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Review on the sensitization of turbulence models to rotation/curvature and the application to rotating machinery

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ABSTRACT

The complex geometry of rotating machines makes the flows strongly affected by rotation and curvature, which are challenging for turbulence modeling. During the development of CFD, large amount of turbulence models appeared and hence make the user hard to decide which one to choose. The present paper presents a coherent review of the various approaches proposed in the recent literatures on this topic. First, the influence of the rotation and curvature is reviewed and concluded. Then, the basic concepts of RANS and LES are introduced to facilitate the description of the models and each method is classified into several types. A variety of models are then described and assessed either by the results in the literatures or by own results, with special concentration on the application to rotating machines. Finally, a brief introduction to the hybrid RANS/LES is made and assessed, together with the recommendation for the selection of the models. The aim of the review is to provide information on the advantages and limitations of related models and make it easier for the user to choose an appropriate model.

1. Introduction

The flows in rotating machines are highly turbulent and strongly affected by the rotation and curvature effects, through system rotation of the runner (or impeller) and the curved passage respectively. These effects make it a challenging task to accurately capture the complex phenomenon during the operation of the machines by computational fluid dynamics (CFD).

Before the modeling of the flows, it is necessary to know how the rotation and curvature affect the turbulence in advance. The streamline curvature consists of two types, namely the “convex” and “concave”, as illustrated in Fig. 1. According to the analysis by Durbin [1], two kinds of rotation exist in curved surface: (i) the change of the velocity direction along the surface; (ii) the fluid elements rotation corresponding to the gradient of the velocity normal to the surface. For the convex surface, rotation (i) is clockwise and the velocity gradient forces the fluid elements to rotate in clockwise, therefore, the turbulence is suppressed; for the concave surface, rotation (i) is counterclockwise and rotation (ii) is clockwise, then the turbulence is enhanced. The streamline curvature effect was systematically studied by many researchers in various cases [2–6]. Fig. 2 shows the distribution of velocity and its fluctuation near the convex and concave wall in the 90° square bend

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Nomenclature

CFD	computational fluid dynamics
DNS	direct numerical simulation
LES	large-eddy simulation
RANS	Reynolds-averaged Navier–Stokes
SGS	subgrid scale
RSM	Reynolds stress model
SM	Smagorinsky model [17]
DSM	dynamic Smagorinsky model [18]
VM	Vreman model [20]
DNM	dynamic non-linear model [34]
EASSM	explicit algebraic subgrid stress model [37]
DCNM	dynamic cubic non-linear model [38]
SST	shear stress transport model
SST-CC	shear stress transport model with curvature correction
RNG	re-normalization group
EARSM	explicit algebraic Reynolds stress model
LCS	Craft–Launder–Suga model [86]
LRR	Launder–Reece–Rodi model [87]
GS	Gatski–Speziale model [72]
DDES	delayed detached eddy simulation [99]
FBM	filter-based model [102]
FBM-CC	filter-based model with curvature correction
DES	detached eddy simulation
S-A	Spalart–Allmaras

Upper-case Roman

P_k	turbulence kinetic energy production
Re	Reynolds number
R_i	Richardson number
S	characteristic strain-rate, $S=\sqrt{2S_{ij}S_{ij}}$
S_i	source term, $i=1, 2, 3$
S_{ij}	Strain-rate tensor, $i=1, 2, 3$, $j=1, 2, 3$, for LES, $S_{ij}=\frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j}+\frac{\partial\bar{u}_j}{\partial x_i}\right)$, for RANS, $S_{ij}=\frac{1}{2}\left(\frac{\partial\langle u\rangle_i}{\partial x_j}+\frac{\partial\langle u\rangle_j}{\partial x_i}\right)$

Lower-case Roman

f, f_r, f_{r1}, f_{r2}	curvature correction multiplier
k	turbulence kinetic energy
p	pressure
r	distance from the rotation axis
t	time
u_i	velocity, $i=1, 2, 3$

Upper-case Greek

Δ	filter width
$\widehat{\Delta}$	test filter width
Ω_i^{rot}	angular velocity, $i=1, 2, 3$
Ω_{ij}	rotation-rate tensor, $i=1, 2, 3$, $j=1, 2, 3$, for LES, $\Omega_{ij}=\frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j}-\frac{\partial\bar{u}_j}{\partial x_i}\right)$, for RANS, $\Omega_{ij}=\frac{1}{2}\left(\frac{\partial\langle u\rangle_i}{\partial x_j}-\frac{\partial\langle u\rangle_j}{\partial x_i}\right)$
Ω_{ij}^a	absolute rotation-rate tensor, $\Omega_{ij}^a=\frac{1}{2}\left(\frac{\partial\langle u\rangle_i}{\partial x_j}-\frac{\partial\langle u\rangle_j}{\partial x_i}\right)+2\xi_{mji}\Omega_m^{rot}=\Omega_{ij}+2\xi_{mji}\Omega_m^{rot}$, $i=1, 2, 3$, $j=1, 2, 3$
Ω	characteristic rotation rate, $\Omega=\sqrt{2\Omega_{ij}\Omega_{ij}}$

Lower-case Greek

δ_{ij}	Kronecker delta, $i=1, 2, 3$, $j=1, 2, 3$
ε	dissipation rate
ξ_{ijk}	Levi-Civita symbol, $i=1, 2, 3$, $j=1, 2, 3$, $k=1, 2, 3$
ν	kinetic viscosity
ν_t	eddy viscosity
ω	specific dissipation rate