УДК 53

Взаимодействие двух противоположно вращающихся сверхзвуковых вихрей

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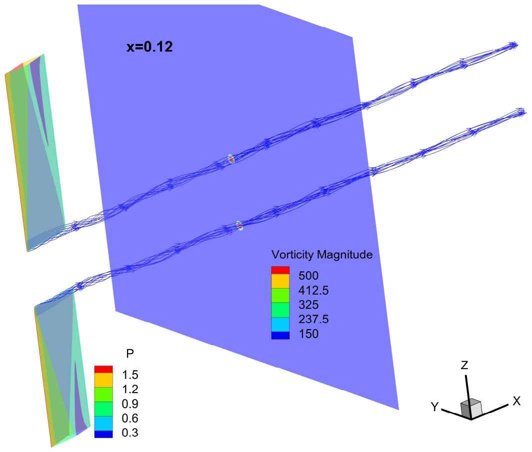
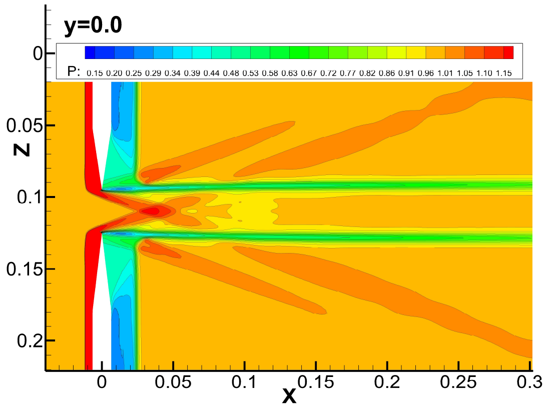
Аннотация

В работе представлено численное исследование двух противоположно вращающихся сверхзвуковых вихрей. Два соосных прямых полукрыла с острыми передней и задней кромками рассматривались в качестве вихре-генераторов при числе Маха набегающего потока $M_\infty = 3$. Численные расчеты были проведены на суперкомпьютерной системе К-60 в Институте Прикладной Математики им. М.В. Келдыша РАН с использованием параллельного алгоритма для моделирования турбулентных течений. Был применен подход, основанный на методе URANS с моделью турбулентности SA. Численные результаты были получены в области равной 10 хордам крыльев от оси крыльев вниз по потоку. В вихревом следе были численно получены параметры течения, в частности, данные на осях концевых вихрей и в поперечных сечениях. Был проведен анализ данных в зависимости от расстояния от крыльев-генераторов.

Ключевые слова: сверхзвуковые течения, турбулентные течения, противоположно вращающиеся вихри, концевой вихрь.



Генераторы контр-вращающихся вихрей с распределением давления на них, линии тока с концевой хорды, модуль завихренности в поперечном сечении $x = 0.12$, $M_\infty = 3$



Взаимодействие ударной волны и концевых вихрей: распределение давления в сечении вдоль потока, проходящем через общую ось крыльев-генераторов ($y = 0.0$) $M_\infty = 3$

Interaction of Two Counter-Rotating Supersonic Vortices

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Abstract

A numerical investigation of two counter-rotating wingtip vortices propagation in a supersonic flow was performed in this paper. A straight coaxial wings with sharp leading and trailing edges at an attack angle of 10 degrees were considered as wingtip vortices generators at Mach number of incoming flow $M_\infty = 3$. Numerical simulations were carried out on the supercomputing system K-60 at the Keldysh Institute of Applied Mathematics RAS using the parallel algorithm for turbulent flow simulation. An approach based on the URANS method with using the SA turbulence model was applied. Numerical data were obtained in the domain of 10 wing chords downstream from a wings axis. A numerical data on the flow parameters in the vortex wake was obtained, in particular, data on the wingtip vortices axis and in the cross-sections. The data was investigated depending on a distance from the wings - vortex generators.

Keywords: supersonic flow, turbulent flow, counter-rotating vortices, wingtip vortex.

1. Introduction

The study of tip vortices, including supersonic ones, is an important problem of aerodynamics. This is primarily due to aviation safety associated with trailing-vortex hazard, but also to the impact of aircraft on the environment. For supersonic aircrafts, the study of tip vortices is also concerned the danger of tip vortex hitting on other elements of the aircraft located downstream and the solution of the aircraft visibility problem. In addition to studying individual tip vortices, studying the influence of acoustic disturbances on them [1, 2], it is important to understand how the mutual propagation of several tip vortices occurs. In particular, the mutual propagation of two supersonic tip vortices is an important aerodynamics problem. One of the last extensive reviews of vortex pair dynamics and interactions was made in [3] as well as in [4]. Experimental data and investigations on a dynamics of vortex pairs concern mainly subsonic regimes.

The aim of this work is to study the mutual propagation of two supersonic counter-rotating wingtip vortices. The results will be detailed in 4th paragraph.

This work is a continuation of the series of studies effectuated by co-authors and dedicated to supersonic wingtip vortices. The main of ones are [5, 6, 7, 8]. In these previous works, supersonic semi span wing tip vortices at a great distance from the wing-generator (30 wing chord downstream the wing axis) and an influence of acoustic-type perturbations on them at different Mach numbers of the incoming flow were investigated. For steady state incoming flow a comprehensive numerical-experimental data on the position and dimension of the single vortex core for different inflow Mach numbers with quantitative data on the distribution of gas-dynamic characteristics of the flow have been obtained [5, 8]. The influence of acoustic type disturbances on the wingtip vortex was studied numerically [6, 7, 8]. The investigated semi span wing from the mentioned works was the same as one of the vortex generators in this study (the one that is longer). In this paper, in paragraph 3, the main results of the previous works of the authors concerning the study of the wing tip vortex dependence on the Mach number at large distances from the wing in supersonic regimes for steady state incoming flow are briefly presented. The results for the influence of acoustic type disturbances on the wingtip vortex may be found in [6, 7, 8], where the disturbances were introduced in steady state incoming flow in the form of a monochromatic plane wave with small amplitude at the inlet boundary by analogy with the [9].

2. Model description

2.1. Numerical method

A system of unsteady Reynolds averaged Navier – Stokes equations (URANS) with the one-parameter Spalart – Allmaras (SA) turbulence model for compressible flows [10] with Edwards modification [11] was used for describing a supersonic flow of a perfect viscous compressible fluid. SA is one of a widely-used turbulence models, especially in aerodynamics. It was first published in 1992[12] and afterwards a number of modifications and a great number of validations were carried out [13, 14 etc.]. This model appears to be the most accurate for practical turbulent-flow applications [15] among one-equation models and it is used in many well-known software packages such as CFL3D, Ansys etc. In previous works of co-authors an application of the SA model gives a satisfactory agreement between numerical and experimental data [5].

The finite volume method based on the reconstruction schemas of the second order (TVD) or the third order (WENO) was used for the discretization of equations. Time approximation was performed by means of either an implicit scheme based on the LU-SGS method or by an explicit scheme. A more detailed description of the numerical algorithms and the mathematical model used in this work is given in [16].

The numerical simulations have been performed at the Keldysh Institute of Applied Mathematics RAS using the hybrid supercomputer system K-60 [17].

An unstructured grid with hexagonal cells was used. Number of cells was 7 284 116. In previous work of co-authors associated with a single half-wing [5], the grid had about 18 000000 cells but calculating domain was three times longer downstream from the wing axis. In those simulations, a comparison of numerical data with experimental data was carried out, which showed a satisfactory agreement that suggest sufficiency of constructed grid.

The grid was refined in the zone of vortex formation (especially near the wing tip chords, fig.2 – b) and in the zone of the wingtip vortices propagation throughout all simulation area. It was done in such a way that the average size of the cells in the vortex zone approximately corresponds to the size of the same ones in work [5].

All calculating values were nondimensionalized during numerical simulations. Nondimensionalization was carried out in a standard way for URANS equations [18].

2.2. Geometry

The supersonic flow behind two wings – wingtip vortex generators was studied. The wings were coaxial straight with sharp leading and trailing edges and sharp tip chord. The wings had a diamond-shaped base which small diagonal was 4.5 mm, a chord $b = 30$ mm, a half-span 75 mm and 95 mm (fig. 1, fig. 2, *a*). The distance between wingtip chords was 30 mm. The wings attack angle was 10 degrees. The problem was considered in a dimensionless statement.

Numerical grid was constructed for nondimensionalized variables where the chord length was 0.03. Length of simulation domain was 10 wing chords downstream from the wings axis. The Mach number of incoming flow was $M_\infty = 3$ and Reynolds number $Re = 1\times10^7$. Represented Reynolds number corresponded to a linear size of 1 m. The simulation aria was a parallelepiped. The origin of coordinates was located on the common axis of the wings. The plane $x = 0$ passed through common wings axis and was perpendicular to the incoming flow direction. The plane $y = 0$ passed through common wings axis and was parallel to the incoming flow direction. Common wings axis coincided with axis z. The direction of the axis x coincided with the direction of the input free stream. The wings-generators were fixed by a root chord on the walls, so the width of the considered domain (domain z size) was 0.2.The mentioned walls were parallel to the plane $z = 0$ and coincide with the planes $z = 0.2$ and $z = 0.22$. The height of the considered domain (domain y size) was 0.225. Coordinate x changes from -0.04 till 0.3018.

The parameters of the incoming flow were set as the initial conditions.

Boundary conditions were as follows. On the inlet boundary the incoming flow was set. On the vortex generators and on the walls of their attachment, the wall no-slip boundary condition was set, i.e., the velocity vector was equal to zero. On the other two side surfaces the incoming flow was set. On the outlet boundary supersonic outlet condition was set: the gradients of all variables were set zero in normal direction.

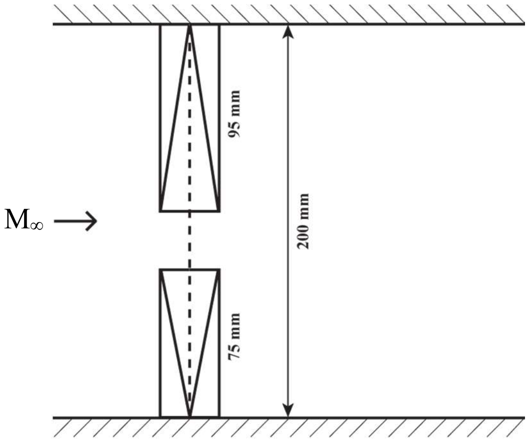
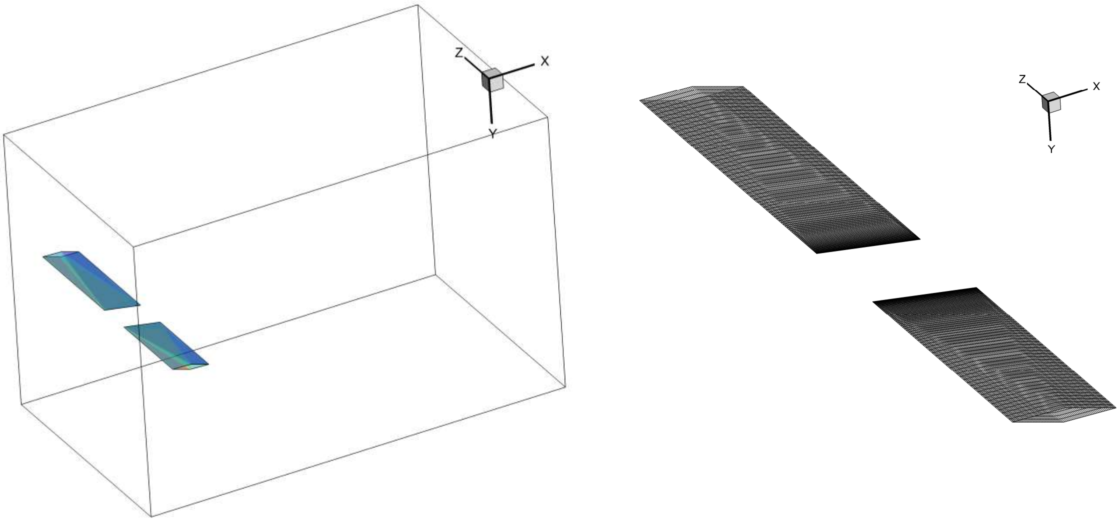


Fig. 1. Schema of study problem



a *b*

Fig. 2. Wing – generators: simulation domain (*a*) and wing surface mesh (*b*)

3. Wingtip vortex in steady state incoming flow at wide distance

Previously with the same numerical approach the authors have been investigated the supersonic wingtip vortex for different incoming Mach numbers $M_\infty = 2$, 3 and 4 for a large distance of 30 wing chords downstream from wing axis [5, 8]. The wing-generator had the same geometry as the longer one in this work. These results will be briefly outlinedbelow in this section for completeness.

A formed supersonic wingtip vortex develops as a kind of longitudinal structure with an axis (fig. 3). This axis is characterized by a minimum of such values as density, pressure; by static temperature increase and a maximum of longitudinal vorticity *X Vorticity* and of *Helicity*. Helicity $H = \mathbf{V} \cdot \nabla \times \mathbf{V}$ have a topological interpretation as a measure of vortex lines knottiness in the flow, where $\mathbf{V} = (u, v, w)$ is a velocity vector. At the boundary of the wingtip vortex core, a maximum of the tangential Mach number M_{yz} and of the mass flow root-mean-square pulsations are observed.

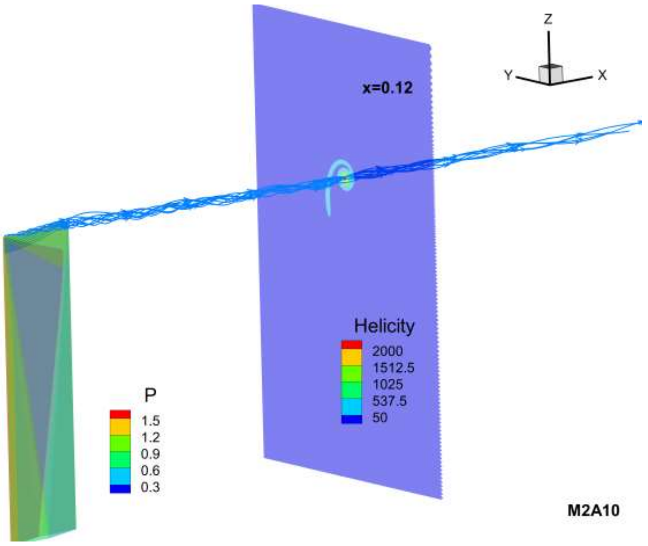
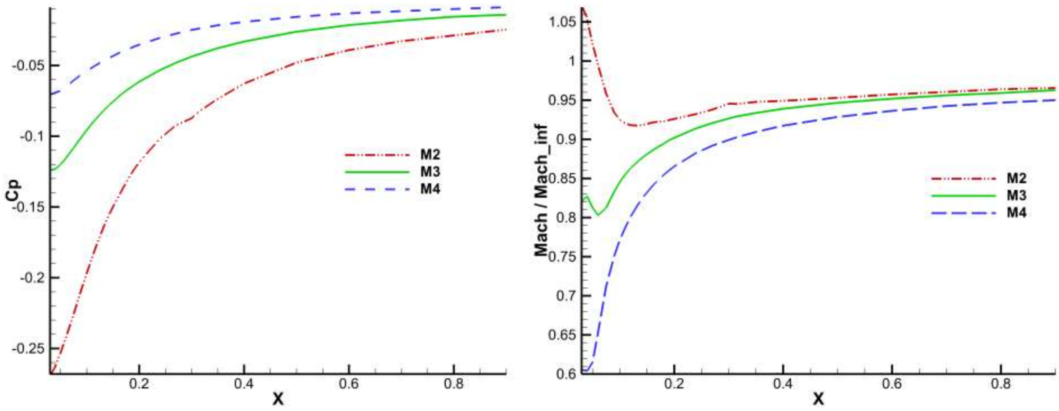


Fig. 3. Pressure P on the wing-generator, the stream traces passing through/near the wingtip and helicity contours in the cross section $x = 0.12$ for $\mathrm{M}_\infty = 2$

It was found that the wingtip vortex loses intensity when moving downstream from the wing-generator, but it spreads over the entire simulation region and the vortex flow parameters do not reach their values in the free flow. For example, on the figure 4 there are two parameters on the vortex axis: a pressure coefficient C_p, $C_p = (P - P_\infty) / 0.5 \rho_\infty \mathbf{V}_\infty^2$, and normalized Mach number. This two parameters increase with increasing of coordinate x (i.e. downstream from the wing).



a *b*

Fig. 4. Pressure coefficient C_p (*a*), and normalized Mach number (*b*) on the wingtip vortex axis along the coordinate x for different inflow Mach numbers

A satisfactory agreement between numerical and experimental mass flow data was confirmed in [5].

It was foundthat with increasing Mach number the intensity of the wingtip vortices increases in the sense of decreasing on the vortex axis such parameters as pressure or pressure coefficient, and ascending on the axis of the vorticity magnitude, and ascending of the tangential Mach number in the vortex body [5−8]. A wake-like type flow was found in the supersonic wingtip vortices (when normalized Mach number is less than one) except the near region behind the wing-generator at incoming Mach number $M_\infty = 2$ when flow was jet-like (fig. 4, *b*). Aerodynamic parameter values in wingtip vortices do not reach the values of the incoming flow until the end of the calculation region, i.e. the vortices do not disappear in the considered region of 30 wing chords.

4. Two counter-rotating wingtip vortices

As mentioned above, a mutual propagation of two counter-rotating supersonic vortices is numerically investigated in this work up to the distance of 10 chords downstream from the axis of coaxial wings-generators at Mach number $M_\infty = 3$.

Figure 5 gives a general representation of the obtained flow. It shows a pressure distribution *P* on the wings - vortex generators surfaces, tip edge streamtraces and vorticity magnitude contours in the cross section $x = 0.12$. The wingtip vortices extend from the tip edge of the wings downstream along the calculation area.

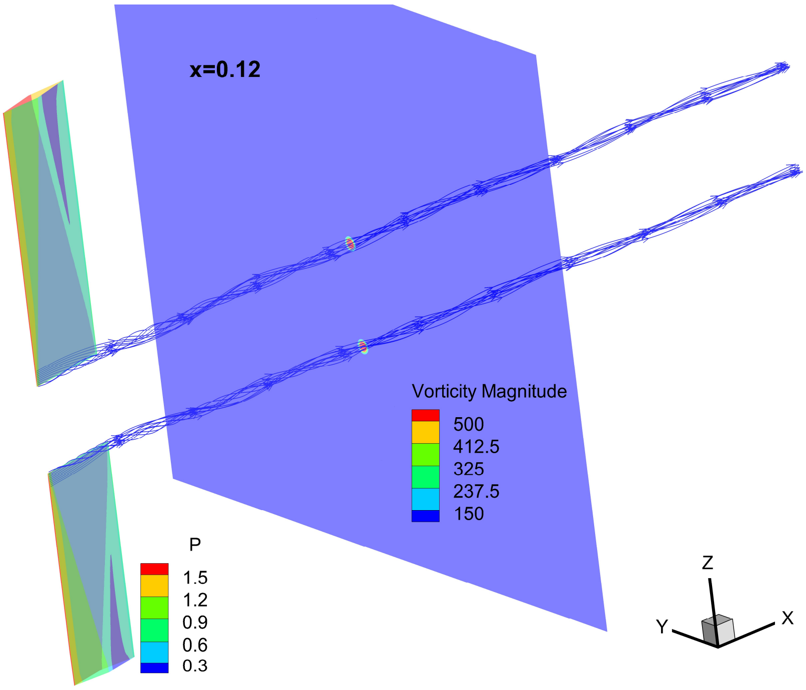


Fig. 5. Wings-generators with pressure distribution on it, tip edge streamtraces, vorticity magnitude in the cross section $x = 0.12$, $M_\infty = 3$

Figure 6 shows pressure distribution in the stream wise section passing through the wings-generators mutual axis ($y = 0.0$). Figure 7 shows pressure distribution in the cross-section $x = 0.09$, coordinate axis y is directed from the leeward side to the windward side of the wings. There is an interaction between wingtip vortices and relatively weak compression waves from the neighbour wing on these figures. Vortices pass the region of these relatively weak compression waves without significant changes. The magnitude of the pressure change in these waves is comparable to the amplitude of the pressure fluctuation at a distance of 30 chords ($x = 0.9$) downstream from the wing axis in the study of the influence of acoustic disturbances on a single wingtip vortex at $M_\infty = 3$ and $\omega = 100$ (fig. 15 in [7]).

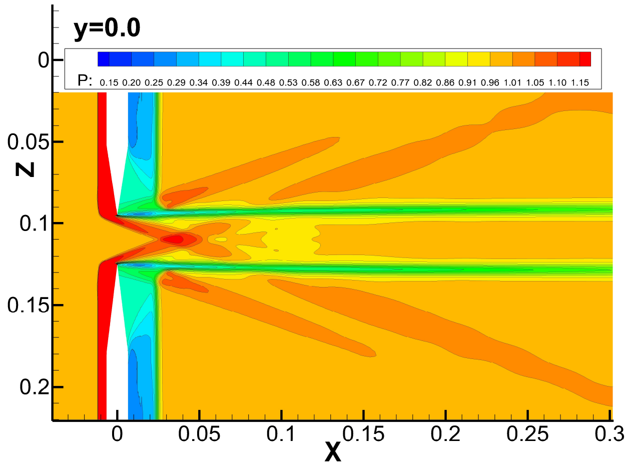


Fig. 6. Shock waves wingtip vortices interaction: pressure distribution in the stream wise section $y = 0.0$ passing through the wings-generators axis, $M_\infty = 3$

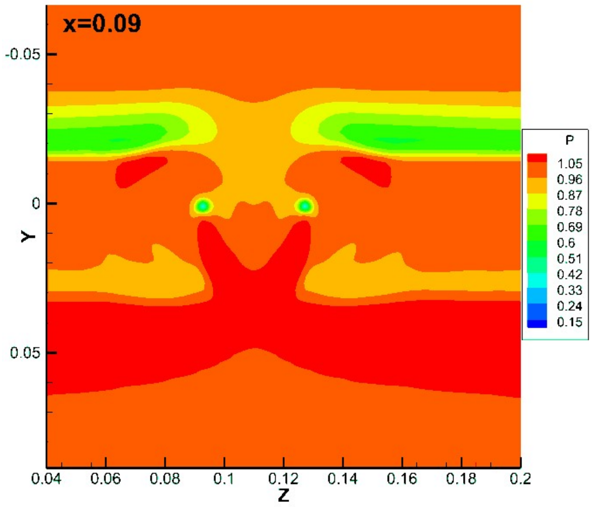
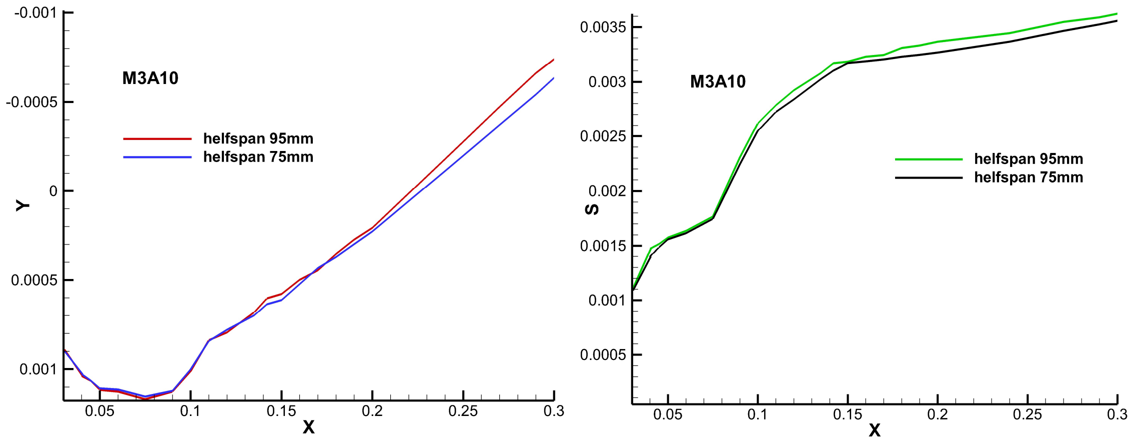


Fig. 7. Shock waves wingtip vortices interaction: pressure distribution in the cross-section $x = 0.09$, $M_\infty = 3$

The position of the wingtip vortex axes is of particular interest. Figure 8, *a* shows the vertical vortex axes coordinates *y*, fig. 8, *b* shows the horizontal vortex axes coordinates i.e. coordinates along direction of wings mutual axis (coordinate *z*).

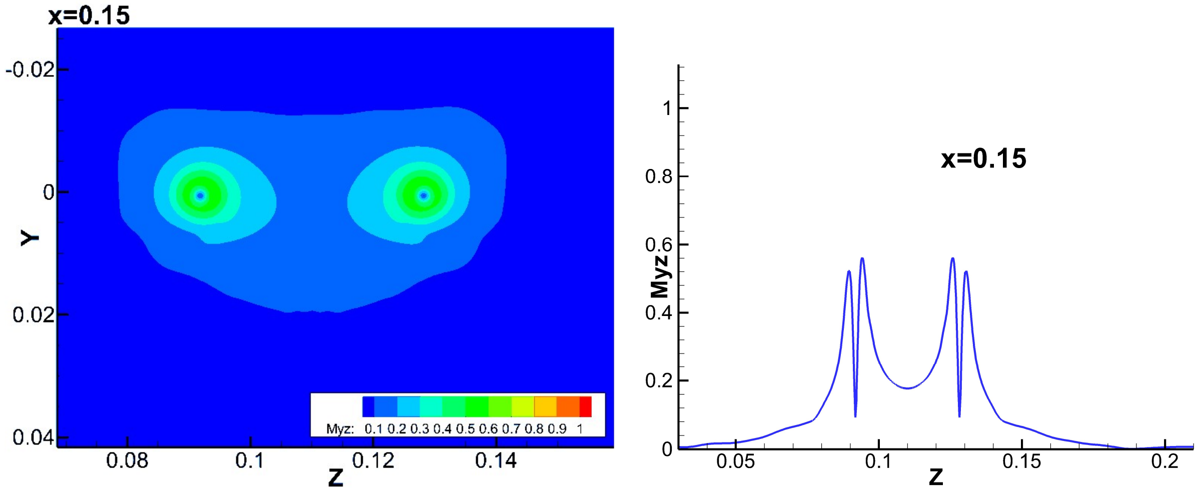


a *b*

Fig. 8. Vortex axis coordinates of wings – generators: *y* (*a*) and *S* (*b*)

S is the distance between the vortex axis coordinate *z* and the tip chord of corresponding wing - generator. The wingtip vortex axes mutual upward displacement is noted (fig. 8, *a*) i.e. axes displacement in the direction of the *y* axis decreasing, which is directed from the leeward wing side to the windward wing side. This fact is in agreement with other data from a literature [19, 20]. Also it can be stated that the convergence of vortices is not observed at the considered distances. On the contrary, there is a slight repulsion of the vortex axes from each other. Similar results were obtained in [20]. Small differences in the graphs of vortex axes coordinates require a further study. Presumably, the reason for this is the mutual influence of vortices.

Separately, it is worth noting the change in the shape of vortices (fig. 9). There is a skew of the tangential Mach number value in the core of the wingtip vortices towards the neighbour vortex. That is, the Mach number in the vortex cores is greater from the side of the neighbour vortex. This is due to additional velocity induction from a neighboring vortex.



a *b*

Fig. 9. Tangential Mach number M_{yz} : (*a*) in cross-section $x=0.15$; (*b*) in cross-section $x=0.15$ along the line $y=0.00126784$

The values $y=0.00126784$ presented on the fig. 9 and $y=-0.00018033$ presented on the fig. 10 correspond to *y* coordinate of half-span 95 mm wingtip vortex axis in cross-sections $x=0.15$ and $x=0.24$ respectively.

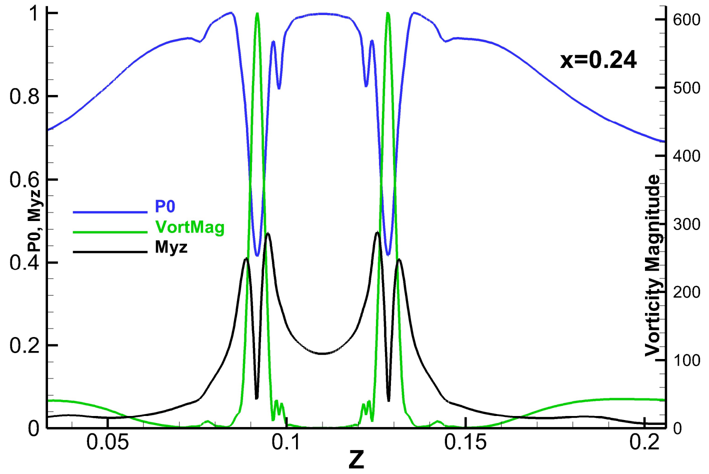


Fig. 10. Total pressure P_0, tangential Mach number M_{yz} and *Vorticity* magnitude in cross-section $x=0.24$ along the line $y=-0.00018033$

The tip vortex of wing with a half-span 95 mm is located on the right side of each of these graphs. In the fig. 10 three flow parameters are presented in the cross-section $x = 0.24$ along the line $y = -0.00018033$: total pressure P_0, tangential Mach number M_{yz} and *Vorticity* magnitude. The main properties of vortices are clearly distinguishable on this figure, such as the minimum of the total pressure and the maximum of the vorticity magnitude on the vortex axes and the maximum of the tangential Mach number in the vortex cores. A skew in the shape of the vortex cores in the sense of increasing of the tangential Mach number values from the side of the neighboring vortex is also noted.

5. Conclusions

This paper presents the results of the numerical study of two counter-rotating supersonic vortices mutual propagation behind two coaxial wings-generators in the supersonic flow at Mach number $\mathrm{M}_\infty = 3$. Wingtip chords situated at distance of one chord from one another. A numerical simulation was performed for the region of 10 chords downstream within the framework of the URANS approach with the Spalart−Allmaras turbulence model. The flow parameters in the vortices wake were obtained as a result of the calculations.

The analysis of the results showed that there is an interaction of two vortices with shock waves from the neighbor wing-generator. However, these shock waves are rather weak and the vortices pass through this region without significant changes.

A shift of the vortex axis towards the leeward side of the wings was obtained. The spacing between vortex axis increases with the distance downstream from the wings-generators in the considered domain.

Vortex core facing to the neighbour vortex has greater values of tangential Mach number M_{yz}.

Acknowledgments

The work was supported by the Russian Foundation for Basic Research (the project No. 19-01-00765a).

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Статья поступила в редакцию 18 марта 2020 г.