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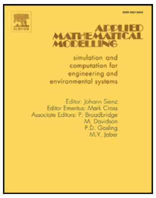

Large-eddy simulations of an autorotating square flat plate

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ABSTRACT

Large-eddy simulation (LES) turbulence models are underdeveloped in the area of fluid–structure interaction (FSI), specifically in autorotation applications. To gain a better understanding of FSI simulations, under the influence of strong turbulent interactions, several LES simulations were conducted to study the autorotation of a thin plate and compared to experimental measurements and RANS simulations found in literature. The plate is allowed to spin freely about its center of mass and is located near the center of a wind tunnel with a free stream velocity of 5 m/s. Wall effects from the wind tunnel enclosure are neglected. In this work, a coupled Computational Fluid Dynamics (CFD) – Rigid Body Dynamics (RBD) model is proposed employing the delayed-detached-eddy simulation (DDES) and the Smagorinsky turbulence models to resolve the subgrid-scale stress (SGS). The qualitative prediction of vortex structures and the qualitative computation of pressure coefficients are in good agreement with experimental results. When compared to RANS, the results from the LES models provide better predictions of the pressure coefficient. Moreover, LES accurately captures the transient behavior of the plate and close correspondence is found between the predicted and measured moment coefficient.

1. Introduction

The term autorotation was first introduced by Riabouchinsky in 1935 [1] and was later defined as the continued rotation of an object lacking an external power source due to a stream of air [2]. Accurate prediction of the fluid and rigid body dynamics of autorotation is known to be very challenging due to the complex unsteady flow dynamics, involving fluid–structure interaction (FSI), turbulent flow and flow separation, and most importantly the strong coupling of the two-way interaction between the fluid and solid. As a result, accurate unsteady and non-dissipative turbulence modeling is critical when resolving the aerodynamic non-linearity of autorotation. Many industrial applications, such as wing flutter and bridge oscillations, experience strong FSI effects which can cause catastrophic failure, especially when materials susceptible to fatigue are involved [3]. Further research is required to develop current state of the art FSI methods, in specific the turbulent and rigid body motion interaction, before optimization, coupled with CFD, can be used in the design of successive industrial applications.

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At present, Reynolds average Navier–Stokes (RANS) equations based models are widely used for low run times when simulating turbulence, although they lack precision in the accurate prediction of flow separation given its time averaging of fluctuations and modeling of the Reynolds stress tensor. As a result, RANS models make it hard to preserve the vortex characteristics involved leaving a flow field void of incoherent structures. In contrast, large-eddy simulation (LES) models have proven to be a good alternative to RANS models as they preserve the characteristics of the vortex as shown by Eisenback and Friedrich [4], and most recently the Smagorinsky model with Van Driest damping has been implemented by Im et al. [5] achieving good agreement with experimental observations. LES has also been successful when used in particle tracking [6], compressible flow [7], combustion [8–10] and now in autorotation.

Recently, LES has been successfully implemented in the study of turbo-machinery as published by Li et al. [11], Tyacke et al. [12] and Watson et al. [13]. However, as shown by Breuer et al. [14] and Feymark [15], there is still the need for further LES investigation in the area of FSI, especially in autorotation without a prescribed set rotation. A great deal of the work in FSI is conducted using hybrid models, combining both RANS and LES methods, as presented by Wang [16], Wang and Zha [17], and Shinde et al. [18]. The work on this paper aims to provide new contributions to LES in the developing field of autorotation, a subfield of FSI.

Not only are LES models promising, but they perform better than RANS models, and overcome several of the RANS model disadvantages. In LES, the governing equations are spatially filtered on the scale of the numerical grid. The large energy containing scales are resolved numerically, and the small scale eddies, which are generally more homogeneous and universal, are modeled. The large eddies are strongly affected by the flow field geometry boundaries, therefore the direct computation of the large eddies by LES is more accurate than modeling the large eddies by RANS. This in turn helps to better simulate flow separation, an important factor in autorotation. Separated vortices create large pressure gradients on the surface of origin, which is the driving force of this autorotation, i.e., in laminar flow the autorotation is not sustained. The effect of the unresolved small scales of motion in LES is typically modeled by a subgrid-scale (SGS) model [19–23] or by the inherent dissipation in the numerical schemes [24–29]. Because the statistics of the small scale turbulence are more isotropic and universal, a general physical model for small scale eddies is more plausible.

For certain applications and complex flows that require solving for the wall boundary layer, the CPU resource needed by LES is close to that of the Direct Numerical Simulation (DNS). As a result, pure LES might not be rigorously implemented for another 3 decades in engineering applications [30] and several hybrid RANS and LES models have been developed to overcome the intensive CPU requirements for LES, with runtimes between those of RANS and LES. One of these models was introduced by Spalart et al. in 1997 called detached-eddy simulation (DES) [30] which divides a flow domain into a LES region far away from a solid wall and a RANS region near a solid wall. Previous work for turbulence simulations for airfoils, cylinders and for bodies using DES have shown encouraging results as seen in work done by Travin et al. [31], Spalart [32], Hansen and Forsythe [33], Viswanathan et al. [34], and Subbareddy and Candler [35].

The original DES model suffers from the downside that the transition from RANS to LES may not be grid independent and as a result Spalart suggested a modification to his original model in 2006 [36], called delayed-detached-eddy simulation (DDES). In order for the transition to be independent from grid spacing, Spalart used a blending function to limit the DES length scale similar to the one used by Menter and Kuntz [37] for the Shear Stress Transport (SST) model. The DDES model has shown excellent agreement with experimental data as well as a significant improvement from DES in work done by Wang and Zha [38], Coronado Domenge et al. [39] and Im et al. [5].

For turbulence modeling, additional adjustments for the DDES model, improved DDES (iDDES), are then outlined by Travin et al. [40] concerning the definition of the LES length scale and the Wall-Modeled Large-Eddy Simulation (WMLES) helping to resolve the turbulence definition near solid walls. For a more comprehensive review of the LES and hybrid models mentioned in this paper the reader is directed to the review paper by Argyropoulos and Markatos [41].

In this paper, the flow around an autorotating flat plate is simulated, using several LES models, which was analyzed experimentally by Martinez-Vazquez et al. [42] and previously simulated using RANS models by Hargreaves et al. [43].

2. Computational method and models

2.1. Computational method

2.1.1. Smagorinsky

The LES Smagorinsky model performs spatial filtering of the velocity fluctuations to decompose them into large scales, which are numerically resolved, and small scales, which are modeled. The Smagorinsky–Lilly model with Van Driest damping [19] models the SGS by employing an eddy viscosity approach. In this approach it is hypothesized that a turbulent eddy viscosity exists at the small scales and that the stresses are in equilibrium at the interface between the large and small scales. The eddy viscosity ($\tilde{\mu}_t$) is defined as:

$$\tilde{\mu}_t = \bar{\rho} C_s^2 l^2 \sqrt{2 S_{ij} S_{ij}}, \tag{1}$$

where C_s is the Smagorinsky constant, S_{ij} is the rate-of strain tensor, and l is the model length scale given by:

$$l = (\Delta)^{1/3} \sqrt{(1 - \exp(-y^+/26))^3}, \tag{2}$$

where Δ is the volume of the cell.