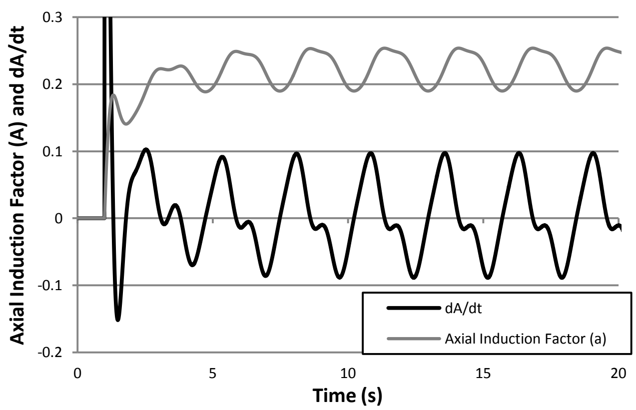

Fig. 7. Axial induction factor and the time rate of change of axial induction factor verse time for the yaw case.

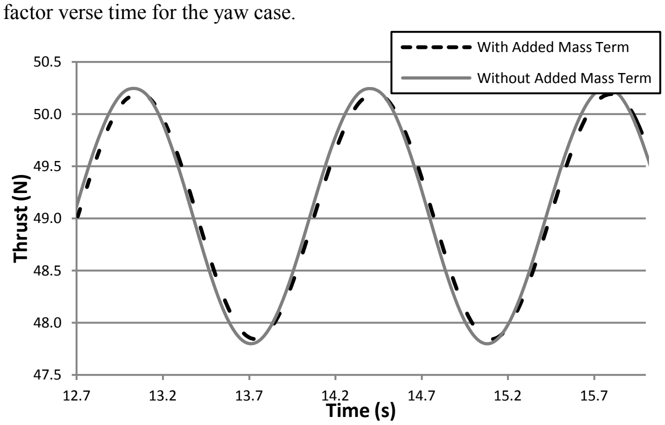

Fig. 8. Thrust force vs time for the yaw case.

VI. CONCLUSION

The results indicate that the added mass model works as expected and has a noticeable influence on blade structural loads. The model could be improved by including the body accelerations of the turbine blade in the computation of the added mass force. This will require passing the body accelerations from FAST to AeroDyn, or moving the added mass computation routine into FAST.

Applicability of the GDW theory to water turbines is uncertain, because the current GDW model in AeroDyn is tuned for large wind turbines. Validation of the added mass model and the application of GDW theory to MHK turbines will require unsteady hydrodynamic experimental data for a MHK horizontal-axis turbine. Until such experimental data is available, models with fewer physical assumptions than the GDW theory can be used to calibrate, validate, or replace the GDW model in AeroDyn for MHK turbine analysis.

The next stage of this research will be to develop an unsteady free-wake vortex method for MHK HAWT analysis which will replace the AeroDyn GDW model in FAST. The investigation explained in this paper is the initial step toward a more comprehensive added mass model that will eventually be included in the under development unsteady FWVM-FAST code.

APPENDIX

VERSIONS OF THE CODE

The results in this paper were generated using FAST version "v7.00.00a-bjj, 31-Mar-2010", which was not modified for this research. The water turbine version of AeroDyn used to generate the results presented in this paper was based on the latest released wind turbine version of AeroDyn at the beginning of the project: "v13.00.00a-bjj 31-Mar-2010 B. and J. Jonkman." The latest version of the code designed for water turbines, including the added mass model described in this paper, is AeroDyn version "v13.00.00g-dcm 5-Aug-2010; this version of AeroDyn is not publicly available.

Comparing results from versions of the code with and without the added mass model requires compiling a version of FAST and AeroDyn with the added mass model turned on and a separate model with the added mass term turned off. Turning the added mass model on and off requires setting the added mass force to zero within AeroDyn.

Changes to the Code

A subroutine in the previous version of AeroDyn (version) fixed the speed of sound to the value for sea-level air. The subroutine (called "BEDDAT") is part of the dynamic stall model in AeroDyn. Even though the dynamic stall model was turned off, it still had an effect on the speed of sound calculation in other parts of the code. This subroutine was modified in the added mass water turbine version of AeroDyn to use the speed of sound in sea water (1500 m/s, 4921 fps). The speed of sound is fixed in this part of the code, although future versions of AeroDyn will be available to read the speed of sound from the input file.

The GDW routine becomes unstable for high induction factors, which typically occur at low wind speeds. Therefore, at low wind speeds AeroDyn switches to BEMT. In the previous version of AeroDyn, this cut-off speed was set at 8 m/s, which is above the operating range for most water turbines. In the water turbine version of AeroDyn, the cut-off wind speed has been set as zero, to allow the GDW solution to always be used for water turbines. Future versions of AeroDyn should use the induction factor as a measure of when the GDW routine will be likely to be unstable, rather than wind speed.

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