CFD MODELLING OF TURBINE STAGE STATOR/ROTOR INTERACTION

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Abstract: Issues related to numerical analyses of turbine stage stator/rotor interactions are discussed, with special focus on the selection of grid parameters to secure proper modelling of the stator wake's dissipation. Unsteady calculations of the flow through a high-pressure turbine stage, based on 3D URANS equations, are employed in the grid resolution analysis. Their results are compared with those obtained with other methods, both developed by the author or available in the literature. As a result, the 3D grid resolution of the order of 2 000 000 cells per one stator and/or one rotor passage has been determined as the necessary minimum for properly modelling the dissipation of the stator's wake on its way through the rotor's cascade, under the circumstances determined by the used CFD code. A generalization of this result is proposed.

Keywords: stator wakes, grid resolution, vortices

1. Introduction

Numerical analyses of unsteady stator/rotor interactions in fluid-flow machine stages remain quite a challenge for research workers, at least partly due to difficulties in proper selection of parameters for a calculation grid that would eliminate the effect of its resolution on the final results. For two-dimensional cases the problem was analysed by Arnone *et al.* [1, 2], who concluded that grid-independent solutions can only be obtained with grids of the order of no less than 15 − 20 thousand cells per one cascade passage. To the present author's best knowledge, no such assessments have been made for 3D cases, although the course and effects of stator/rotor interactions have been the subject of numerous studies published over more than twenty years. Judging from the information on grid parameters given by the authors of these studies, one may conclude that the condition of sufficient grid resolution has been fulfilled only by some of them. Generally, this condition does not have to be met in qualitative analyses of the phenomenon, *e.g.* those aimed at recognizing characteristic trends, and much valuable material can still be obtained in this way, provided that the grid is fine enough to properly detect all structural components of the examined flow. However, there are situations when the accuracy with which quantitative effects of stator/rotor interaction are calculated is very important, including calculations of the kinetic energy loss, used in HP turbine stage design, or evaluation of the stator wake's intensity at the stage exit, required in analyses of the clocking phenomenon. The article presents an attempt to assess the minimum resolution of a 3D grid required to consider its effect on the calculated stator/rotor interaction negligible under the circumstances determined by the properties of the applied CFD code, with further discussion on the possible generalization of the obtained results.

2. The methodology

The basic material for examining the above mentioned effect has been the results of flow calculations through an HP turbine stage.

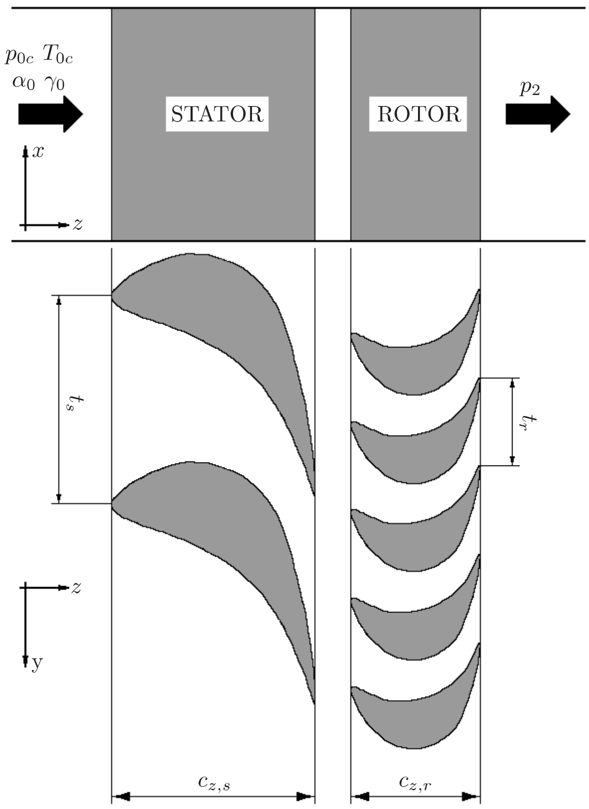

Figure 1. Turbine stage geometry and flow parameters assumed in URANS calculations

The assumed geometry and flow conditions of the stage are shown in Figure 1. The calculations were performed using FlowER, a specialized code developed for calculating flows through steam turbine rows, stages and stage sections. The code solves the system of Navier-Stokes equations in the averaged version proposed by Reynolds. The basic equations are complemented by a model of turbulence, the algebraic Baldwin-Lomax model in the reported case, selected after examining its influence on the course and effects of the stator/rotor interaction [3]. The code makes use of a structural H-type grid. A detailed description of the code's algorithm and its theoretical and numerical fundamentals can be found in [4].

FlowER has a URANS option of unsteady calculations taking into account the relative motion of the rotor with respect to the stator in the turbine stage. In this option the condition of so-called time-space periodicity is employed [5].

Flow parameters assumed at stage inlet and exit had been recorded in a real turbine stage in operation. A set of these parameters included four inlet values, *viz.* total pressure $p_{0c} = 79\,\text{bar}$, total temperature $T_{0c} = 746.3\,\text{K}$ and two inlet flow angles representing the axial flow in the meridional and the circumferential planes. These data were complemented by a single exit value, *viz.* static pressure $p_2 = 71\,\text{bar}$, and the radial equilibrium condition.

The URANS calculations were performed in two variants of grid resolution. The first variant used a grid with $56 \times \underline{52 \times 84} = 244\,608$ ($\underline{4368}$) nodes in one stator passage and $56 \times \underline{52 \times 116} = 337\,792$ ($\underline{6032}$) nodes in one rotor passage (the underlined numbers represent grid resolution in the circumferential plane, $y0z$). This grid resolution had been used by the author in a number of earlier numerical analyses on unsteady flow effects in turbine stages [2, 6, 7]. The parameters of the other grid, $52 \times \underline{100 \times 120} = 624\,000$ ($\underline{12\,000}$) nodes in the stator passage and $52 \times \underline{80 \times 168} = 698\,880$ ($\underline{13\,440}$) nodes in the rotor passage, were selected as the maximum data that could be handled by FlowER. The relation of the latter grid resolution to that warranting grid-independent results of 3D calculations was checked using as reference experimental data and 2D numerical results of stator/rotor studies available in the literature [8]. A detailed discussion of these results and the resultant conclusions can be found in Chapter 3 below.

The URANS calculations were performed at the Courant number equal to 20. Three grid levels were used, each successive grid being obtained by doubling the number of nodes in each direction. The number of iterations for the coarse, intermediate and fine grid was 50 000, 50 000 and 150 000, respectively, the latter number being determined through current monitoring of the convergence process.

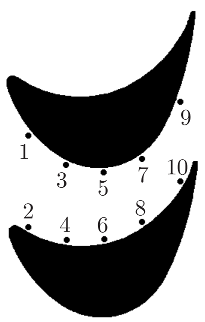

Figure 2. Velocity recording points in the rotor passage

The URANS calculations returned direct results in the form of discrete values of pressure, density and three velocity components at central cell points. In the unsteady calculations these results were recorded for an assumed number of instants during a time period separating two successive, identical configurations of stator and rotor blades. These data constituted the basis for determining time-histories of velocity fluctuations recorded at selected points in the rotor passage due to stator wake motion in their vicinity. The positions of these points are shown in Figure 2. Particular pairs of points, 1–2, 3–4, 5–6, 7–8 and 9–10, were located at a dimensionless axial distance of $z/c_{z,w} = 0.1$, 0.3, 0.5, 0.7 and 0.9, respectively, from the rotor blade's leading edge, at a distance of $1/16^{\mathrm{th}}$ of the rotor pitch, t_w, from the blade's surface in the y direction. The velocity fluctuations recorded, *i.e.* numerically generated, at those points are discussed in Chapter 4.

3. Validating the reference data in the model turbine stage

An attempt to examine the effect of grid resolution on the results of numerical calculations of the stator/rotor interaction by merely increasing the grid's resolution and recognizing the resultant tendencies did not seem to be an appropriate approach. The personal experience of the author with CFD codes, as well as that reported by other research workers, led him to the conclusion that increasing grid resolution might or might not result in increased accuracy of the obtained results. In some cases such approach would generate effects of purely numerical nature, unrelated to the physics of the examined phenomenon. Instead, an independent research tool seemed to be necessary to provide highly reliable results as reference data for RANS verification.

Obviously, the most reliable data are those recorded experimentally, when the studied phenomenon can be examined directly under the conditions in which it takes place.

Unfortunately, the present case of stator/rotor interaction could not be examined in this way, as the examined stage was a part of a real turbine in operation in a Polish power plant. To overcome this difficulty, an indirect method had to be used, after validating it on the available reference data recorded under other reliable conditions.

A method which could be used for this purpose was a numerical method based on the vortex dynamics theory (VDT). The present state of knowledge on the structure of the stator wake allows us to treat it as a sequence of vortices forming a part of the von Karman vortex street [9, 10]. Modelling the wake's structure with the aid of point vortices in two dimensions makes it possible to trace the deformation of the wake on its way through the rotor passage and analyze the relevant velocity field fluctuations. Theoretical fundamentals of this modelling can be found in the author's earlier publications [11, 12].

In order to obtain reliable results, the VDT code had to be verified on even more reliable, preferably experimental data. Despite a relatively large number of numerical and experimental studies recently published on the stator/rotor interaction, finding an appropriate publication in which wake analysis went as deep as the vortex structure of the wake proved to be very difficult. The most comprehensive and helpful analysis was published by Kost *et al.* [8] and includes the results of examination of the stator/rotor interaction in a single-stage model turbine, presented *inter alia* in the form of time-histories of velocity fluctuations recorded at various points in the rotor passage. The distribution of these points was identical to that shown in Figure 2.

As the model turbine stage examined by Kost *et al.* [8] differed from that shown in Figure 1 in geometry and flow parameters, comparison can only be made on qualitative basis. Basic differences between the two stages have been collected in Table 1.

Table 1. Basic differences in geometry and flow conditions between the model and real turbine stages

	Real turbine stage	Model turbine stage
Flowing medium	Steam	Air
Stage type	Impulse	Reaction
Stator-to-rotor pitch ratio, t_k/t_w	2	3/2
Stage inlet flow velocity	43.6 m/s	40.0 m/s
Number of stator vortices passing one rotor passage	14	10

The above data reveal comparable flow velocities at the stage inlet and comparable numbers of vortices constituting a stator wake fragment passing one rotor passage. Different properties of the medium flowing through the stage are not expected to affect the qualitative nature of the stator/rotor interaction, as long as the flow is subsonic and no wave systems are observed in the rotor passage. Different stage types mean that the flow acceleration takes a different course in each rotor. If we assume that the stator wake deformation rate is approximately the same in both cases, the combined action of the two above factors may result in certain differences in velocity fluctuations generated by the wake in each passage. These differences have been hypothetically assumed to be limited and have no qualitative effect on the course of stator/rotor interaction.

The time-histories of the velocity fluctuations experimentally recorded and numerically generated at corresponding points within the rotor passages of the real and model turbine stages are shown in Figure 3. Due to different steady-flow velocity levels at these points the curves in particular diagrams only represent velocity increments, dv, with respect to the average velocity. Continuous black lines show the results obtained with the VDT method, while the two remaining curves represent the results presented by Kost *et al.* [8]. The red curve with thickened dots shows the experimental results and the thin blue line – URANS calculations performed on a 2D grid with very fine resolution, approximately corresponding to 20 000 cells per one rotor passage.

A comparison of the experimental and VDT curves in particular diagrams reveals close similarity of their pattern, especially at points near the rotor blade's pressure side. The greatest differences can be observed in diagrams 1 and 7. These two points are located near the blade's suction side, in the area where most of stator wake vortices have their trajectories [11]. It can be shown that, when approaching point 1, the stator wake has a linear shape resembling a segment of the von Karman vortex street (see [8, 11]). On its way through the rotor passage the wake deforms into two vortices of opposite rotation. Relatively great differences in the intensity of velocity fluctuations observed at point 1 may result from insufficient accuracy of modelling the vorticity distributed in the linear wake as a sequence of point vortices.

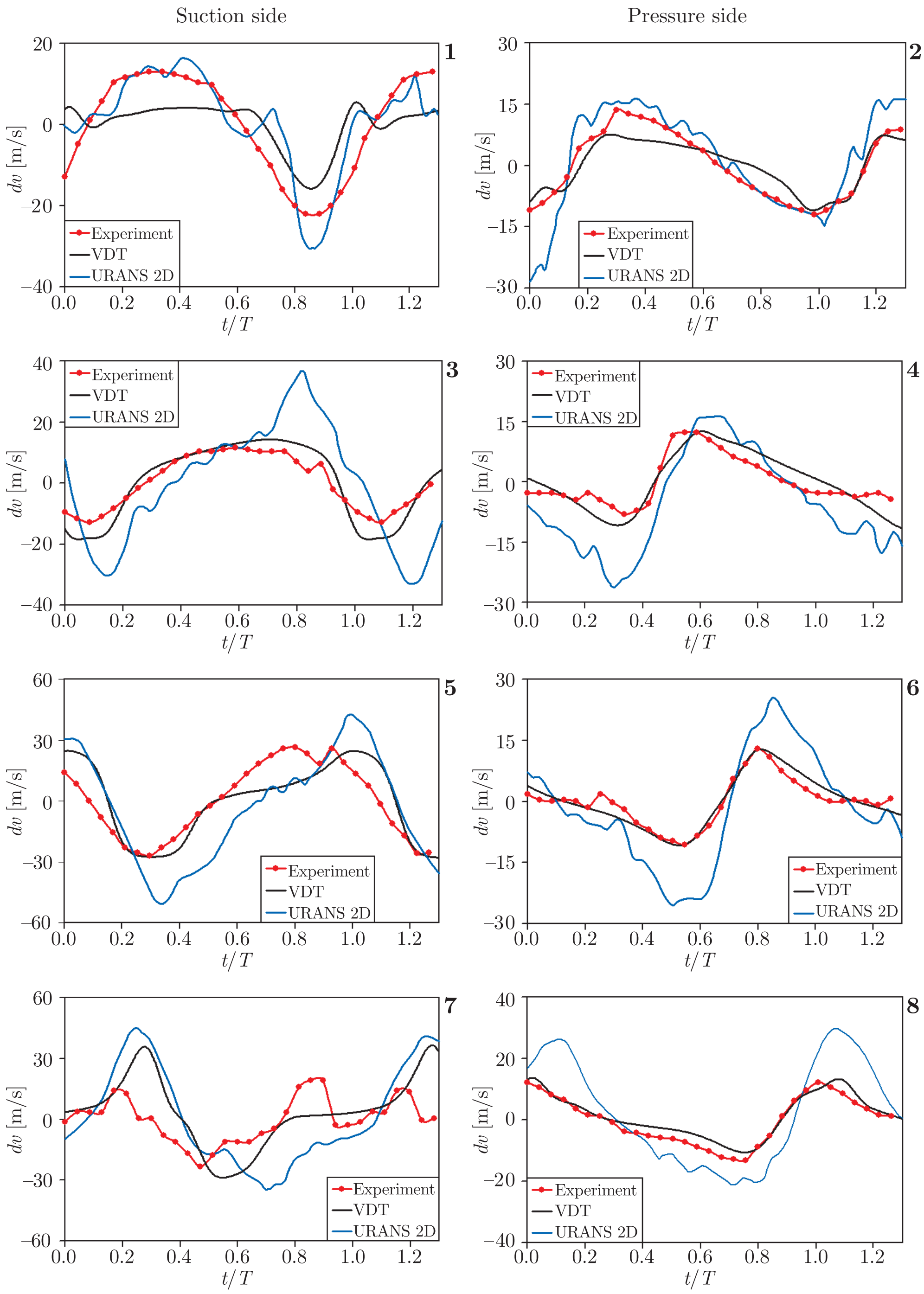

Figure 3. Time-histories of velocity fluctuations in the model turbine rotor passage

When the wake deforms (points 2–6) these differences decrease significantly, and remarkable differences can be observed again at point 7 only. This time they are both quantitative, referring to the amplitude of fluctuations and qualitative, observable as different shapes of the curves. It is difficult to indicate the origin of these differences; they could be due to different exit flow conditions, especially flow angles, calculated and recorded in the experiment. Such origin is made even more probable by the fact that the results of 2D URANS calculations reveal similar differences to those observed in VDT time-histories.

Considering the main goal of the present analysis, *viz.* assessing the effect of grid resolution on the results of CFD calculations of stator/rotor interaction, it is of paramount importance to check whether the grid resolution used by Kost *et al.* [8] in their 2D URANS calculations is sufficient to model properly the process of stator wake dissipation. For this purpose, velocity fluctuation amplitudes have been calculated at each recording point. The definition of this term and the method of its determination are shown in Figure 4.

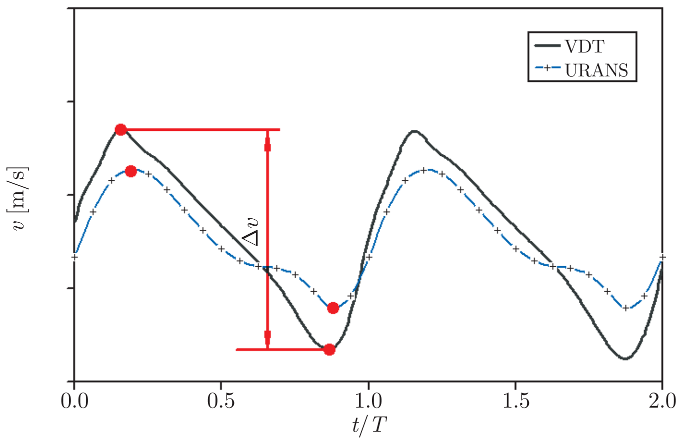

Figure 4. Definition of velocity fluctuation amplitude

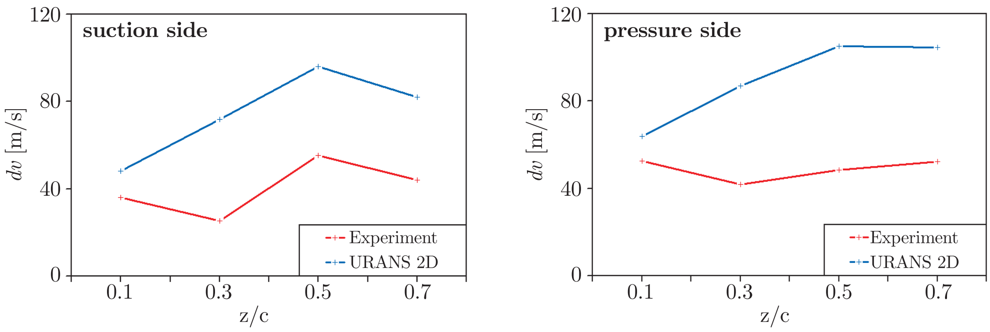

Figure 5. Velocity fluctuation amplitudes in the model turbine rotor passage

Changes of velocity fluctuation amplitudes along the rotor passage are shown in Figure 5. The lines obtained from 2D URANS calculations and experimental measurements reveal good consistency at points located both near the pressure and the suction sides, which allows us to conclude that *2D URANS calculations performed with grid resolution approximately corresponding to 20 000 nodes per one passage allow correct modelling of the dissipation of the stator wake on its way through the rotor passage.*

An extrapolation of this conclusion into 3D space, based on the assumption that the same grid resolution is preserved in the third direction, leads to the next conclusion: *the number of nodes securing grid-independent results of stator/rotor interactions in 3D calculations should be of the order of 2 000 000 nodes per one passage.*

4. URANS calculations in real turbine stage

When attempting to meet the above condition, a URANS code user can face certain technical and/or economic difficulties. These difficulties include limitations imposed by computer software, in some cases preventing assumption of matrix dimensions large enough to meet the satisfactory resolution condition. The technical limitations can origin both from the computer system and the code used. Another source of possible difficulties is time limitation. Increasing the number of grid nodes not only directly increases the time of calculations, but also decreases their convergence, as a result of which more iterations should be calculated to reach an acceptable convergence level. A combination of these factors may extend the total computing time beyond acceptable limits.

Some difficulties were also present in the reported case. To overcome them, a grid was assumed for URANS calculations with the highest possible resolution acceptable by FlowER and the computer system – see Chapter 2, grid variant 2. The reason for considering this grid representative for unsteady stator-rotor interaction calculations was that, as has been mentioned in the Introduction, the quantitative effects of this phenomenon are frequently of interest for turbine designers, facing certain restrictions on the acceptable time consumption of these calculations. In these two respects, FlowER abilities and design applications, variant 2 of the grid was a compromise between an earlier grid version used by the author [2, 6, 7] and the condition following from the analysis of results published by Kost *et al.* [8].

Figure 6 shows the URANS time-histories of velocity fluctuations recorded at the rotor passage points defined in Figure 2. It also includes velocity curves representing VDT calculations at these points, used as reference material.

It is advisable to start the discussion of results presented in Figure 6 from the pressure side, *i.e.* points 2, 4, 6, 8 and 10. As has been stated above, the stator wake in the turbine stage tends to take a trajectory close to the suction side of the rotor blade. Therefore, velocity fluctuations recorded at the pressure side, at a distance from the wake trajectories, are more regular and easier for interpretation and comparison. It should be mentioned here that, unlike the case discussed in Chapter 3, all variants presented in Figure 6 were calculated for the same stage geometry (represented by the mid-section circumferential plane in 2D VDT calculations) and the same flow conditions. Thus, their direct comparison, concerning not only velocity fluctuations but also its average values, is fully justified.

As could be expected, at the points located in the vicinity of the pressure side of the rotor blade the time-histories of the velocity fluctuations are very similar to each other. Another noticeable feature is that the URANS results obtained for the fine grid, with better resolution, are closer to the VDT curves than those obtained for the coarse grid. The observed differences between URANS and VDT curves seem to be

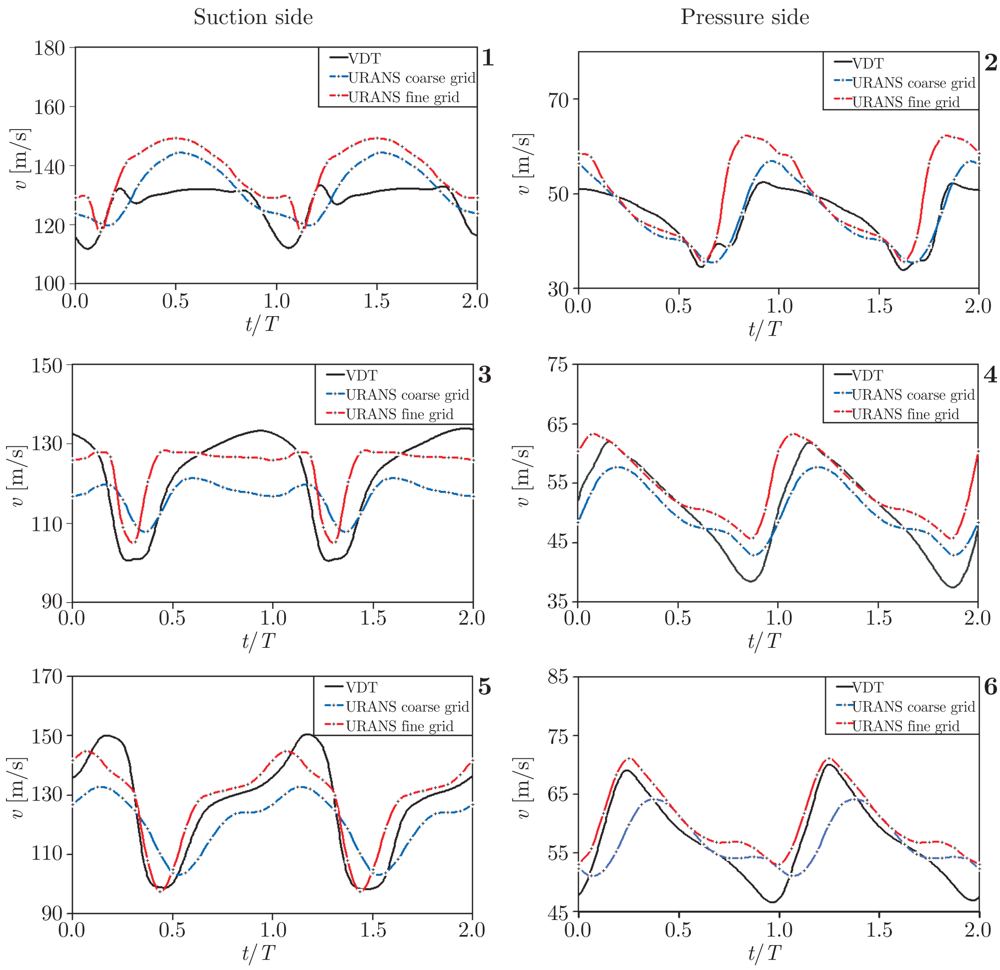

Figure 6. Time-histories of velocity fluctuations in the real turbine rotor passage

accidental and exhibit no regular tendency. Average velocities at the same points are slightly higher in URANS than in VDT calculations.

In the vicinity of the suction side of the rotor blade (points 1, 3, 5, 7 and 9) the differences in the shapes of URANS and VDT curves are more pronounced. Paradoxically, the greatest differences can be observed in two leading sections located close to the rotor passage inlet. Downstream, the shapes of the corresponding curves become closer to each other. Like for the pressure side, the URANS results obtained on the fine grid are closer to the VDT results than those obtained on the coarse grid.

Special attention should be paid to the results recorded at point 9. This point is located near the rotor passage exit, close to the rotor blade's suction side and to the hypothetical trajectories of stator wake vortices. The physical differences between the URANS and VDT approaches to modelling the stator/rotor interaction and numerical errors that cumulate during the time-consuming calculations are expected to be the most remarkable at this point. However, the URANS curve obtained on the fine grid reveals a pattern similar to that representing the VDT calculations. What is more, comparable locations and intensities of local extremes can be observed as well.

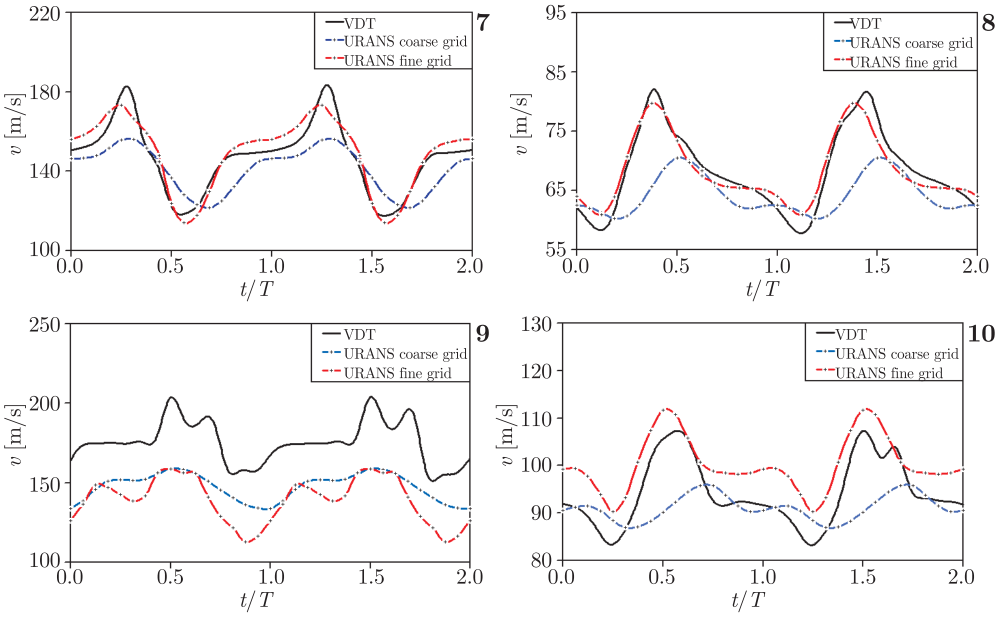

Figure 6 – continued. Time-histories of velocity fluctuations in the real turbine rotor passage

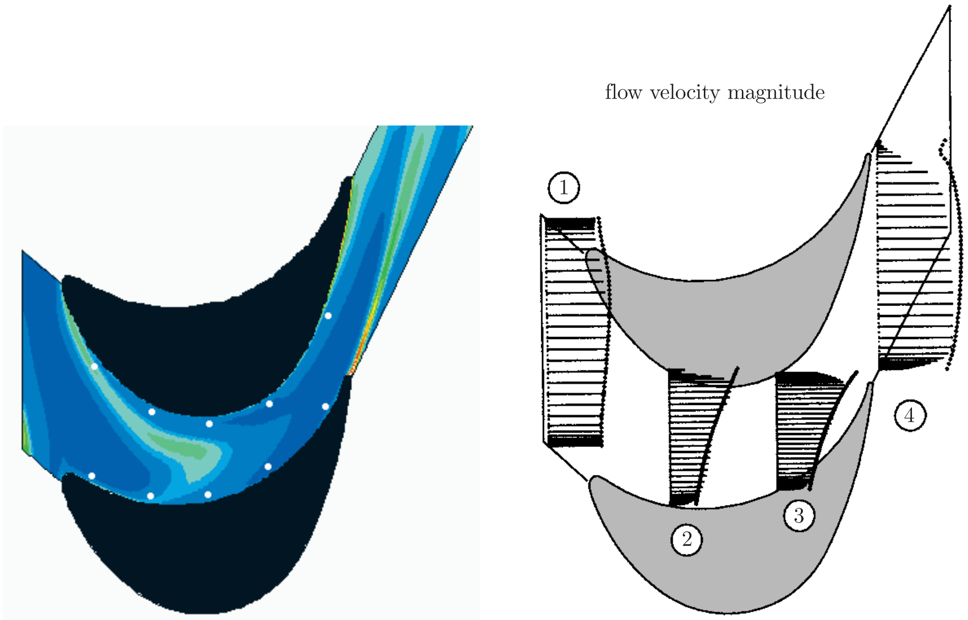

Figure 7. Locations of measuring points against instantaneous wake flow pattern (left) and flow velocity profiles in the rotor passage (right)

The most remarkable difference between URANS and VDT results recorded at point 9 is in the average velocity level, significantly lower in the URANS calculations. The source of this difference can be traced in Figure 7. Its left panel shows the locations of the recording points against the flow pattern for an arbitrary instantaneous position of the stator wake, while the right panel presents a comparison of velocity profiles

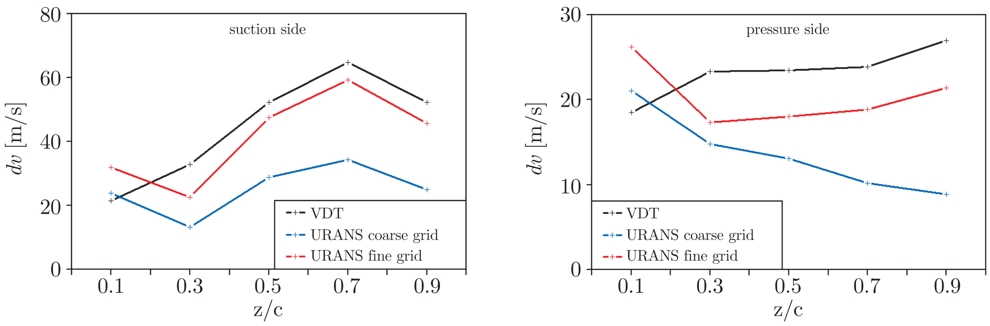

Figure 8. Velocity fluctuation amplitudes in the real turbine rotor passage

calculated using the two methods. The velocity profiles were taken in the sections corresponding to $z/c_{z,w} = -0.15$, 0.25, 0.67 and 1.02. The bars in the diagram represent velocity magnitudes calculated by URANS and the small crosses near the bars' tops are those obtained from the VDT calculations. The greatest differences between these two sets of velocity profiles are observable in the vicinity of the rotor exit, close to the suction side of the rotor blade, exactly in the area where point 9 is located. Generally, the positions of the recording points were chosen so that they were expected to be slightly *off* the boundary layer on both the suction and the pressure sides of the blade. Point 9 turns out to be *within* the boundary layer, which happens to be thicker in this area, a specific feature of the flow through the examined rotor cascade.

In order to assess the correctness of modelling the stator wake's dissipation with the 3D URANS model, velocity fluctuation amplitudes were calculated in successive rotor passage cross-sections in the way identical to that shown in Figure 4. The amplitude curves, this time obtained for a real turbine stage, are shown in Figure 8.

Increasing grid resolution in URANS calculations has led to a considerable reduction in wake dissipation. This tendency is illustrated by increased consistency of the amplitude change pattern obtained from URANS calculations with that representing the VDT solution, in which wake dissipation is ignored.

5. Conclusions

The effect of grid resolution on the results of numerical calculations of the stator/rotor interaction in a turbine stage has been analyzed using material obtained from calculations of two variants of the flow through a selected HP stage of a real turbine differing in grid resolution. The reference data were the results of calculations of the stator/rotor interaction in the same stage using the VDT method and validated on the available experimental data and 2D URANS results obtained on a very fine grid.

It follows from the analysis that the condition for correct modelling of the stator wake's dissipation in 3D URANS calculations of flow through a turbine stage is the use of grid resolution of approximately 2 000 000 cells per one rotor passage. Although the assessment has been made for conditions determined by the properties of FlowER, the code used in the reported analysis, in particular by the H-type grid provided by the code's preprocessor, it should also be valid for other types of grids, both structured and unstructured, created once for the entire calculation process. Unlike steady-state calculations, in which the most dramatic changes of flow parameters are expected mainly in the boundary layer and the wake behind the blade's trailing edge, in unsteady calculations it is impossible to predict a priori in which part of the computational area the grid should be refined. Consequently, to secure proper accuracy in each unsteady wake-cascade configuration, the grid has to cover the entire passage with relatively uniform resolution. This is how the requirement of 2 000 000 cells per one passage is to be understood.

This requirement can be considerably reduced for adaptive grids created on the basis of instantaneous distributions of flow parameters, although the situation is less clear there. Judging from the instantaneous wake pattern in the rotor passage shown in Figure 7, the reduction can be substantial and reach as much as 50–60 per cent. However, this does not necessarily entail a net saving in the total calculation parameters, in particular time, considering that adaptive grids are to be calculated individually before each iteration and their calculation times are comparable with those of the iterations themselves.

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