ANALYSIS OF THE GUST IMPACT ON INLET VORTEX FORMATION OF THE FUSELAGE-SHIELDED INLET OF AN JET ENGINE POWERED AIRCRAFT

Adam Kozakiewicz, Michał Frant

Military University of Technology, Faculty of Mechatronics and Aviation, Warsaw, Poland
e-mail: adam.kozakiewicz@wat.edu.pl; michal.frant@wat.edu.pl

Selected problems of a complex structure, namely the fuselage-shielded inlet model of a turbine jet engine for numerical analysis purposes of the intake vortex formation phenomenon are presented in this paper. As a result of numerical analysis, an intake vortex has been developed. The analysis of the impact of changes in speed, angle and the direction of gust on vortex development has been conducted. Also, consequences of ingestion of foreign objects by the inlet and relevant statistics concerning damage to turbine engines have been presented.

Key words: turbine-jet engine inlet, intake vortex, numerical fluid dynamics

1. Introduction

The thrust of turbojet and turbofan engine, according to Euler's equation, depends on the value of airflow entering and leaving the engine. In order to obtain full comprehensibility connected with the justification of the mass flow increase passing through the engine, it is acceptable, in the first approximation, to assume that both airflows are equal, i.e. the stream of exhaust gases equals the stream of the incoming airflow ($\dot{m}' \approx \dot{m}$), with approximately 2% accuracy

$$\mathbf{K} = \Sigma(\dot{m}'\mathbf{c}_5 - \dot{m}\mathbf{V}_H) \tag{1.1}$$

where: $\mathbf{K}$ is the thrust of turbojet engine, $\dot{m}$ – inlet mass flow, $\dot{m}'$ – mass flow of exhaust gases, $\mathbf{c}_5$, $\mathbf{V}_H$ – inlet and outlet velocity, respectively.

It results in the dependence of thrust on the product of the inlet stream $\dot{m}$ and the stream velocity increase by factor $\Delta \mathbf{c}$ ($\Delta \mathbf{c} = \mathbf{c}_5 - \mathbf{V}_H$). There is constant tendency ib growth of the value of the inlet mass stream in all types of jet engines. In the case of fan-turbo jet engines (for transport and communication purposes) the level of $1200\,\mathrm{kg/s}$ (Trent 1000) has been achieved, whereas in the case of by-pass turbojet engines with a mixer (military aircraft engines) the level is lower by the order of magnitude ($120\,\mathrm{kg/s}$ – F100-PW229). For constructional reasons (connected with design of an aircraft itself), the inlets of such engines are located very low above the ground surface (taxiways or holding bays). Frequently, the distance is approximately 1 meter.

Operating in such conditions, the engine intaking the air indispensible for it to work creates a spatial velocity field. The characteristic feature of this field is an inlet stagnation point and line where it connects with the surface of the earth (Szczepanik, 1978; Wojciechowski, 1989). External disturbances, for example in form of a crosswind, can cause appearance and development of a vortex rotating around the stagnation line (Fig. 1). Such a phenomenon may occur at zero plane speed or while taxiing along. This phenomenon is conducive to the ingestion of foreign concrete objects and other impurities from the runway surface or other objects from the tarmac that results in serious breakdowns of the fan and compressors palisades, which may have a disastrous

Fig. 1. Operation of turbojet engine inlet RB211-524G by Rolls-Royce on the ground (pic. P. Thomas)
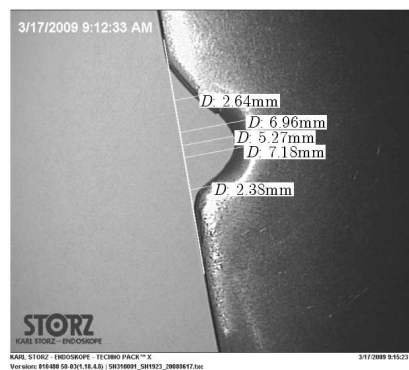

Fig. 2. A damaged fan blade with the blown-up damage area (pict. A. Kozakiewicz)

impact on the flight safety. These breakdowns may generate fatigue cracks, whose speed of cracking is approximately 1 mm/h beginning from the crack appearance (Lewitowicz, 2007).

A list of factors causing damage to the engine is extremely broad. The most substantial factors are as follows:

- defect in the design or a technical fault

- mechanical defects

- operating deficiencies

- climatic factors

The ingestion of foreign objects is classified as an operating deficiency. Its importance has been shown in Fig. 3. It presents a serious problem both to military and civil aviation, and causes considerable losses for all groups of aircraft users.

The problems concerning the formation of the intake vortex and the ingestion of foreign objects by turbine jet engines have been already analyzed by Polish researchers. However, the research conducted concerned the previously used aircraft such as MiG-21, TS-11 Iskra or Iryda aircraft (Madej, 1990; Rusek, 1994; Szczepanik, 1978).

This article aims at presenting the susceptibility of a fuselage-shielded inlet system of a modern combat aircraft to the formation of the inlet vortex and determining the influence of the flow direction and velocity on its formation.
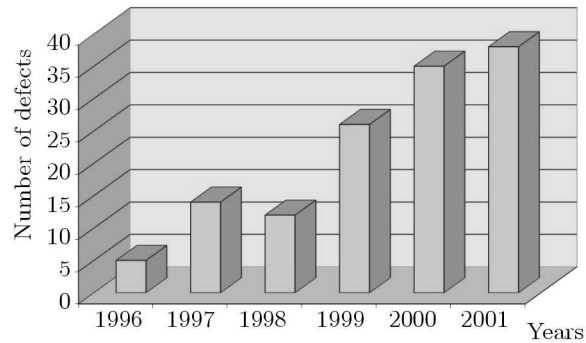
Fig. 3. The level of damage to the power unit connected with induction of foreign objects in the years 1996-2001 in the U.S. Air Force (Drozdowski, 2004)

2. Numerical analysis of the impact of the gust angle on formation of the inlet vortex in F-16

Inlet vortices in turbine engines start in the boundary layer at the stagnation point and then form around the stagnation line which connects the surface of the airfield stagnation point with the engine inlet (Fig. 4). The vortex is produced only when there is circulation around the vertical axis in the flow. Further increase of the angular velocity in the spinning fluid is directly connected with the momentum conservation law. Stokes' theorem, which describes the process taking place in the vortex tube of S_1 and S_2 cross-section at the angular velocity $\boldsymbol{\omega}$ of the fluid element, is used in research on rotary vortex motion (Hirsch, 2007)

$$\iint_{S_1} \boldsymbol{\omega}_1 \cdot \mathbf{n}_1 \, dS_1 = \iint_{S_2} \boldsymbol{\omega}_2 \cdot \mathbf{n}_2 \, dS_2 \qquad (2.1)$$

where: $\boldsymbol{\omega}_1$, $\boldsymbol{\omega}_2$ is the angular velocity, $\mathbf{n}_1$, $\mathbf{n}_2$ – normal vector to cross-section, S_1, S_2 – cross-sections.

Expression (2.1) provides information that in the case of cross-section reduction, there must be an increase in the angular velocity inside the tube.

Fig. 4. An inlet vortex formed at F-16's inlet (indicated with the arrow)

The inlet vortex flow field comprises circulations of high velocity and the flow in the vortex core as well as in the boundary layer by the surface. Above the surface of the ground, the tangential component changes with the radial distance from the core of the vortex. Inside the

core, the pressure is lower than the surrounding one, which generates tangential velocity. The outcome is a centrifugal force. The tangential and radial velocities above the surface have impact on the boundary layer (reducing its thickness) which leads to an increase in the vortex ingestion force and its capability to lift foreign objects from the tarmac.

In the course of previously conducted simulations (Kozakiewicz and Frant, 2011), the possibility of realizing calculations simulating the operation of F-16's inlet static conditions on the ground ($V_H = 0$ and $H = 0$) has been detected, whereas in first attempts at simulating the inlet vortex formation in F-16 aircraft have been made.

The process of constructing a virtual geometry of the front part of F-16's fuselage with the inlet tube and the process of discretization was presented by Kozakiewicz and Frant (2011). The shape of computational area discretization has been shown in Fig. 5.
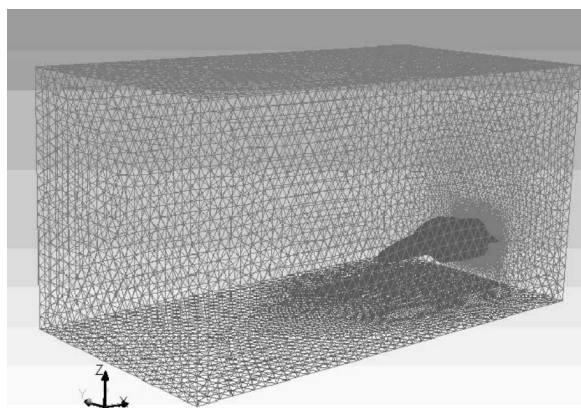

Fig. 5. Discretization of the entire computational area

To carry out calculations, the commercial computational package CFD Fluent has been used. The package is based on the finite volume method. Undoubtedly, the main advantage of the method is the possibility to build non-orthogonal and non-uniform computational grids, which is of vital importance in the case of computational tasks for objects of a complex shape (Kazimierski, 2004).

The method is based on direct discretization of equations expressing mass, momentum and energy conservation law in the physical space.

The above mentioned equations are subsequently subjected to averaging in accordance with the equations given by Elsner (1987), Gryboś (1998), Lumley and Yaglom (2000), Wilcox (1994), leading to equations known as Reynolds equations. Reynolds equations have been applied to solve the problem. It must be stressed that the previously mentioned process of averaging makes the closed system of equations an open one since 6 complementary relationships defining the components of turbulence stress tensor are missing. Therefore, the necessity of applying turbulence models is absolutely essential.

The conducted and published tests in Kozakiewicz and Frant (2011) proved the correctness of the constructed virtual object and computational grid as well as the correctness of the applied boundary conditions. Test calculations have been conducted at zero gust speed and without adaptation of computational grids.

To perform the analisys of the influence of the gust angle on the inlet vortex formation, solutions for β gust angles in the horizontal plane xy (Fig. 6a)) $0°$, $15°$, $30°$, $45°$, $60°$, $90°$, $120°$, $150°$ and 180 degrees (crosswinds) and in the vertical plane xz and for the α angle (Fig. 6b) measuring respectively $0°$, $-5°$, $-10°$, $-15°$ and 20 degrees (downthrust) have been conducted. The test calculations have been carried out for $\mathrm{Ma} = 0.0025$ (that is approximately $0.87\,\mathrm{m/s}$), $\mathrm{Ma} = 0.005$ ($1.73\,\mathrm{m/s}$), $\mathrm{Ma} = 0.0075$ ($2.6\,\mathrm{m/s}$), $\mathrm{Ma} = 0.01$ ($3.47\,\mathrm{m/s}$) or $\mathrm{Ma} = 0.015$ ($5.21\,\mathrm{m/s}$).
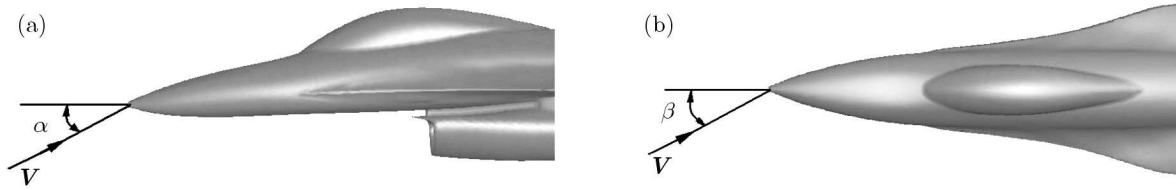
Fig. 6. Definition of the gust angle in the examined object, (a) α – gust angle in the xz plane, (b) β – gust angle in the xy plane

The calculation results shall be presented in form of a chart for all examined inlet angles both in the vertical and horizontal plane providing for the inlet velocity. The symbol "+" stands for the inlet vortex occurrence for the given calculation case, whereas the symbol "−" stands for its lack.

The first studied case was the gust of Ma = 0.0025.

Table 1

α	β								
	0°	15°	30°	45°	60°	90°	120°	150°	80°
0°	−	+	+	+	+	+	+	+	−
−5°	−	+	+	+	+	+	+	+	−
−10°	−	+	+	+	+	+	+	+	−
−15°	−	+	+	+	+	+	+	+	−
−20°	−	+	+	+	+	+	+	+	−

On the basis of simulations performed, it can be concluded that in the studied case the inlet vortex occurs in almost all analyzed ranges of the α angles, except for $\beta = 0°$ and 180°, i.e. the front or rear gust. The selected case of the inlet vortex formation for one of the discussed cases has been shown in Fig. 7.
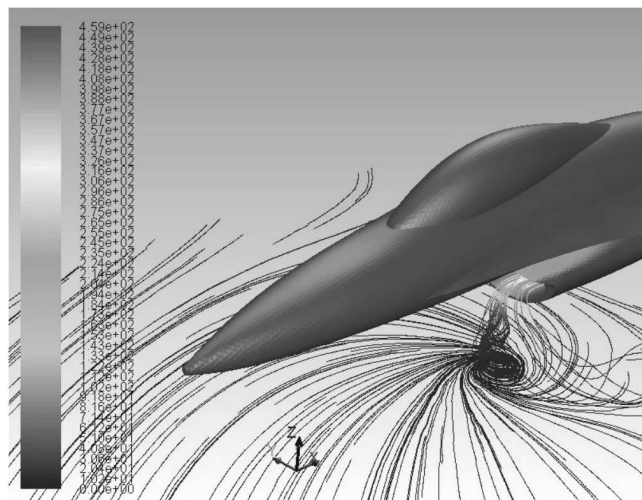

Fig. 7. The streamline flow for Ma = 0.0025, $\beta = 60°$, $\alpha = -15°$

For the gust of Ma = 0.005, the vortex is generated in conditions identical to those in the previous case and, additionally, where $\beta = 0°$ and gust angles in the vertical plane $\alpha = -10°$, $-15°$ and $-20°$, which has been presented in Table 2.

Table 2

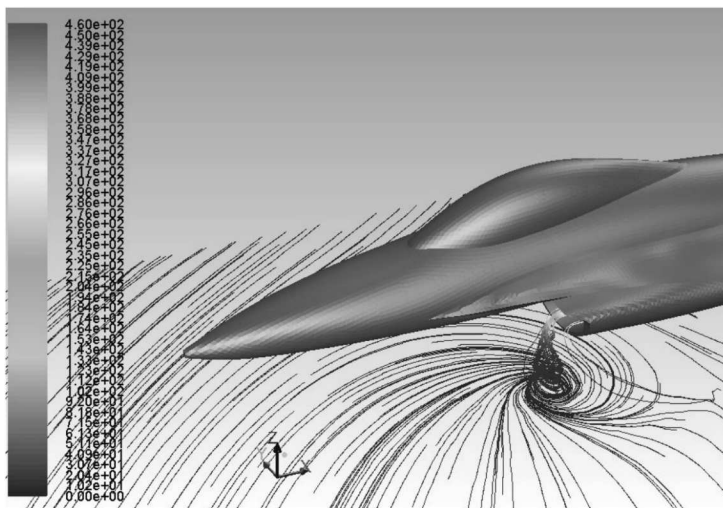| α	β								
	0°	15°	30°	45°	60°	90°	120°	150°	80°
0°	−	+	+	+	+	+	+	+	−
−5°	−	+	+	+	+	+	+	+	−
−10°	+	+	+	+	+	+	+	+	−
−15°	+	+	+	+	+	+	+	+	−
−20°	+	+	+	+	+	+	+	+	−

Fig. 8. The streamline flow for Ma = 0.005, $\beta = 60°$, $\alpha = -15°$

Some qualitative changes can be noted between the vortex generated at Ma = 0.0025 (Fig. 7) and the one formed at Ma = 0.005 (Fig. 8). Further Mach number increase by 0.0025 in comparison with the previous case, results in shift of the inlet vortex formation where $\beta = 0°$ in the direction of bigger negative angles in the horizontal plane (from $\alpha = 15°$ to $\alpha = -20°$), which has been presented in Table 3 and the chosen case in Fig. 9.

Table 3

α	β								
	0°	15°	30°	45°	60°	90°	120°	150°	80°
0°	+	+	+	+	+	+	+	+	−
−5°	+	+	+	+	+	+	+	+	−
−10°	+	+	+	+	+	+	+	+	−
−15°	−	+	+	+	+	+	+	+	−
−20°	−	+	+	+	+	+	+	+	−

The gust of Ma = 0.01 (Table 4) leads to formation of the inlet vortex, where $\alpha = 0°$ for all examined angles, except for 180° angle. Nonetheless, in the case of the crosswind angles of 120° and 150°, the development of the inlet vortex for all examined α angles can be noted. In addition, the formation of the inlet vortex has been observed, where $\beta = 15°$ and $\alpha = -10°$ or $\alpha = -15°$ as well as in the case where $\beta = 60°$ and $\alpha = -5°$, which has additionally been presented in Figs. 10 and 11.

The last examined case was the streamline flow at Ma = 0.015, whose results are given in Table 5, and two selected gust cases are presented graphically in Figs. 12 and 13.
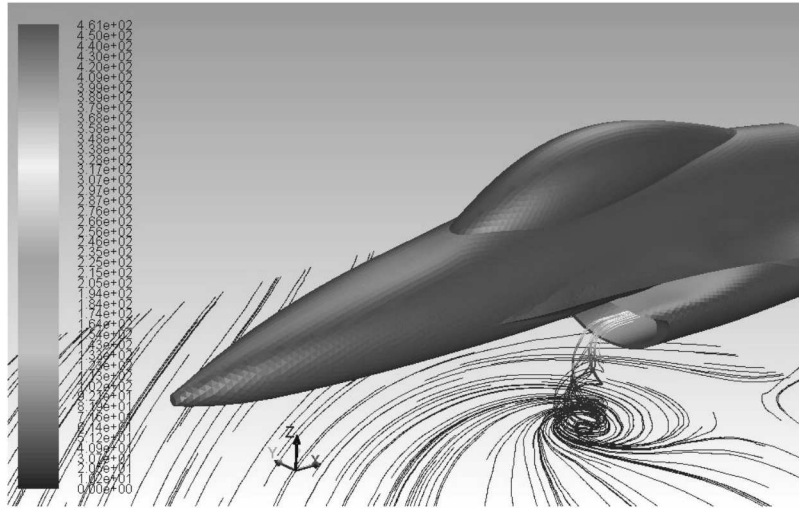
Fig. 9. The streamline flow for Ma = 0.0075, $\beta = 60°$, $\alpha = -15°$

Table 4

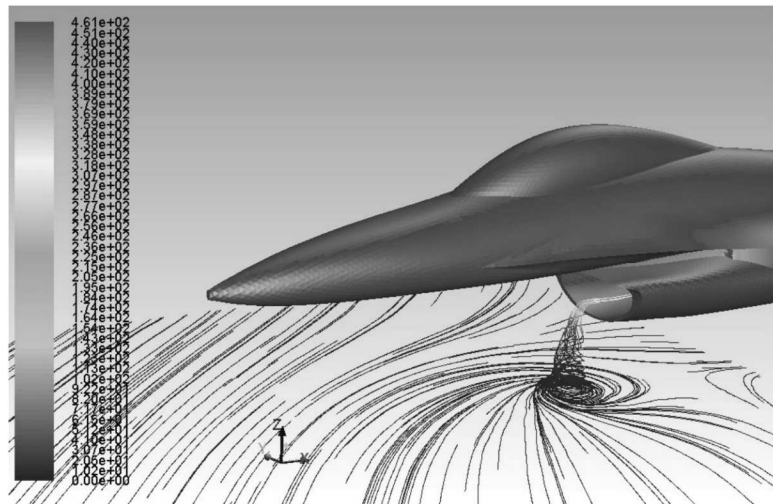| α	β								
	0°	15°	30°	45°	60°	90°	120°	150°	80°
0°	+	+	+	+	+	+	+	+	−
−5°	−	−	−	−	+	−	+	+	−
−10°	−	+	−	−	−	−	+	+	−
−15°	−	+	−	−	−	−	+	+	−
−20°	−	−	−	−	−	−	+	+	−

Fig. 10. The streamline flow for Ma = 0.01, $\beta = 60°$, $\alpha = -5°$

On the basis of the presented results, it is clear that the gust at Ma = 0.015 does not generate formation of the intlet vortex except for several specific cases: where On the basis of presented results it is clear that the gust where Ma = 0.015 does not generate an intlet vortex except for several specific cases: where $\beta = 0°$ with $\alpha = 0°$, $\beta = 120°$ with $\alpha = 0°$, $\alpha = -10°$ and $\alpha = -15°$, $\beta = 150°$ with $\alpha = 0°$, $\alpha = -5°$ and $\alpha = -10°$ and $\beta = 180°$ with $\alpha = 0°$, $\alpha = -5°$.
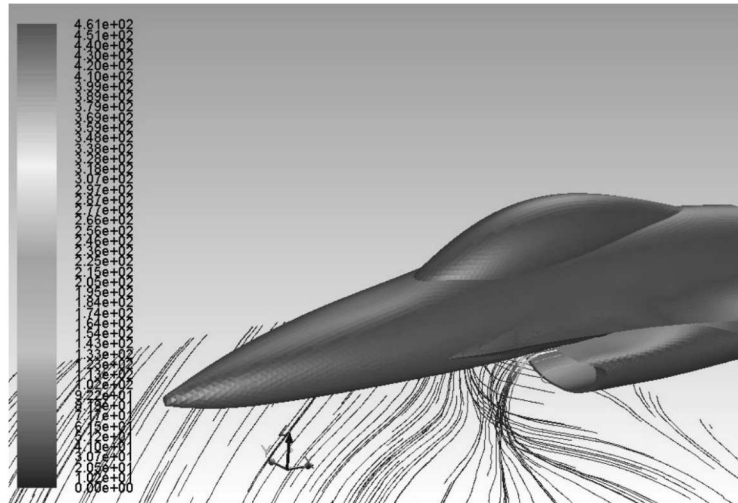
Fig. 11. The streamline flow for Ma = 0.01, $\beta = 60°$, $\alpha = -15°$

Table 5

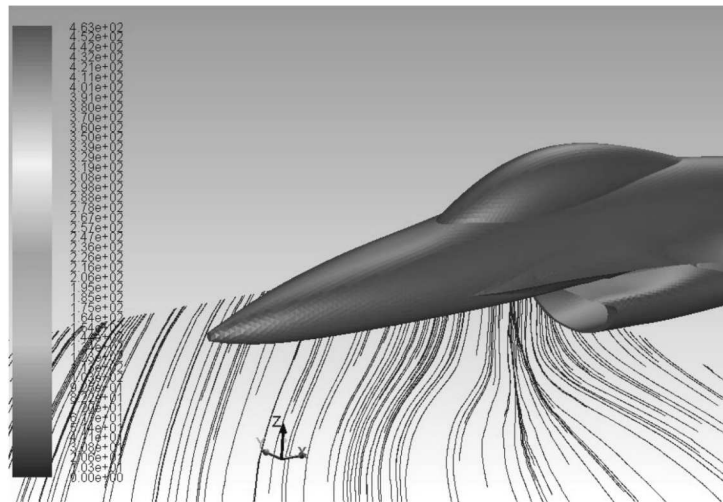| α	β								
	0°	15°	30°	45°	60°	90°	120°	150°	80°
0°	+	−	−	−	−	−	+	+	+
−5°	−	−	−	−	−	−	−	+	+
−10°	−	−	−	−	−	−	+	+	−
−15°	−	−	−	−	−	−	+	−	−
−20°	−	−	−	−	−	−	−	−	−

Fig. 12. The streamline flow for Ma = 0.015, $\beta = 60°$, $\alpha = -15°$

3.   Summary

Taking all the discussed cases into consideration, it can be concluded that gusts of winds blowing in the horizontal plane pose the biggest threat to operation of the shielded-fuselage inlet. The inlet vortex in the discussed cases occurs almost at each gust speed and each gust angle in the horizontal plane. In the cases where the flow angle is $\beta = 120°$ or $\beta = 150°$ and at each discussed speed, the inlet vortex develops virtually at each katabatic gust angle α. The most significant conclusion that can be drawn on the basis of the conducted calculation tests, is that
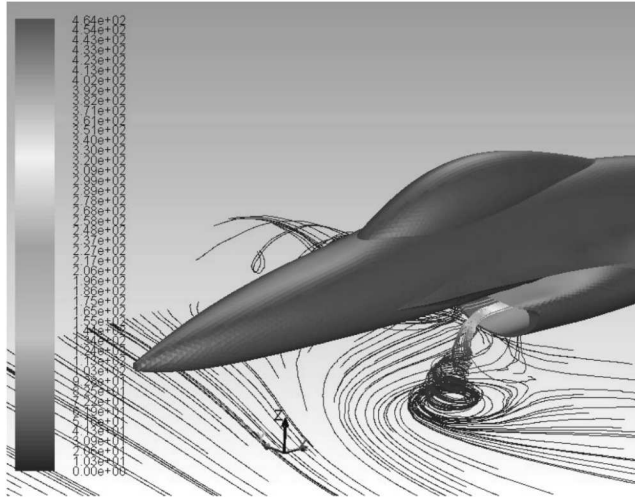
Fig. 13. The streamline flow for $\mathrm{Ma} = 0.015$, $\beta = 120°$, $\alpha = -15°$

the gust of low speed is the most dangerous. It is due to the fact that low speed gusts contribute to formation of the inlet vortex regardless of the α angle for the range of β angles $15°$-$150°$. The increase of flow speed up to the value of $\mathrm{Ma} = 0.01$ to 0.015 considerably reduces the inlet vortex formation susceptibility (Tables 4 and 5).

The formed vortices may be a source of compressors stall, which, in turn, can result in unstable engine operation (Kolesnikov, 2010). The ingestion of a foreign object can also cause serious damage to fans and compressors blades. Therefore, research on such types of phenomena is of vital importance (Balicki *et al.*, 2009). In the case of actual process taking place at the inlet area, the precise measurement of inlet vortex parameters (pressure, speed or wind strength) is difficult. In addition, the process is extremely dynamic due to its susceptibility to external factors. The process of migration of the stagnation point on the plane, shown in Fig. 14, may be an example of this problem. The authors purpose to discuss this problem in the following studies.
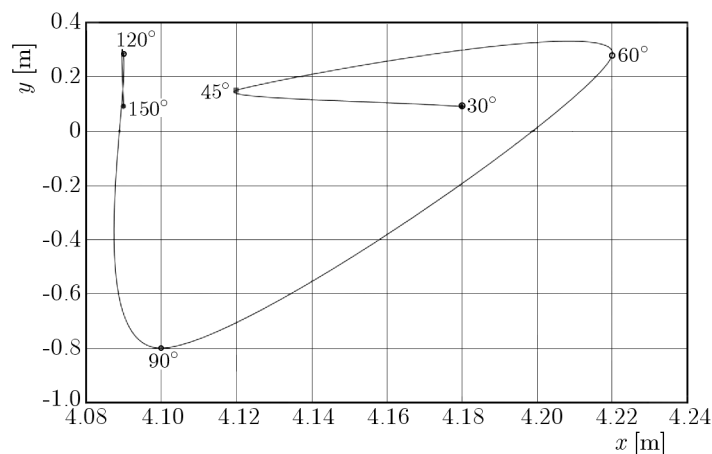

Fig. 14. The course of delocalisation of the stagnation point for $\mathrm{Ma} = 0.01$, change of the angle of gust from $30°$ to $150°$

Consequently, theoretical and experimental research on the matter is critical to providing the information on how to prevent from the occurrence of such an adverse phenomenon. Currently, the basic methods applied to counteract the process (for engines in operation) are the engine thrust reduction and the reduction of engine operation time at the maximum range. In the case of newly designed engines, such calculations can be used to construct the inlet system.

References

1. BALICKI W., KAWALEC K., PĄGOWSKI Z., SZCZECIŃSKI S., CHACHURSKI R., KOZAKIEWICZ A., GŁOWACKI P., 2009, Intakes of turbojet engines endangered by the phenomenon of intake vortex (in Polish), *Prace Instytutu Lotnictwa*, **4**, 199, Warszawa

2. DROZDOWSKI Z., 2004, Hazard results from the introduction of new aviation technology (in Polish), *Przegląd WLiOP*, **II**, Poznań

3. ELSNER J.W., 1987, *Flow Turbulence*, PWN, Warszawa

4. GRYBOŚ R., 1998, *Fundamentals of Fluid Mechanics* (in Polish), t. 2, PWN, Warszawa

5. HIRSCH C., 2007, Numerical computation of internal and external flows, *Fundamentals of Computational Fluid Dynamics*, 2nd Ed., Elsevier

6. KAZIMIERSKI Z., 2004, *Fundamentals of Fluid Mechanics and Methods of Flow Computational Symulation* (in Polish), Politechnika Łódzka, Łódź,

7. KOLESNIKOV K.C., 2010, *Encyclopedia: Airplanes and Helicopters* (in Russian), Moskva, Mashinostrenie

8. KOZAKIEWICZ A., FRANT M., 2011, Development of a model for the intake system of the F-100-PW-229 engine for the F-16 aircraft in order to analyze formation of a intake vortex (in Polish), *Prace Instytutu Lotnictw*, **213**, 55-65

9. LEWITOWICZ J., 2007, *Fundamentals of operations of aircraft* (in Polish), IV, Wydawnictwo ITWL, Warszawa

10. LUMLEY J.L., YAGLOM A.M., 2000, A century of turbulence, *Proceedins of VII European Turbulence Conference*, Barcelona

11. MADEJ L., 1990, The flow analysis in the pre-intake-zone of turbojet engines aircraft "IRYDA" in the aspect limitation of the susceptibility to the induction of mechanical contaminations (in Polish), PhD Thesis, Military University of Technology (WAT), Warsaw

12. RUSEK Z., 1994, The analysis of parameters attributable to blow airstreams in order to protect intakes of turbojet engines against suction of foreign bodies (in Polish), PhD Thesis, Military University of Technology (WAT), Warsaw

13. SZCZEPANIK R., 1978, Badania Researches conditions the induction of mechanical contaminations from the airfield to inlets of turbojet engines (in Polish), PhD Thesis, Military University of Technology (WAT), Warsaw

14. WILCOX D.C., 1994, *Turbulence Modeling for CFD*, DCW Industries

15. WOJCIECHOWSKI Z., 1989, The influence the shape of inlets of turbojet engines on the susceptibility of affect formation of an intake vortex (in Polish), PhD Thesis, Military University of Technology (WAT), Warsaw