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ANALYSING STATOR/ROTOR INTERACTIONS IN ROTATING MACHINES

Stator/rotor interaction in a rotating machine stage is analysed using URANS and VDT codes, the latter taking into account vortex structure of the stator wake. It was shown that despite averaging on the stator/rotor sliding plane, URANS analyses correctly predict real effects of the S/R interaction.

rotating machine, stator/rotor interaction, vortex wake, stochastic process, grid resolution

Introduction

Stator/rotor (S/R) interactions in rotating machine stages and their effect on machine performance have been the object of investigation for decades. Initially the phenomenon was mainly studied experimentally to provide heuristic formulas linking kinetic energy loss attributed to unsteady effects with main stage geometry and flow parameters [1]. In that time the stator wake, the main actor of the S/R interaction, was believed to have the form of a regular band of fluid, without any internal structure, in which continuously decreasing velocity deficit and increased turbulence level were observed. No wake deformation was taken into account. More detailed studies of S/R interactions were only possible after extremely rapid development of computer technology and resultant appearance of computer codes allowing the phenomenon to be studied numerically. Most recent attempts have been made using so-called URANS codes that solve unsteady Navier-Stokes equations in the averaged form proposed by Reynolds for the flow of viscous and compressible fluid in two- or three-dimensional stage geometry. In these analyses the shape and physical parameters of the wake are obtained as part of the solution. At present such an approach is dominating and used in the overwhelming majority of S/R interaction studies.

It is commonly believed that the URANS codes have reached the level of development making it possible to use them for evaluating quantitative effects of S/R interaction, applicable in designing and evaluating performance of rotating machine stage constructions. However, to be effectively used for these purposes, the S/R interaction results obtained from URANS calcualtions are to be confronted against the most recent knowledge, collected in experiments, on the stator wake and the course of its interaction with the rotor cascade. The paper discusses two aspects of this knowledge, which are the internal structure of the wake and the loss of its activity during particular stages of the S/R interaction.

1. Vortex model of the stator wake

Standard URANS analyses of the S/R interaction produce the stator wake which has the “classical” form of a regular band of fluid revealing higher turbulence and velocity deficit, without traces of inner structural differentiation. However, experimental examination of stator wakes has delivered data testifying to the presence of regular coherent vortices in the wake [2,3]. Moreover, detailed numerical analyses of flow through the stator cascade alone, which were carried out on grid with sufficiently fine resolution and time step, also resulted in the generation of two rows of vortices arranged in the form of the von Karman vortex street. [4,5]. In this context, a problem of high significance for further S/R interaction studies is to find out whether and how the presence of active vortex structures in the wake affects the pattern of its behaviour known from URANS analyses. This problem is illustrated in Fig. 1 in which the stator wake is shown in two approaches, as a continuous band of fluid, obtained from URANS calculations, and the modified structure recorded using the Vortex Dynamics Theory (VDT).

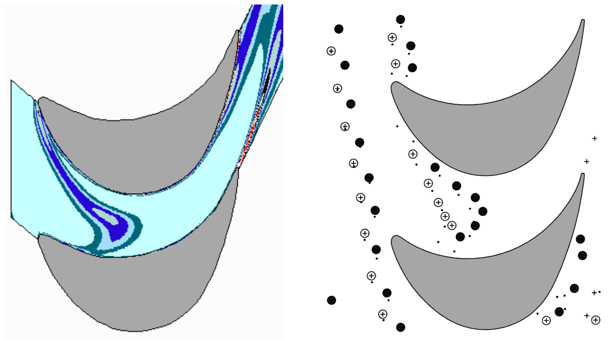

Fig. 1. Instantaneous stator wake pattern in the rotor passage in classical model (left) and that taking into account vortex structure of the wake (right)

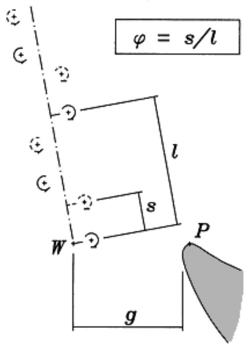

Fig. 2. Instantaneous arrangements of vortices in the wake

First consequence of the vortex structure of the wake is that the S/R interaction begins to reveal stochastic nature. [6]. For the classical model of the wake it is of no importance when the wake is cut off by the rotor blade – further course of its interaction with the rotor is always the same. On the other hand, when the wake reveals vortex structure, the course of its interaction with the rotor depends - for the same global geometrical, kinetic and thermodynamic parameters - on instantaneous positions of vortices in the wake when it is cut apart by the rotor blade. Since there are no data suggesting otherwise, it should be assumed that the above vortex arrangement is of random nature. This problem is illustrated in Fig. 2, showing two arrangements of wake vortices, displaced with respect to each other by the dimensionless distance $\varphi = s/l$, a measure of relative phase shift of vortices in the wake.

Trajectories of individual wake vortices in their motion through the rotor passage and, as a further consequence, kinetic and dynamic effects of its interaction with the rotor cascade will be different for different values of phase shift φ. That leads to a conclusion that: **different fragments of the same stator wake can behave differently in one and the same rotor passage.** This conclusion is of high importance from the point of view of experimental examination of the S/R interaction, in which a commonly used methodology is to record different realisations of the interaction for different time instants and then reconstructing a general interaction pattern from this material. The above-formulated conclusion says that in this situation we should take into account some inconsistence of the recorded data, connected with the stochastic nature of the interaction resulting from arbitrary phase shifts φ at the cut-off time.

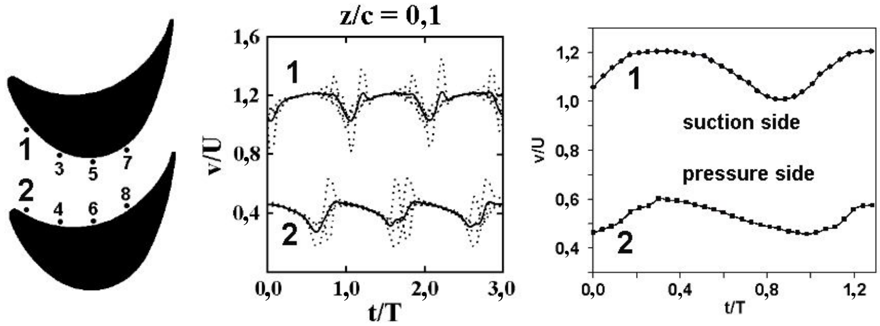

Fig. 3. Velocity fluctuations generated by different realisation of S/R vortex interaction. Left: sketch of rotor passage with marked locations of recording points, centre: VDT results [6], right: experimental results [7]

Sample effects of the above-mentioned stochastic nature of S/R interaction are given in Fig. 3 showing flow velocity fluctuations (related to the flow velocity in front of the stator cascade) at two selected points, point 1 and 2, situated inside the rotor passage close to the rotor passage inlet, z/c = 0,1. The central diagram shows time-histories of velocity fluctuations generated by VDT based calculations. Dotted lines represent four individual realisations of the S/R interaction obtained for four different phase shifts, while the continuous line marks the curve resulting from their averaging. The right-hand diagram, based on Ref [7], shows velocity fluctuations experimentally recorded in a model stage rotor having similar geometry and flow characteristics. The experimental curves were obtained by averaging 20 individual realisations. What is noticeable here is good agreement between the averaged curves recorded experimentally and generated by VDT at corresponding points. It is worth mentioning that similar agreement was recorded at all remaining points, 3 through 8, at which experimental data were recorded [6].

Confronting the conclusions resulting from the above analysis with the URANS procedure of calculations, a basic question can be formulated whether and to which extent the URANS calculations, performed, as a rule, for a single realisation, can be treated as representative of the general S/R interaction process. This question becomes even more justified in we take into account that the URANS calculations provide rather limited opportunities for re-constructing vortex structure of the wake in the rotor calculation area. Except for individual special cases, it would require the calculation region to cover all passages in stator and rotor cascades, which, taking into account the necessary grid resolution, goes well beyond calculating abilities of even biggest computers. In URANS calculations the above problem is usually solved using a special periodicity condition bearing the name of phase lag, which allows the entire calculation region to be reduced to one stator and one rotor passage. Between the stator and rotor cascade a sliding plane is placed, on which the phase lag condition is met.

When the wake is treated in a classical way as a uniform structure, the phase lag condition allows instantaneous wake parameters to be effectively passed from the stator to rotor calculation area. Unfortunately, the vortex structure of the wake is destroyed in this process due to a conflict, in general, between the phase shift of the wake vortices and the phase lag defining instantaneous position of the rotor cascade with respect to stator blades. As a consequence, the wake approaching the rotor calculation area is an average version of various realisations representing different vortex phase shifts. In this situation the above formulated question can be rephrased to **whether the wake, numerically "averaged" at the inlet to the rotor calculation region, will behave in an identical way, i.e. generate the same (averaged) effects as the real wake in multiple realisation.** The answer to this question is presented in Section 3.

2. Numerical accuracy

An important issue, which unfortunately is given little attention in publications on S/R interactions is selecting parameters of the calculation grid. Theoretically, the grid resolution should be sufficiently fine to eliminate numerical effects. In case of the S/R interaction this problem is difficult to analyse as high requirements concerning grid resolution force the calculations to be performed using full calculating potential of the available computer, which leaves no space for resolution analyses. It should be stressed that in most of the published S/R interaction analyses the presented results are of mainly qualitative nature, and aim at recognising the general course of interaction and its local effects. Quantitative results are usually oriented on predicting local pressure or velocity fluctuations, while the balance data, such as kinetic energy loss or stage efficiency are not examined. In those analyses the problem of grid resolution is not as important as in case of design calculations which aim at obtaining not only qualitative but also quantitative agreement of the results with the reality.

The problem of grid resolution in S/R interactions was studied in two dimensions by Arnone et al. [8, 9]. Important and useful conclusion from these investigations was that the grid-independent results can only be obtained when the grid is of an order of 17 000 cells in one rotor passage. The literature offers very limited data on the problem in three dimensions. Here, only author's own analysis can be mentioned [10], in which an attempt was made to assess necessary grid resolution based on comparing results presented in [7, 9] with own experience. A final conclusion of this study was assessing the grid consisting of 2 000 000 cells in one rotor passage as the minimum resolution securing preservation of real dynamics of the S/R interaction and, consequently, real level of generated losses.

3. Effects of wake deformation in VDT and URANS formulation

In order to find an answer to the question formulated at the end of Section 2, comparison was made between velocity fluctuations recorded at two points situated close to the rotor blade trailing edge, $z/c = 0{,}9$, at the pressure and suction side of the rotor blade. The data used for comparison were obtained from VDT and URANS calculations performed for the same rotor geometry and the same flow conditions. The URANS calculations were performed for two grid resolutions. The coarse grid, with an approximate number of rotor passage cells equal to 300 000, was in the past used by the author of the present article for S/R interaction studies, while the resolution of the fine grid on the circumferential plane y0z was assumed following recommendations given by Arnone et al [9].

The upper diagram in Fig. 4 presents velocity fluctuations determined at a point situated close to the pressure side of the rotor blade, as shown in the sketch at the upper left diagram corner. The continuous curve represents fluctuations obtained from VDT calculations, while broken and dotted line - URANS results obtained on the coarse and fine grid, respectively. Good agreement between VDT and URANS (fine grid) curves is not surprising here as the recording point is situated at a distance from the trajectories of the wake vortices. A similar opinion can be formulated for the remaining points, marked in Fig. 4, which are situated on the same side of the rotor blade [10]. The velocity fluctuation curve generated by URANS calculation on the coarse grid suggest that quantitative assessment of global effects of the S/R interaction on stage performance (forces, losses, efficiency) can be burdened with rather substantial error.

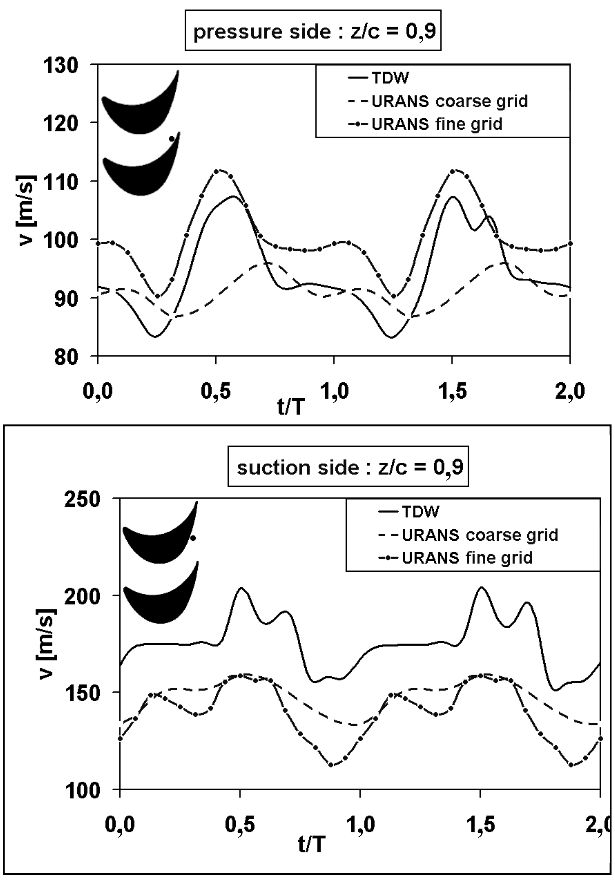

Fig. 4. Velocity fluctuations at the vicinity of the rotor blade trailing edge

The second selected point was also situated in the vicinity of rotor blade trailing edge, but close to its suction side. Such location of the recording point means that velocity fluctuations recorded here come from an already strongly deformed stator wake moving in the direct vicinity of the recording point. In other words, at this point most remarkable differences can be expected between VDT and URANS curves, due to both substantial methodological differences and purely numerical errors. In this situation, good agreement between VDT and URANS (fine grid) curves should be highly valued, as definitely positive answer to the question asked in Section 2. **URANS calculations, performed on a sufficiently fine grid and making use of a numerically "averaged" stator wake, properly predict time averaged effects of the real course of S/R interaction**.

Conclusions

The article presents an analysis of potential use of URANS codes for determining quantitative effects of S/R interaction in a rotating machine stage for design purposes. The assumed criterion of applicability was the level of agreement of the obtained results with real effects of S/R interaction. Differences were indicated between the uniform pattern of the stator wake obtained in URANS calculations and the vortex structure of the real wake, the latter leading to stochastic nature of S/R interaction. It was stated, however, that despite the above differences the URANS results properly predict time-averaged effects of real S/R interaction. The process of averaging the vortex structure of the wake on the sliding plane between stator and rotor calculation regions can be treated as sort of numerical "averaging" of different realisations of vortex S/T interaction.

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