THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING
IN
THERMO AND FLUID DYNAMICS

Time-accurate Turbulence Modeling of Swirling Flow for Hydropower Application

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Abstract

Hydraulic turbomachines have played a prominent role in the procurement of renewable energy for more than a century. Embedded in the context of general technological progress, their design for efficiency and reliability has reached an outstanding level of quality. At the design point, water turbines generally operate with little swirl entering the draft tube and no flow separations, but at off-design, at both high- and low-load, the flow leaving the turbine has a large swirling component.

The present work describes the turbulence modeling of a wide range of physical mechanisms that produce pressure pulsations in swirling flows. The available knowledge about these pulsations are still far from complete. If the swirl exceeds a certain level, the flow patterns associated with the swirl dominated vortex motions vacillate. A key feature of strongly swirling flows is vortex breakdown. The vortex breakdown is an abrupt change in the core of a slender vortex and typically develops downstream into a recirculatory "bubble" or a helical pattern. The swirl motion and the helical pattern has for long been of interest to scientists and engineers who have constantly strived in reproducing the naturally occurring phenomena and take advantage of their performance enhancing effects thermal and mass transport applications. The swirl effects are usually seen as either the desired result of design or unavoidable, possibly unforeseen, side effects which comprise a forced vortex core centered around its axis of rotation. The core is due to viscous forces, increases in size with successive increases in viscosity and varies over widely dissimilar length and time scales depending on the physical context.

The pulsations and their impact on the efficiency and hydraulic structures of water turbines depend on the flow rate, the velocity distribution after the runner, the shape of the draft tube, and the dynamic response of the whole hydraulic structure. The high level of unsteadiness in the flow field necessitates the utilization of advanced turbulence treatment to predict the small-scale structures.

Time-accurate Reynolds-averaged Navier-Stokes (URANS) models are primarily useful for capturing large-scale flow structures, while the details of the small-scale turbulence eddies are filtered out in the averaging process. In many cases also the large-scale structures are damped by the URANS modeling, which is formulated to model all the turbulence. The quality of the results is thus very dependent on the underlying turbulence model. Better approaches should be used to handle the anisotropic and highly dynamic character of turbulent swirling flows. An extended series of turbulence models are scrutinized in this work while the main focus is on hybrid URANS-LES and LES methods. Detached-eddy simulation (DES) is a promising hybrid URANS-LES strategy capable of simulating internal flows dominated by large-scale detached eddies at practical Reynolds numbers. The method aims at entrusting the boundary layers with URANS while the detached eddies in separated regions or outside the boundary layers are resolved using LES. DES predictions of massively separated flows, for which the technique was originally designed, are typically superior to those achieved using URANS models, especially in terms of the three-dimensional and time-dependent features of the flow. Scale-adaptive simulation (SAS) is another hybrid URANS-LES method which is based on detecting the unsteadiness according to the velocity gradients in the flow field. The present work gives a thorough comparison between the different levels of unsteady turbulence modeling, applied to swirling flow and the rotor-stator interaction.

Keywords: Hydropower, Swirling Flow, Vortex Breakdown, Turbulence Modeling, LES, Hybrid RANS-LES, DES

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The computational facilities are provided by C3SE, the center for scientific and technical computing at Chalmers University of Technology, and SNIC, the Swedish National Infrastructure for Computing.

Ardalan Javadi
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Preface

List of publications:

Paper A Javadi, A. and Nilsson, H., 2014, LES and DES of swirling flow with rotor-stator interaction, *proc. 5th Symposium of Hybrid RANS-LES Models, Texas A&M University, Texas, USA.*

Paper B Javadi, A. and Nilsson, H., 2014, A comparative study of scale-adaptive and large-eddy simulations of highly swirling turbulent flow through an abrupt expansion, *27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada.*

Paper C Javadi, A. and Nilsson, H., 2014, Unsteady numerical simulation of the flow in the U9 Kaplan turbine model, *27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada.*

Paper D Javadi, A., Bosioc, A., Nilsson, H., Muntean, S. and R Susan-Resiga, R., 2014, Velocity and pressure fluctuations induced by the precessing helical vortex in a conical diffuser, *27th IAHR Symposium on Hydraulic Machinery and Systems, Montreal, Canada.*

Paper E Javadi, A. and Nilsson, H., 2014, LES and DES of Strongly Swirling Turbulent Flow through a Suddenly Expanding Circular Pipe, *In preparation for submission to a scientific journal.*

Paper F Javadi, A. and Nilsson, H., 2014, Time-accurate Numerical Simulations of Swirling Flow with Rotor-Stator Interaction, *In preparation for submission to a scientific journal.*

Contents

Summary of Papers

1 Summary of Papers

1.1 Paper A

LES and DES of swirling flow with rotor-stator interaction

Paper A provides advanced numerical simulations of the flow in a swirl generator. A highly swirling turbulent flow engendered by the rotor-stator interaction of a swirl generator is investigated using LES and DES. A deeper understanding of such a flow physics is only possible with advanced numerical simulations which are rarly available in the literature. The delayed DES Spalart-Allmaras (DDES-SA), improved DDES-SA, shear stress transport DDES, and a dynamic k-equation LES are studied. A mesh sensitivity study is performed on the hybrid methods, including the ability of capturing the details of the flow field. It is shown that all methods are capable of predicting the large-scale flow features, e.g. the vortex breakdown and the corresponding on-axis recirculation region. It is also shown that all hybrid methods capture most of the small-scale coherent structures, even with a relatively coarse mesh resolution. The various shielding functions of the hybrid methods are analyzed, distinguishing the location of the transition between RANS and LES mode. The high Reynolds number of the flow causes problems for LES to capture detailed unsteadiness of the flow, although the main feature of the flow (precessing vortex and vortex breakdown) are simulated reasonably. The precessing vortex occurs far from the wall. It is thus possible to use a relatively coarse mesh resolution at the walls together with the hybrid methods. The LES model, on the other hand, needs a much finer mesh also at the walls.The hybrid methods are capable of capturing the flow field accurately even with the coarse resolution.

Division of Work

Javadi did all the work on geometry cleaning, mesh generation, numerical simulations, analysis, and writing of the paper. Nilsson initiated and supervised the work, and gave feedback in the writing of the paper.

1.2 Paper B

A comparative study of scale-adaptive and large-eddy simulations of highly swirling turbulent flow through an abrupt expansion

Paper B is assigned to assess the ability of the SAS model to capture the vortex breakdown of highly swirling flows in vortex breakdown of highly swirling flows. The strongly swirling turbulent flow through an abrupt expansion is investigated using highly resolved LES and SAS, to shed more light on the stagnation region and the helical vortex breakdown. The vortex breakdown in an abrupt expansion resembles the so-called vortex rope occurring in hydropower draft tubes. It is known that the large-scale helical vortex structures can be captured by regular RANS turbulence models. However, the spurious suppression of the small-scale structures should be avoided using less diffusive methods. The present work compares LES and SAS results with the experimental measurement of Dellenback *et al.* (1988). The computations are conducted using a general non-orthogonal finite-volume method with a fully collocated storage available in the OpenFOAM-2.1.x CFD code. The dynamics of the flow is studied at two Reynolds numbers, $Re = 6.0 \times 10^4$ and $Re = 10^5$, at the almost constant high swirl numbers of Sr=1.16 and Sr=1.23, respectively. The time-averaged velocity field and the root mean square of the velocity fluctuations are captured and investigated quantitatively. The flow with the lower Reynolds number gives a weaker outburst although the frequency of the structures seems to be constant for the plateau swirl number. Both models are capable of capturing the physics of the flow while SAS better predicts turbulent structures immediately after the expansion. The case $Re = 6.0 \times 10^4$, Sr=1.16 has larger flow structures, for which LES presents a better agreement compared with the other operation condition, $Re = 10^5$, Sr=1.23. The SAS model has an extra term in the "ω" equation which is responsible for detecting the unsteadiness. The flow field after the expansion is intertwined and unsteady. The SAS term switches itself on and increases "ω". This leads to resolve the turbulent structures especially in the region after the expansion.

Division of Work

Javadi did the pre-processing, processing and post-processing of the numerical simulations and writing of the paper under supervision of Prof. Håkan Nilsson.

1.3 Paper C

Unsteady numerical simulation of the flow in the U9 Kaplan turbine model

Paper C is contributed to explore the flow in the U9 Kaplan turbine at the best efficiency point. The Reynolds-averaged Navier-Stokes equations with the RNG $k - \epsilon$ turbulence model closure are utilized to simulate the unsteady turbulent flow throughout the whole flow passage of the U9 Kaplan turbine model. The U9 Kaplan turbine model comprises 20 stationary guide vanes and 6 rotating blades (700 RPM), working at full load (0.71 m^3/s). The computations are conducted using a general finite volume method, using the OpenFOAM-1.6.ext CFD code. A dynamic mesh is used together with a sliding GGI interface to include the effect of the rotating runner. The hub and tip clearances are included in the runner. An analysis is conducted of the unsteady behavior of the flow field, the pressure fluctuation in the draft tube, and the coherent structures of the flow. The tangential and axial velocity distributions at three sections in the draft tube are compared against LDV measurements. The numerical result is in reasonable agreement with the experimental data, and the important flow physics close to the hub in the draft tube is captured. The hub and tip vortices and an on-axis forced vortex are realistically captured. The numerical results show that the frequency of the forced vortex is 1/5 of the runner rotation frequency.

Division of Work

Javadi did all the work on geometry cleaning, mesh generation, numerical simulations, analysis, and writing of the paper. Nilsson initiated and supervised the work, and gave feedback in the writing of the paper.

1.4 Paper D

Velocity and pressure fluctuations induced by the precessing helical vortex in a conical diffuser

Paper D provides a survey of the behaviour of the vortex in a diffuser downstream a swirl generator, and assesses the ability of URANS models to predict the flow features. about the physics of different level of swirl and applicability of URANS model to predict the flow features. The flow unsteadiness generated in the draft tube cone of hydraulic turbines affects the turbine operation. Therefore, several swirling flow configurations are investigated using a swirling apparatus in order to explore the unsteady phenomena. The swirl apparatus has two parts: the swirl generator and the test section. The swirl generator includes two blade rows being designed such that the exit velocity profile resembles that of a turbine with fixed pitch. The test section includes a divergent part similar to the draft tube cone of a Francis turbine. A new control method based on a magneto rheological brake is used in order to produce several swirling flow configurations. As a result, the investigations are performed for six operating regimes in order to quantify the flow from part load operation, corresponding to runaway speed, to overload operation, corresponding to minimum speed, at constant guide vane opening. LDV measurements are performed along three survey axes in the test section. The first survey axis is located just downstream the runner in order to check the velocity field at the swirl generator exit, while the next two survey axes are located at the inlet and at the outlet of the draft tube cone. The measured unsteady velocity components are used to validate the results of unsteady numerical simulations, conducted using the OpenFOAM-1.6.ext CFD code. The computational domain covers the entire swirling apparatus, including strouts, guide vanes, runner, and the conical diffuser. A dynamic mesh is used together with sliding GGI interfaces to include the effect of the rotating runner. The Reynolds averaged Navier–Stokes equations coupled with the RNG $k-\epsilon$ turbulence model are utilized to simulate the unsteady turbulent flow throughout the swirl generator. For conditions where the vortex rope disappears, the tangential velocity decreases and the numerical results show better agreement with the experimental results. In reverse, when the tangential velocity increases, the vortex rope is larger and an on-axis recirculation region is formed. In such cases the numerical results overpredict the recirculation region. The precessing vortex rope is rotating in the opposite direction of the runner for 400 rpm and 500 rpm. The vortex rope disappears or is very small for 600 rpm and 700 rpm. The precessing vortex rope is rotating in the same direction as the runner for 800 rpm and 925 rpm. The numerical results capture a slightly lower frequency of the vortex rope than the experimental one, for 925 rpm.

Division of Work

The experimental investigation is done by our scientific partner at the University Politehnica Timisoara, Timisoara, Romania. The pre-processing, processing and post-processing of the numerical simulations are done by the author under supervision of Prof. Håkan Nilsson.

1.5 Paper E

LES and DES of Strongly Swirling Turbulent Flow through a Suddenly Expanding Circular Pipe

Paper E delineates the physics of the highly swirling turbulent flow in a suddenly expanding circular pipe, using a wide range of operating condition and advanced turbulence treatments. The delayed DES Spalart-Allmaras (DDES-SA), improved DDES-SA (IDDES-SA), a dynamic k-equation LES (oneEqLES), dynamic Smagorinsky LES (dynSmagLES) and implicit LES with van Leer discretization (vanLeerILES) are scrutinized in this study. A comprehensive mesh study is carried out and the results are validated with experimental data. The LES and DES results of different operating conditions are compared and described qualitatively and quantitatively. The features of the flows are distinguished mainly owing to different level of the centrifugal force for different swirls. The numerical results capture the vortex breakdown with its characteristic helical core, the Taylor-Görtler and the turbulence structures. The hybrid behavior of DDES-SA and IDDES-SA is discussed. The results confirm that LES and DES are capable of capturing the turbulence intensity, the turbulence production, and the anisotropy of the studied flow fields. the DDES-SA is capable of capturing the physics of the flow with reasonable accuracy while still being sensitive to the wall-parallel resolution. The IDDES-SA behaves as a wall-modeled LES in the flows with high recirculation level although, no turbulent content is applied at the inlet. The key feature of the high swirl flow is the vortex breakdown and the on-axis recirculation region. The distribution of the on-axis recirculation region varies with different Re and Sr. The intertwined nature of the coherent structure due to the vortex breakdown is wider and steeper for higher Re and Sr.

The dominant frequency of the flow, due to the precessing helical vortex, is insensitive to the Reynolds number for swirl number about unity. The level of the turbulence and the turbulence production increases remarkably with the swirl number, while the state of isotropy is not susceptible to Re and Sr. The flow is anisotropic immediately after expansion, while it further downstream rapidly becomes isotropic due to the redistribution between velocity fluctuations.

Division of Work

Javadi did all the work on geometry cleaning, mesh generation, numerical simulations, analysis, and writing of the paper. Nilsson initiated and supervised the work, and gave feedback in the writing of the paper.

1.6 Paper F

Time-accurate Numerical Simulations of Swirling Flow with Rotor-Stator Interaction

Paper F presents a series of numerical simulation to study a highly swirling turbulent flow generated by a rotor-stator interaction. Four high-Reynolds URANS, two low-Reynolds URANS, three hybrid URANS-LES, and one LES turbulence models are scrutinized. These are standard $k - \epsilon$, SST $k - \omega$, realizable $k - \epsilon$ and RNG $k - \epsilon$, Launder-Sharma $k - \epsilon$ and Lein-Cubic $k - \epsilon$, three hybrid RANS-LES, delayed DES Spalart-Allmaras (DDES-SA), DDES SST $k - \omega$ (DDES-SST) and improved DDES-SA (IDDES-SA) and an dynamic k-equation LES (dynOneEq). The purpose is to understand effect of turbulence models in a swirling flow with high level of the unsteadiness, large pressure pulsation, and a significant generation and the dissipation of the turbulence in the main stream. In addition, a mesh resolution study is performed and boundary conditions are analyzed. The URANS models are capable of capturing the main feature of this flow, the vortex rope, which is formed by the strong centrifugal force. The force forms an on-axis recirculation region which is overestimated by the RANS models. Although the low-Reynolds formulations treat the wall-effect in inter-blade passages more accurate, they still encounter difficulty to predict the main stream features in the draft tube. A better resolution of the coherent structures and the turbulence is necessary to capture the disintegration of the vortex rope. The turbulent structures in the runner affects the vortex sheet separated from the runner blade. These coherent and turbulent structures determine the character of the vortex rope and its disintegration. The hybrid method predicts these aspect of the flow reasonably well. The mesh generation is a vital part of the solution because the cells quality influences the flow circumstances qualitatively and quantitatively. The flow is not well predicted in the downstream of the runner blade where the wall effects are more important. The flow in the runner region is not predicted accurately with LES, due to the insufficient resolution of the boundary layers. However, the vortex rope and the on-axis recirculation region are captured rather well with LES.

Division of Work

Javadi did all the work on geometry cleaning, mesh generation, numerical simulations, analysis, and writing of the paper. Nilsson initiated and supervised the work, and gave feedback in the writing of the paper.