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Bi-directional fluid–structure interaction for large deformation of layered composite propeller blades

Jitendra Kumar*, Frank-Hendrik Wurm

Institute of Turbomachines, University of Rostock, Albert-Einstein-Strasse-2, 18059 Rostock, Germany

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ABSTRACT

Bi-directional fluid–structure interaction becomes important when viscous flow changes the geometry of the domain significantly because of the pressure load. Large deformation in domain causes numerical convergence problems, which are solved by mesh smoothing, re-meshing and a time discrete iterative solver algorithm using industrial computational fluid dynamics and finite element analysis code. In this paper, this approach is used for laminated composite propellers considered as mixers. It experiences heavy thrust, which causes large deformations. Each layer of laminate is modeled as a solid element with anisotropic material data. Comparative study is presented between uni-directional and bi-directional fluid–structure interaction for mixer blades. Change in pressure distribution, stress distribution, thrust, torque and pitch angle of the blade are presented in later parts of the paper.

1. Introduction

Some application of propellers lead to large deformation of rotor blades, for example, ship propellers at static thrust (thrust at zero ship's speed), wind turbines, tide turbines and mixers. The large deformation in all directions leads to a change in operational behavior and a strong increase in mechanical stresses on the structure. The prediction of the operational behavior and the risk of breakage require coupled simulation of different physical models within same comprehensive computational model. Such numerical capability would be very beneficial to many applications, such as a wind turbine, ship propeller and mixer. Coupled 3-D FEM/VLM (PSF-2) method was presented by Lin and Lin (1996) for propellers where geometrical nonlinearity of structures was included, and in 1997, they applied the same procedure for layered composite propellers (Lin and Lin, 1997). Flow-induced oscillations of a single-bladed, single-stage sewage water pump were investigated by Benra (2006) using a one-way coupling method in commercial software and data exchanged was performed via output file at interface surfaces. Young (2008) exploited the advantages of composite propellers using a coupled 3-D BEM/FEM computational model to study the fluid structure interactions for flexible propellers in sub-cavitation and cavitation flow. Campbell and Paterson (2011) developed and validated fluid structure interactions of an expandable impeller pump using OpenFOAM and they developed a structural solver. Recently, some commercial software have a well-developed fluid and a structural solver. Still, it is an open issue to find literature for strongly coupled bi-directional fluid–structure interactions (FSI) under large deformation using a mesh-deformation method of a composite propeller blade with a coupled CFD/FEM model.

* Corresponding author. Tel.: +49 381 4989042; fax: +49 381 4989032.
E-mail address: jitendra.kumar@uni-rostock.de (J. Kumar).

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In this paper, complete modeling and simulation for bi-directional FSI is presented for large deformation composite bodies using commercial solvers based on mesh mapping and grid deformation method. For analysis and validation of simulation results layered composite mixers are used, which deform largely in real applications because of thrust. Mixers are used for mixing operations, which are essential for chemical treatment in productive industries and can add significantly to the fixed and variable costs of such treatments. These submersible mixers are used for homogenization of sewage and preventing sedimentation in tanks, channels or oxidation ditches. The submersible mixer is operated by an electric motor, which is coupled to the mixer's propeller, either directly or via a planetary geared speed reducer. They are designed to generate fluid velocity and fluid shear in the tank behind the propelling blade, which imparts kinetic energy to the fluid and keeps particles in suspension through frictional forces (Wang and Gao, 1997). As an improvement, traditional metallic mixer blades are replaced by composite blades because of several advantages such as high strength-to-weight ratios, less corrosion and a high acoustic damping property (Mouritz et al., 2001). Global and local stress reductions and increases in the load-carrying capacity of composite blade are possible greatly by optimizing the orientation of the fibers in each layer. Presently, all large mixer manufacturers use composites to reduce manufacturing and maintenance costs, but these composite blades experience large deformation in real applications, which lead to a change in operational behaviors and increase the risk of damage. Prediction of these events by simulation is still arguable.

1.1. Previous works on mixers

Mixer blades experience large thrusts and torque to perform effective mixing and to keep fluid in flow. One of the repercussions of using composites is that blades deform by large amounts in real applications, which lead to change in the flow field, thrust and torque of the mixers for which it was designed. Ultimately, platforms and strategies are needed for strong fluid–structure interactions so that correct behaviors would be predicted prior to product applications. Extensive studies show the challenges of strong fluid–structure interactions for mixers. Accurate prediction of thrust and torque using computational fluid dynamics techniques is extremely important for designing effective and efficient submersible mixers. Mixers generate turbulent jet flow behind its blades as shown in Fig. 1. Petersson et al. (2000) investigated experimental development of turbulent jets generated by a mixer using laser Doppler velocimetry (LDV) technique. Sieg et al. (2009) presented characteristics of submerged, unconfined, swirling jet behavior behind different size mixers experimentally using an LDV technique. Tian et al. (2013) performed numerical simulations of submersible mixers with two blades using FLUENT with a tetrahedral mesh. Kumar et al. (2012) studied the effects of mixer blade geometry and deformation on jet flow shape and sedimentation. The importance of thrust and torque is well understood, but numerical simulation for studying jet flow behavior with justified turbulence model to calculate correct thrust and torque values is still an open issue.

1.2. Objective

The objective of this paper is to do a comprehensive study of composite mixers with the following aspects:

The first aspect is to understand the flow behavior, the thrust and torque behind the mixer with variation in boundary conditions and turbulence models using computational fluid dynamics (CFD). Thrust and torque values are sensitive to inlet speed, rotational speed and other boundary conditions, and the accuracy of simulation depends upon turbulence models and the quality of the mesh. Extensive study is required to set correct numerical models for analysis to make benchmarks for the fluid–structure interaction (FSI) analysis of this product.

The second aspect is to create numerical models for layered composites using finite element method (FEM) to understand the interaction of each layer and the areas of stress concentrations during real applications. Modeling of each layer of composite using solid elements is investigated along with a validation of material models using optical measurement methods.

The main motive of this study is to focus on a bi-directional, FSI calculation for large deformation flexible composite blades using mesh deformation and domain re-meshing method. A comparative study is performed to see the importance of

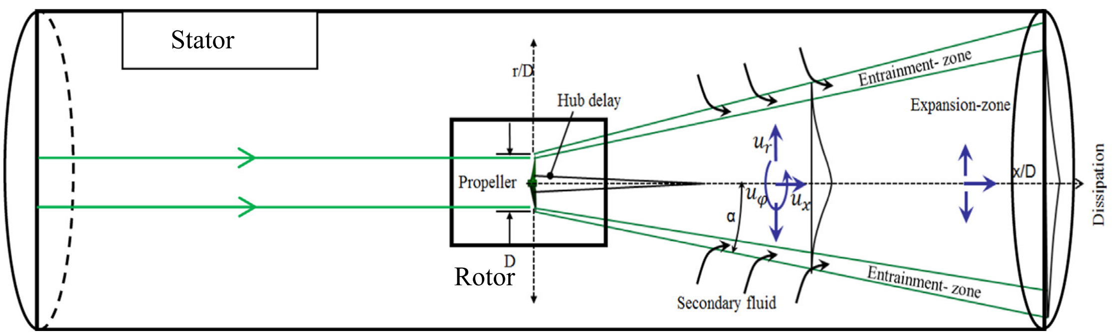

Fig. 1. Schematic view of domain and theoretical flow behavior, where D, u_x, u_r, u_φ and α are the diameter of mixer, axial velocity, radial velocity, circumferential velocity and expansion angle, respectively.