On determining the vortex core center in wing wake at $M = 2$

A M Shevchenko, A S Shmakov and V V Kulikov
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
4/1, Institutskaya str., Novosibirsk, 630090, Russia
shevch@itam.nsc.ru

Abstract. The paper presents the processing of the results of numerical simulation of the vortex flow in the wing wake, the purpose of which is to search for the vortex core center. It is based on the results of numerical simulation of the vortex flow in the wake behind of the rectangular wing, performed at the Keldysh Institute of Applied Mathematics RAS. The center of the vortex core was determined in several ways: by the minima of the total and static pressure, the axial Mach number, mass flow rate, the maximum of axial vorticity, and as the center of mass of the axial vorticity distribution. A comparison of the results of determining the position of the vortex core center showed good quantitative agreement. As a result dependencies of vortex core center coordinates on longitudinal coordinate were obtained.

1. Introduction
The study of vortex flows is one of the urgent tasks of modern aerodynamics. The relevance of investigation of free vortex wake caused by potential application study results for solving the following tasks: decreased visibility of supersonic aircraft; air traffic security; the effect of the vortex wake on ground facilities. It is well known that flowfield wing wake is accompanied by a pressure and axial velocity loss in the vortex core center, circumferential velocity maxima at vortex core boundary [1].

As a result of numerical modeling, we get a complete set of gas-dynamic parameters ($P, \rho, U, V, W$). In contrast to numerical simulation, a limited set of gas-dynamic parameters can be obtained in the experiment. It can be either data on pressure and Mach number, or data on mass flow rate. And these data are not enough to close the system of gas-dynamic equations. 5-hole pressure probe data [2,3] and hot-wire anemometer data [7–10] were presented in earlier studies. Recently a possibility to extract integral density data from flow visualization results was showed [11–13].

To validate the results of numerical simulation, it is necessary to establish whether it is possible to use experimental mass flow rate data to determine the center of the vortex core. Thus, the main purpose of this work is to compare information on the position of the vortex core center, determined by various parameters obtained in the numerical simulation.

2. Results
As the source material for the search for the center of the vortex core, we used the results of wing wake numerical simulation performed at Keldysh Institute of Applied Mathematics RAS [4–6].
Rectangular half-wing with sharp edges with a chord of \( b = 30 \) mm and semi-span of \( l = 95 \) mm was used as a vortex wake generator. Numerical simulation performed at \( M = 2 \) and wing angle of attack of \( \alpha = 10^\circ \). In detail computational technique was reported in [6].

**Figure 1.** Mass flow rate field at \( X/b = 10 \).

**Figure 2.** Axial vorticity distribution at \( X/b = 10 \).

The numerical data were approximated to a regular grid with a step of 0.1 mm in a ranges of \( Y \in [-45, 45] \) mm and \( Z \in [-95, 45] \) mm and in a wide range of longitudinal coordinate \( X \in [15, 900] \) mm. As a result, for each cross section of \( X = \text{const} \), a field of gas-dynamic parameters was obtained.

Figure 1 shows typical example of mass flow rate field with plots showing the distribution of this parameter across the center of the vortex core. The figure demonstrates a technique of vortex core center detection on a minima of mass flow rate.
Figure 2 shows typical example of axial vorticity field with plots showing the distribution of this parameter across the center of the vortex core. The figure demonstrates a technique of vortex core center detection on a maxima of axial vorticity.

Vortex core center coordinates were found in several ways:

- as coordinates of minima of static pressure \( P \), Pitot pressure \( P_t \), axial Mach number \( M_X \), mass flow rate \( \rho U \),
- as coordinates of maxima of axial vorticity \( \Omega_X \)

\[
\Omega_X = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z},
\]

- as ‘center of gravity’ of axial vorticity \( \Omega_X \) field according the following equations

\[
Y_c = \frac{\int y \Omega_X dy dz}{\int \Omega_X dy dz}; \quad Z_c = \frac{\int z \Omega_X dy dz}{\int \Omega_X dy dz}.
\]

Figures 3 and 4 shows dependencies of vortex core coordinates on longitudinal coordinate. It is clearly seen quite good agreement in coordinates found by different ways.

Errors in determining the center of the vortex core at small values of the longitudinal coordinate \( X/b \) are explained by the fact that the vortex core in the near sections has not yet been formed.
Figure 5 shows axial vorticity distribution across the vortex core at different distances far downstream from the wing. The plots clearly indicate two peaks of the same order in two nearest cross-sections ($X/b = 0.5$ and 0.66). $\Omega_X$-distributions at $X/b > 1$ unlike the near wake demonstrate typical plots with one peak located at the center of the vortex core.

3. Conclusions

Based on the analysis of the results of numerical simulation and its comparison with experimental data the position of the center of the vortex core in the wing wake at $M = 2$ was determined. It was found that the values of the center coordinates determined by different values are close to each other. In the near sections, the vortex core is not formed, which confirmed by the presence of several peaks of the same order in distribution of longitudinal vorticity.

Acknowledgments

The work was carried out with the partial financial support of the Russian Foundation for Basic Research (Grant No. 19-01-00765).

References

[1] Brodetsky M D and Shevchenko A M 1998 Thermophysics and Aeromechanics 5 281
[2] Shevchenko A, Kavun I, Pavlov A and Zapryagaev V 2005 Proc. European Conf. for Aerospace Sci. (Moscow, Russia, July, 4-7)
[3] Shevchenko A M, Lutsky A E, Chernoguzov A S and Polkova K Y 2007 Proc. XIII Int. Conf. Methods Aerophysical Res. (Novosibirsk: Parallel Publ.) pp 215-220
[4] Borisov V E, Davydov A A, Konstantinovskaya T V, Lutsky A E, Shevchenko A M and Shmakov A S 2018 AIP Conference Proceedings 2027 030120
[5] Borisov V E, Konstantinovskaya T V, Davydov A A, Lutsky A E, Shevchenko A M and Shmakov A S 2018 Journal of Physics: Conference Series 1250 012037
[6] Borisov V E, Davydov A A, Konstantinovskaya T V, Lutsky A E, Shevchenko A M and Shmakov A S 2018 Simulation of supersonic flow in the wake behind a wing at $M=2$-4 KIAM Preprints 50 pp 1-19
[7] Shmakov A S, Shevchenko A M, Yatsikh A A and Yermolaev Yu G 2016 AIP Conference Proceedings 1770 030019
[8] Shmakov A S and Shevchenko A M 2017 AIP Conference Proceedings 1893 030089
[9] Shmakov A S and Shevchenko A M 2018 AIP Conference Proceedings 2027 030103
[10] Shmakov A S and Shevchenko A M 2019 AIP Conference Proceedings 2125 030108
[11] Shevchenko A M, Golubev M P, Pavlov A A, Pavlov Al A, Khotyanovsky D V and Shmakov A S 2017 Technical Physics Letters 43 473
[12] Pavlov Al A, Shevchenko A M, Shmakov A S and Pavlov A A 2017 AIP Conference Proceedings 1893 030079
[13] Shmakov A S, Pavlov Al A, Golubev M P and Shevchenko A M 2018 AIP Conference Proceedings 2027 040065