

Comparison of a Blade Element Momentum Model to 3D CFD Simulations for Small Scale Propellers

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ABSTRACT

Many Small Unmanned Aerial Vehicles (SUAV) are driven by small scale, fixed blade propellers. Flow produced by the propeller can have a significant impact on the aerodynamics of a SUAV. Therefore, in Computational Fluid Dynamic (CFD) simulations, it is often necessary to simulate the SUAV and propeller coupled together. For computational efficiency, the propeller can be modeled in a steady-state view by using momentum source terms to add the thrust and swirl produced by the propeller to the flow field. Many momentum source term models are based on blade element theory. Blade element theory divides the blade into element sections in the spanwise direction and assumes each element to operate independently as a two-dimensional (2D) airfoil. Blade Element Momentum Theory (BEMT) for two small scale propellers are compared to high-fidelity, time-dependent 3D Reynolds Averaged Navier-Stokes (RANS) CFD simulations to determine the accuracy of approximating the complicated 3D flow associated with small scale propellers. Results show that BEMT acceptably predicts thrust when the propeller operates with little separation and the blade has a high aspect ratio with little or no chord variation. However, in large regions of separated flow and blades of lower aspect ratio and chord variation, the accuracy of BEMT diminishes. A secondary goal of this work is to create a basis for developing a more accurate steady-state surrogate model for the momentum imparted to the flow based on high-fidelity, time-dependent, 3D RANS CFD propeller blade simulations. An overview of this surrogate modeling process is briefly discussed.

CITATION: Carroll, J. and Marcum, D., "Comparison of a Blade Element Momentum Model to 3D CFD Simulations for Small Scale Propellers," *SAE Int. J. Aerosp.* 6(2):2013, doi:10.4271/2013-01-2270.

INTRODUCTION

Small Unmanned Aerial Vehicles (SUAV) are becoming very popular for surveillance and numerous other applications. These SUAVs come in various sizes and the smallest are referred to as Micro Aerial Vehicles (MAV). For the purposes of this paper, SUAV will be used to refer to all UAVs which are portable by a man. SUAVs commonly use small scale fixed blade propellers for propulsion. Fixed blade propellers means the blade is rigidly fixed to the hub so that the blade pitch cannot be changed for various flight conditions. Propellers mounted in a tractor configuration often have significant effects on SUAV aerodynamics. Therefore, to perform Computational Fluid Dynamic (CFD) simulations of a SUAV-propeller system, the SUAV and the propeller must often be simulated in a coupled fashion as the SUAV-propeller interaction is strong.

In the design and analysis of a SUAV, hundreds of SUAV-propeller coupled CFD simulations are needed.

Performing high-fidelity, time-dependent 3D Reynolds Averaged Navier-Stokes (RANS) CFD simulations in which the propeller is rotated relative to the aircraft is very expensive computationally. For compactness, this method will be referred to in this paper as the High-Fidelity Blade Model (HFBM). HFBM is an unsteady problem, therefore steady-state convergence acceleration techniques cannot be used. In addition, the fine grid needed to resolve the detailed flow around the propeller blades makes the overall grid size extremely large. HFBM is the most accurate and high-resolution method of propeller modeling as all the 3D, compressibility, rotational, transitional, and turbulence effects are modeled. However, the high computational cost of HFBM makes it infeasible when numerous simulations are needed as is the case for many SUAV-propeller problems.

For computational efficiency, steady-state models approximate the time-average flow produced by a propeller. These models embed momentum source terms into the propeller region of a mesh to induce thrust and swirl into the

flow field. Many of these momentum source models are based on Blade Element Momentum Theory (BEMT). BEMT determines the thrust and swirl from two-dimensional (2D) airfoil data. However, flow around small scale propellers can be very complex and highly 3D in nature making it difficult for BEMT to accurately predict the propeller performance in many instances. This paper compares HFBM simulations to a BEMT model for two small-scale propellers to determine the validity of using BEMT to model small-scale propellers in a wide range of flight conditions. In addition, an overview of developing surrogate models for the thrust and swirl produced by each blade element from a database of HFBM simulations is discussed.

PROPELLER AERODYNAMICS

A propeller blade is simply a rotating wing in which the lift and drag produce thrust and swirl. Blade Element Theory (BET) views the blade as a combination of 2D airfoil elements which operate independently of one another. The local angle of attack (α), Mach number (M), and Reynolds number (Re) at each blade element are used to calculate the thrust and swirl from 2D airfoil data. The local velocity vectors are a combination of flight velocity, propeller rotation, and induced velocities. To calculate these unknown induced velocities, blade element theory must be coupled with another theoretical model. Numerous models exist for calculating these induced velocities such as those based on momentum theory, lifting-line theory, and many vortex models which describe the wake in varying levels of detail.

Blade element theory's underlying assumption that each blade element operates independently as a 2D airfoil neglects many 3D flow characteristics associated with propeller aerodynamics. Some of the most influential 3D effects are tip loss, hub loss, and stall delay due to rotational effects. A propeller blade is finite and thus flow circulates from the high-pressure side to the suction-side creating tip vortices. These tip vortices affect the induced velocity in the tip region which results in an adverse effect on thrust known as tip loss. Low aspect ratio blades can have a significant portion of the blade affected by tip loss. In addition, flow induced by the hub and blade root can be highly 3D in nature and create hub vortices which also affect propeller thrust.

A significant 3D effect is post stall performance. When propellers operate at advance ratios (J) lower than the design condition, significant separation often occurs on the blades. Advance ratio defined in [Equation 1](#), is the distance a propeller advances forward in one revolution non-dimensionalized by the propeller diameter. The rotation of the blade causes radial pumping which induces large radial components in the boundary layer on the blade. The centrifugal and coriolis forces from the rotation cause the flow to stay attached at higher angles of attack than when compared to a non-rotating flow field thus having a favorable effect on thrust [1]. This effect, known as stall-delay, can significantly affect inboard sections of the blade which often

experience separation. Since many small scale propellers have fixed blades and thus cannot change the blade pitch, operating in non-optimum flight conditions can yield highly separated flows.

$$J = \frac{v}{nD} \quad (1)$$

Numerous correction factors exist for blade element theory to compensate for these various 3D effects on a propeller. Prandtl's correction factors are among the most commonly used for tip and hub loss models, and various stall-delay methods exist. However, many of these models are empirically based or are theoretical approximations which have a difficult time accurately compensating for various propeller geometries and a wide range of flight attitudes.

PROBLEM OVERVIEW

To analyze the significance of 3D effects on small scale propellers, two propellers are simulated using BEMT and HFBM. Both propellers are two bladed, have a 10 inch diameter, and are made using a NACA 4412 airfoil for the blade sections. Propeller 1 has a high aspect ratio of ~ 11 and no chord variation or sweep along the blade. Propeller 2 has an aspect ratio of ~ 5 based on the largest chord in the blade, and it has significant chord variation like many small scale propellers. Pictures of front views onto the rotational axis of the propellers are shown in [Figures 1](#) and [2](#). The two propellers are chosen to highlight the effect that aspect ratio and chord variation have on the 3D propeller effects.



Figure 1. Propeller 1



Figure 2. Propeller 2

Propeller 1 is simulated at low-speed and cruise conditions which correspond to low and high J respectively. The low J is 0.03, and the high J is 0.52. These two different advance ratios are chosen to show the 3D effects resulting from separation. The blade twist of propeller 1 is designed for higher speed flight and thus operation at a low advance ratio will produce separation on the blade while the high J will not. Propeller 2 is simulated at a J which has no separation on the blade. Comparing BEMT to HFBM for propeller 2 intends to show the discrepancy from 3D effects resulting from low aspect ratio and chord variation along the blade. The error in thrust from BEMT compared to HFBM is quantified using an averaged Root Mean Square Error (RMSE) over all the blade elements and normalized by the total thrust of the HFBM