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Streamwise Vortex Interaction with a Horseshoe Vortex

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Flow control in turbomachinery is very difficult because of the complexity of its fully 3-D flow structure. The authors propose to introduce streamwise vortices into the control of internal flows. A simple configuration of vortices was investigated in order to better understand the flow control methods by means of streamwise vortices. The research presented here concerns streamwise vortex interaction with a horseshoe vortex. The effects of such an interaction are significantly dependent on the relative location of the streamwise vortex in respect to the leading edge of the profile. The streamwise vortex is induced by an air jet. The horseshoe vortex is generated by the leading edge of a symmetric profile. Such a configuration gives possibility to investigate the interaction of these two vortices alone. The presented analysis is based on numerical simulations by means of N-S compressible solver with a two-equation turbulence model.

Keywords: flow control, horseshoe vortex, streamwise vortex.

Introduction

Streamwise vortices have already for a very long time been known to play an important role in flow control methods. Typical vortex generators (VG) are currently of the fixed type. Fixed type VG are preferred because of their reliability and maintenance free work. But already in the 70's it was shown that air-jet vortex generators (AJVG) are of the same effectiveness as fixed VGs even in supersonic flows[1]. In the 90's the research on AJVG was continued in subsonic velocities and was focused on the jet shape effect on the streamwise vortex intensity.

In the case of internal flows, as in turbines, many means of flow and heat exchange control devices are used. Very often an injection of coolant through holes and slots is applied. The increased effectiveness of such arrangements may be obtained by enhancement of mixing effectiveness. The cooling jets may also be used for flow control. Enhancement of mixing and flow control effects may be reached by applying jets as streamwise vortex generators. Application of AJVG in turbomachinery needs very careful consideration because the flow structure in these machines is three-dimensional and very complex.

In order to approach these problems the authors considered it as very useful to investigate the interaction of chosen elements of the three dimensional flow with a single streamwise vortex at the beginning. The most typical element of vortical 3-D structure, not only in turbomachinery, is the horseshoe vortex. It is generated by every leading edge being embedded in the boundary layer. The paper presented here deals with the investigation of the streamwise vortex effect on the structure of a horseshoe vortex.

Flow Configuration

The intention was to use a configuration which allows generating of the horseshoe vortex and streamwise vortex in similar conditions as in a turbine nozzle guide vane. Nevertheless, the intention was not to study the complete turbine passage flow but only the horseshoe vortex near the blade leading edge. In order to generate the horseshoe vortex a symmetric profile was used. Its leading edge curvature and the following thickness increase were designed basing on a real NGV profile. The inlet boundary layer thickness has been chosen in proportion to these dimensions. This way the horseshoe vortex formation is similar to a real configuration. The chosen configuration of the calculation domain is shown in Fig.1.

The air jets are located at the bottom wall upstream of the profile. The distance of the jets from the blade

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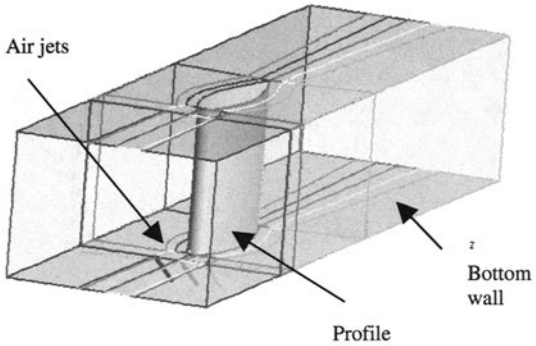

Fig.1 Geometry of the flow for numerical simulations

leading edge was designed in proportion to an existing blade size. In a real machine there is a technical possibility to implement such air jets. Only one jet was used for each flow considered. Three locations of the jets are presented here. Two of the locations are on either side of the blade, at a distance of a quarter of the width of the calculation domain. These locations allowed analysis of the interaction of a streamwise vortex with each branch of the horseshoe vortex, that is, of a different sense of rotation. Hence there are two different phenomena. The third location is chosen in such a way that it coincides with the leading edge and it was shifted until the maximum effect on horseshoe vortex was obtained. This last case involved much more computer time than the other two cases.

The velocity profile is assumed at the inlet. Inlet flow is homogeneous (M=0.3) except for the boundary layer at the bottom wall. This is a typical turbulent boundary layer profile including the distribution of turbulence characteristics, necessary for the two-equation turbulence model which is used in the numerical simulations. Boundary layer thickness is chosen in respect to the blade size. At the outlet the pressure condition is set. The upper limit of the calculation domain is assumed to be symmetry, imposing only the flow direction tangential to this plane. At side surfaces the periodic boundary condition is used. It brings the simulation closer to the cascade situation and this is necessary due to the fact that the air jets are inclined in a transverse direction. A freedom of flow passing through the side surface is necessary. The chosen pitch is also related to the blade size and boundary layer thickness.

Two intensities of the air jets were used. The first one is characterized by the same stagnation parameters as the main flow, so the jet outlet velocity was about M=0.3. In the second case the stagnation pressure was doubled and the jet outlet velocity was about M=0.7. Qualitative effects were, however, the same in both cases. This fact confirms the earlier observation that high jet momentum is not very important for streamwise vortex generation. In order to better illustrate the presentation, the results with higher stagnation pressure of air jets are shown below.

Numerical Approach

Numerical simulations concerned stationary flow. Solver SPARC was used which solves N-S equations for compressible and 3-D flow. The calculation domain is divided into 39 blocks as shown in Fig.1. The calculation grid consists of 3 mln volumes. Domain decomposition allows us to make parallel computing on our PC cluster. The grid is refined inside boundary layers and inside jets in order to keep y^+ below 1. A lot of attention was paid during grid generation in order to keep high space resolution in the area where 3-D flow structures are induced.

Horseshoe Vortex

First of all a numerical simulation of the flow without air jets was carried out. In this simulation the horseshoe vortex is formed at the bottom wall boundary layer. This flow case should give a symmetric horseshoe vortex. The streamlines presented in Fig.2 are streak lines which are generated upstream of the leading edge in the centre of each side of the horseshoe vortex. The location of these marker points (shown in Fig.3) is not ideally symmetric therefore some differences in streak line shape are visible, mostly downstream of the blade trailing edge. This is, however, negligible and it does not mean that the flow is asymmetric.

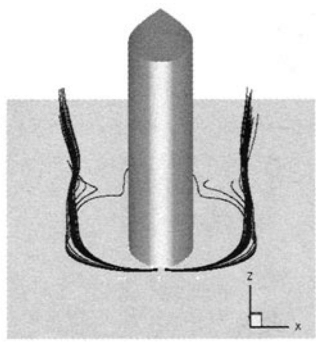

Fig.2 Visualisation of the horseshoe vortex

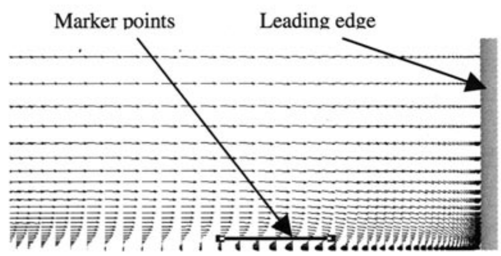

Fig.3 Location of the marker points

In order to visualize the development of the horseshoe vortex three cross-sections (shown in Fig.4, on the left) through the vortex were made and are shown in Fig.4. The cross-section planes are named 1, 2 and 3 and the flow visualisation on these planes is shown in the remaining pictures in Fig.4, marked by a corresponding cross-section number. On each picture contour plots are shown by different shades of grey which present the vorticity value. Each picture also presents the velocity component normal to the cross-section. On all three planes one may clearly find the extremum of vorticity displayed as a white area denoting the horseshoe vortex centre. On the cross-sections some stream lines are shown displaying the structure of flow field based on the velocity projected on these planes. Streak lines originating in the horseshoe vortex close to the leading edge are also shown in the presented pictures.

In cross-section 1 and 2 the flow structure is very similar to each other. Centre of the vortex is located in the place of vorticity extremum. Streamlines show that the flow is spiralling into the vortex core. Streamlines starting from the origin of the horseshoe vortex do not pass through the vortex core at cross-sections. In cross-section 3 the structure is somewhat different. The vortex centre is also of a spiral type but it displays a spiraling-out movement which makes the flow structure change. The spiralling out is connected with dissipation of vortex intensity. Vorticity value at the extremum at planes 1, 2 and 3 are of the value of 73000, 32000 and 9200 respectively. These numbers prove that the vortex intensity decays quite quickly.

Interaction of Sreamwise Vortex with Horseshoe Vortex Branches

Two limiting positions of air jets in respect to the profile (0.25 of pitch from the blade) provide two different phenomena and therefore the 3-D effect may be expected to be different. To make the interpretation of results clear let us look at the flow structure from the inlet section. There is a leading edge of the profile in view.

On the left side of the profile the horseshoe vortex branch rotates in the clockwise direction and on the right side of the profile in an anticlockwise direction. In this system of observation the air jet is blown out to the left side and therefore the generated streamwise vortex rotates in a clockwise direction.

When the jet is blown through the left hole the streamwise vortex interacts with the horseshoe vortex of the same sense of rotation. In Fig.5 the horseshoe vortex is visualised as previously in Fig.4 with cross-sections 1, 2, 3 and 4. The cut plane 1 intersects the streamwise vortex only. Streamlines in cross-section 1 indicate a vortex rotating in a clockwise direction, with streak lines of a jet passing through this area. The centre of the vortex coincides with a white extremum of vorticity. The vorticity in this extremum reaches value of 21000. The streamwise vortex is therefore weaker than the horseshoe vortex at its origin. The cross-section 2 in Fig.5 intersects additionally the horse shoe vortex. Its presence in the picture is indicated by an additional extremum of vorticity displayed as a lighter colour. The same colour of both vortices indicates the same direction of vortex rotation. The streak lines do not indicate spiral motion there because the cross-section is not perpendicular to the horseshoe vortex (compare with cross-section 1 in Fig.4). In cross-sections 3 and 4 both vortices are parallel to each other. At this distance from their origins both vortices integrate and we find a single extremum of vorticity. The main difference is that in the cross-section 3 the vortex is spiralling in and in 4 it is spiralling out.

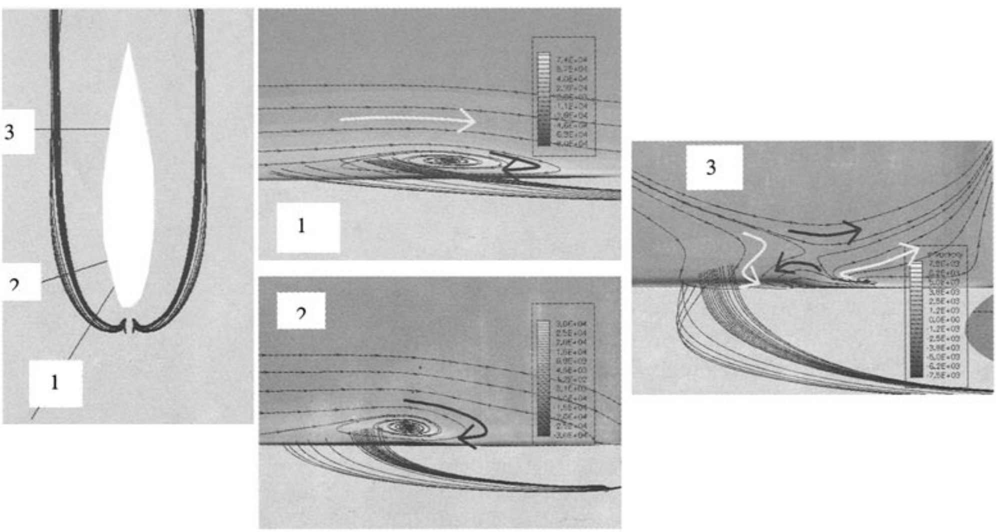

Fig.4 Cross-section location and vorticity contours with streak lines

This means that in 4 the vortex is being disintegrated. To the left side of this vortex at the wall a rotation in the opposite direction is induced.

The existence of the streamwise vortex on the left side of the profile influences also the horseshoe vortex on the right. This is an interesting conclusion which means that the vortex generator has an effect which is not localised but spans the whole inlet channel.

Different effects are observed when the streamwise vortex is located on the right side of the profile. In such a case interacting vortices are counter-rotating. In Fig.6 the interaction process is shown by the streak lines. Four cross-section planes are also used here. The first cross-section goes through the streamwise vortex alone and only one extremum of vorticity is present. It is white, which indicates clockwise rotation. All three other cuts show two extrema of vorticity-black and white. This is indicated by two counter-rotating vortices. The streak lines confirm this fact. The location of these vortices does not change much between cross-sections. It means that they preserve their individuality and do not wind up around each other. At 4, both vortices show a spiraling-out motion. It is the same observation as in previous cases and means the decrease of vorticity in the vortex centre leading to its disintegration.

Interaction of the Streamwise Vortex with the Leading Edge

The most pronounced effect of the streamwise

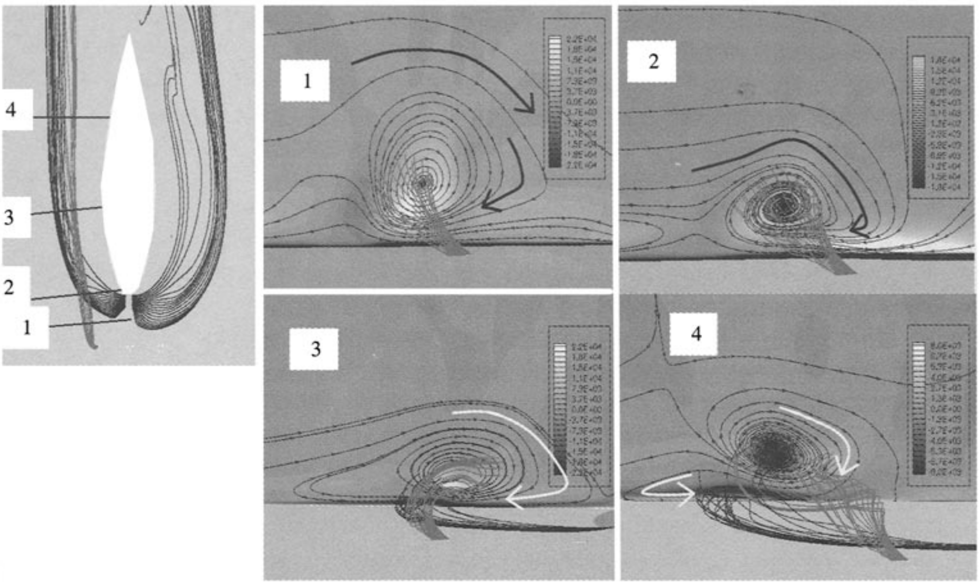

Fig.5 Cross-section location and vorticity contours with streak lines

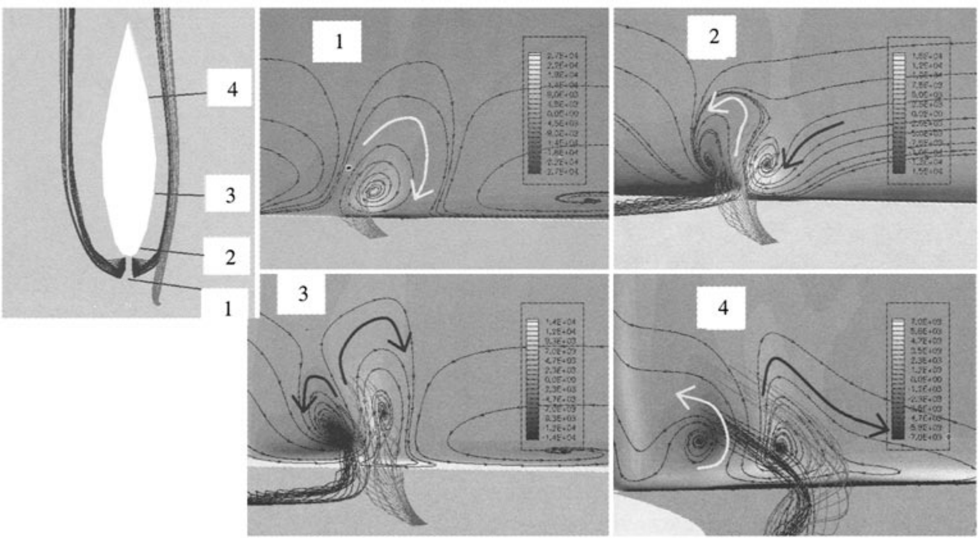

Fig.6 Cross-section location and vorticity contours with streak lines

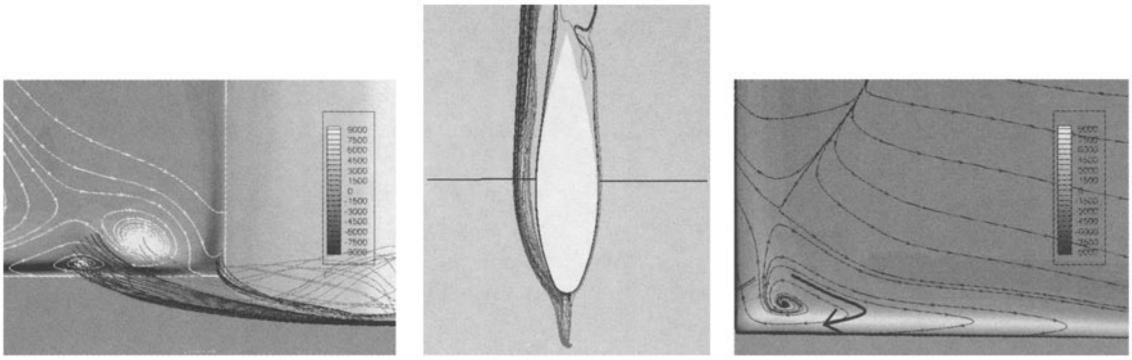

Fig.7 Streamwise vortex at the leading edge

vortex over the horseshoe vortex is obtained when the former impinges on the leading edge of the profile. In such a case the streamwise vortex affects the "heart" of the horseshoe vortex generation process and therefore has a pronounced effect. Fig.7 illustrates the effectiveness of this interaction.

The obtained effect is very sensitive to the relative location of the air jet to the blade leading edge. Nearly all streak lines originating in the horseshoe centre at the leading edge are driven to the left side of the blade. The action of the streamwise vortex has an extremely strong effect. It may be therefore useful to use this method in flow control to disintegrate the horseshoe vortex. The obtained result encourages this method to be used in the cascade flows. Hopefully it may suppress the development of a passage vortex.

In the middle drawing of Fig.7 two lines are drawn on both sides of the profile in the area of maximum thickness. They indicate left and right cross-sections shown on both sides. On the left side a strong clockwise vortex is present which incorporates the streamwise vortex and horseshoe vortex. This vortex induces a small rotation in an other direction further to the left. On the right side of the profile there is a small vortex in the corner which rotates in a clockwise direction. This sense of rotation indicates that it is not the remainder of a horse shoe vortex but that of the streamwise vortex.

Surface Pattern of the Streak Lines

Flow structure is well displayed by surface streaks which clearly show the direction of shear forces. Presentation of such lines is very helpful in the interpretation of the flow structure. In Fig.8 such a streak line pattern is presented for all considered cases. The first picture, described as "NO JET", shows just the horseshoe vortex. Streak lines indicate the separation zone between the main stream and the reversed flow just upstream of the leading edge. The separation is marked by a dotted line in all pictures. Black squares show all three locations of the applied jets. This picture allows us to draw a very important conclusion: the chosen dimensions and the inlet boundary layer thickness cause the air jets to be directly located at the separation line of the horseshoe vortex.

The horseshoe vortex reaches quite far upstream of the leading edge and the separation line is symmetric. At the bottom pictures show what happens when a streamwise vortex is generated on the left or on the right side. In the case of the left vortex the separation line is strongly asymmetric. On the left side it is pushed towards the blade but on the right side separation is pushed away from the blade. In the case of the right vortex the flow configuration is changed considerably. The separation area adjacent to the leading edge is much smaller and more symmetrical around the leading edge although the flow structure is not symmetrical. The most interesting structure is obtained with the vortex located at the centre. The separation area at the leading edge nearly disappeared. From the leading edge towards the jet exit a separation line is formed which divides the flow to two parts travelling along either side of the blade.

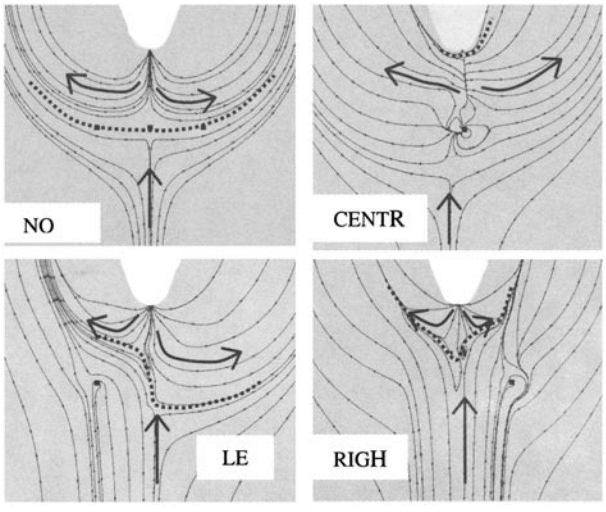

Fig.8 Suface streaks

Conclusions

Geometrical conditions and inlet boundary layer thickness were chosen in reference to the known NGV flow conditions. It turned out that in such a flow the air jets are located at the horseshoe separation line. In consequence, the streamwise vortex intensity is not very high but it showed very good effectiveness in controlling the horseshoe vortex. Effects of streamwise vortex and horseshoe vortex interaction are strongly dependent on the air jet location in respect to the profile leading edge. A streamwise vortex has a clockwise sense of rotation independent of its location. A horseshoe vortex rotates in a clockwise direction on the left side of the profile whilst on the right side in an anticlockwise direction. When the interaction takes place on the left side, the vortices rotate in the same direction. These vortices merge and form a single vortex displayed by the single vorticity extremum and rotation centre in the cross-sections. In this case of interaction a significant effect is also observed on the right side of the profile. Here, the separation line is strongly asymmetric on account of it being pushed closer to the blade on the left side and away from the blade on the right side.

When interaction takes place on the right side of the profile, the vortices are counter-rotating. These vortices preserve their individuality and do not wind-up around each other. Compared to the NO JET case, the separation line moves closer to the profile.

If a jet is placed close to the leading edge one may obtain a situation without horseshoe separation upstream of the leading edge. Instead a separation line is formed between the jet outlet and leading edge. Along this line the flow splits left and right of the profile. On the left side a clockwise vortex is formed and on the right side nearly no vortical motion is observed.

The obtained results show the streamwise vortex's outstanding ability to control the horseshoe vortex. This applies also to the flow structure characteristic of the NGV flows. The results provide good basis for the investigation of AJVG application in cascade flows.

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