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INTERACTION OF HEAVY AIRCRAFT WAKES

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Abstract

In the next few years the problem of heavy aircraft wakes may increase on the account of continuous air transport growth. However, it can be noticed that even today the number of accidents resulting from an interaction with wakes is increasing. That is the reason why methods of wake vortex description should be searched for.

The aim of this study is to analyze interaction of example aircraft wakes. In this paper the characteristics of vortex wake behind three-dimensional wing are presented. It shows how a separation between aircraft affects the decay of vortex. Two- and three-dimensional calculations were performed using commercial RANS code. The following cases have been taken into consideration: flow past a full commercial aircraft, three-dimensional flow over the simplified wing and a two-dimensional analysis of vortex decay caused by the landing aircraft, including the separation effect. For all these cases a CFD simulation of the aircraft wakes was conducted.

One of the main outcome of this work is a confirmation that the interaction between wakes consists of spreading out and lifting wakes. The achieved results show that the two-dimensional simulation is a sufficient tool for a preliminary analysis of wake vortices. Conclusions from this analysis can be used by the managements of busy international airports to enhance safety.

Keywords: CFD, vortex decay, vortex interaction.

1. INTRODUCTION

Wingtip vortices are always generated by aircraft in flight. Differences in pressure between the upper and lower surface of wing causes formation of a vortex. The strength of vortex wake depends on the aircraft's design, gross mass or configuration corresponding to a flight phase, flight altitude and speed.

One of the first studies of vortices, concerning those formed by the wingtip, were published in 1923. At that time, it was noted that vortices occur in a real flow past other bodies [1].

Full scale flight tests for research of wake vortex encounters started in the 1950s [2] and were continued for the next years [3-6]. On the other hand, NASA initiated tunnel tests to study the wake-vortex encounter [7-8]. All those works enabled the development of an Aircraft Vortex Spacing System (AVOSS) concept, which will provide dynamic, weather dependent wake vortex spacing requirements for an advanced automated air-traffic control system [9].

In order to prevent accidents due to wake turbulence, the International Civil Aviation Organization (ICAO) introduced separations in air traffic [10]. Depending on Maximum Certificated Takeoff

Weight (MCTOW) of the leading and following aircraft, a separation distance is determined. Taking into consideration the close inter-dependence between aircraft's design and the strength of vortex wakes, aircraft are divided into the following categories of MCTOW: heavy, medium and light (Tab.1). ICAO's aircraft separation distances to avoid wake vortex encounter are shown in Table 2.

Tab. 1. Weight categories [10]

Weight Categories	Maximum Certificated Takeoff Weight (MCTOW)	Examples
Heavy (H)	MCTOW >=136,000 kg	B 777, B 767, B 747, McDonnell Douglas DC–8, MD–11, and DC–10
Medium (M)	136,000 kg> MCTOW >7,000 kg	B 727, B 737 and B 757, Fokker Friendship, Metro 4, BAe–146, Dash 8, ATR–72, C-130 Hercules, DC–3
Light (L)	MCTOW<7,000 kg	Cessna 402, Islander, Nomad, Piper Navajo, Beech 99

Today, modern calculation tools and optical methods of flow visualization are available. Those methods allow to describe more strictly the wake vortices problem. Predictions of aircraft wakes using numerical methods are shown in [11-14]. In [11] a wake interaction between aircraft on closely spaced parallel paths, obtained using Large Eddy Simulation (LES) method have been shown. The paper [12] covers methods for modelling vortex wakes behind aircraft at a low altitude and close to the ground during takeoff and landing operations. References [13-14] concern a potential risk for rotorcraft encountering wake vortices of the fixed-wing aircraft.

The Boeing 777, a type chosen for the analysis, is a jet airliner developed and manufactured by Boeing Commercial Airplanes. It is long-range wide-body twin-engine airplane and has a typical seating capacity for 314 to 451 passengers, with a range of 9,695 to 17,594 km. Table 3 provides information on specification of the Boeing 777-200, a version used in the analysis. So far, the Boeing company has delivered about 1,283 of such airplanes to 42 customers worldwide [15].

Tab. 2. ICAO aircraft separation distances to avoid wake vortex encounter [10]

Leader aircraft (max. take-off weight)	Follower aircraft	Separation [nautical miles]	Time delay [sec] (approach speed 70 m/s)
Heavy	Heavy	4	106
Heavy	Medium	5	132
Heavy	Light	6	159
Medium	Light	5	132

Tab. 3. Specification of example airplane [15]

Boeing 777-200			
Mean aerodynamic chord	c_a	7.3	m
Maximum takeoff weight	m	300, 000	kg
Speed	V	80	m/s
Wingspan	b	60	M
Wing area	A	427	m^2

The aim of this study is to analyze the interaction between wakes of two aircraft following each other on approach. In this paper, the characteristics of the vortex wake behind the 3D wing is presented. This study shows how separation between aircraft affects the vortex decay. Two- and three-dimensional calculations were performed using commercial RANS code. On the basis of calculations made for three cases: flow past a full commercial aircraft, 3D vortex analysis of the wing and 2D analysis of vortex decay behind the landing aircraft with separations, the analysis of aircraft wakes has been conducted. The achieved results show that 2D analysis is sufficient to make a preliminary assessment of the wake vortices behaviour.

2. METHOD

The flow simulations were computed with the use of Reynolds Averaged Navier Stokes (RANS) method of solving flow equations, using one equation turbulence model (Spalart–Allmaras) [16]. The software code, FLUENT, is based on the finite volume method [17]. The Spalart-Allmaras turbulence model was developed mainly for aerodynamic flows in scales used in the simulation. This model is a transport equation for the eddy viscosity.

The model of the 3D geometry of the Boeing 777 is based on the NASA Common Research Model (CRM, DPW-6) [18]. It is a Standard Research Model agreed between American research facilities to validate results from different aerodynamic wind tunnels. The model is freely available in the form of a CAD drawing. Since the model is based on the B 777 airframe, in this work it has been re-scaled (an original is in a wind tunnel model scale) to the dimensions of a real plane. Figure 1 presents CRM/DPW-6 model geometry.

The Boeing 777 is a low wing monoplane in a classic configuration. Its tapered wing has a high sweep angle, similar for the horizontal stabilizer. The model is not equipped with a vertical stabilizer as usually a mounting device for aerodynamic balance is attached there.

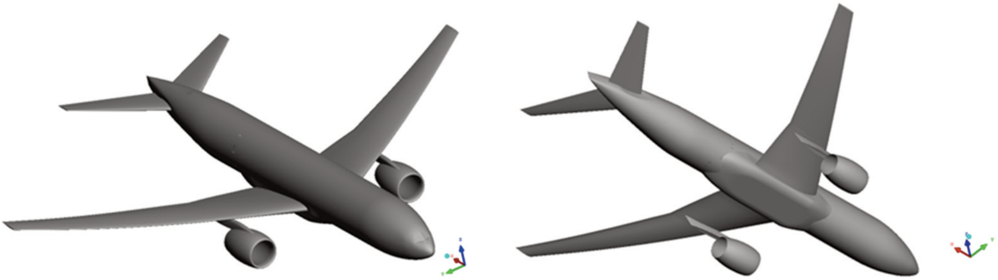

Fig.1. CRM/DPW-6 model geometry [Dziubiński, 2016]

Both wing and horizontal stabilizer have a positive dihedral. An airfoil distribution on the wing is rather complicated, and also wing deformation caused by the flow is introduced, so it is fully reasonable to distribute such geometry in a digital form. Additionally, the model is equipped with empty duct mock-ups for the engine nacelles, mounted on under wing pylons. In the following simulation, the deflections of flaps and slats were not included.

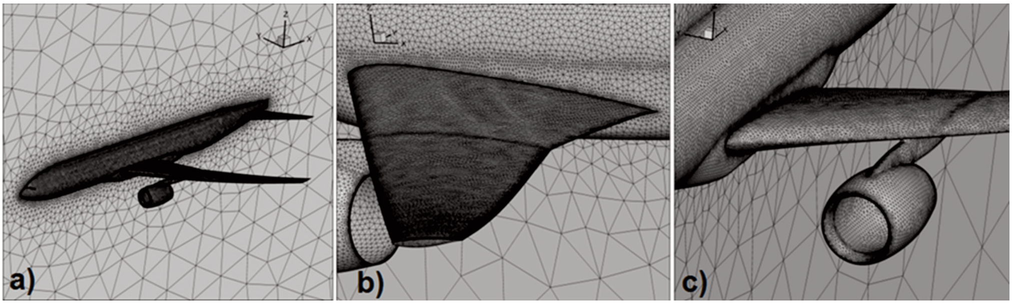

Fig. 2. a) Mesh density on the whole geometry and on the details of the model: b) wing c) nacelle [Dziubiński, 2016]

A tetrahedral mesh with prismatic boundary layer was created around geometry of the aircraft. Mesh density is shown in Figure 2, The boundary layer model has been created to obtain Y+ parameter in 30 - 200 range, as it is suggested for Spalart-Allmaras model. The boundary conditions for 3D computational domain of full aircraft are given in Figure 3.

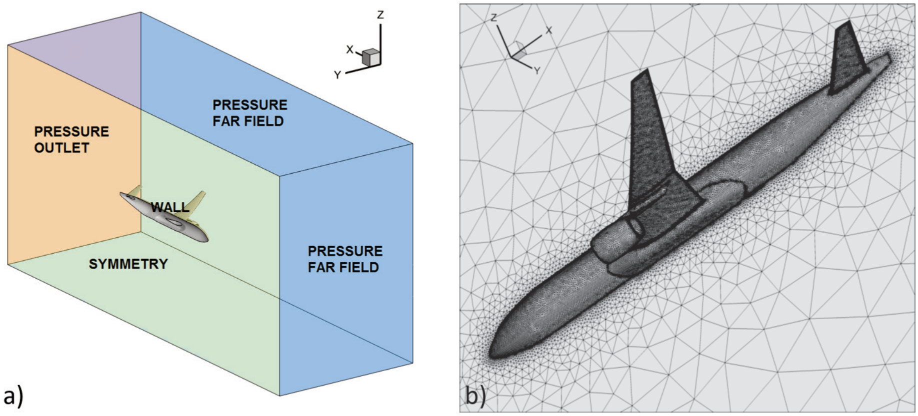

Fig. 3. a) The 3D full aircraft computational domain boundary conditions; b) mesh density on the whole geometry [Dziubiński, 2016]

A two dimensional model reflecting approach position of the airplane was made and used for impact assessment of separation between aircraft on decay vortex. The results of this simulation were also used to make a comparison between results of 2D and 3D simulation of a simplified wing. In this case, the airplane flies 50 m above the ground during the final approach. The 2D computational domain dimensions, boundary condition and mesh are given in Figure 4. The 2D simulation does not include the influence of fuselage and horizontal tail but the longitudinal balance is assumed.

A passing aircraft in the 2D simulation was modelled as a fan boundary condition which corresponds with a model of actuator disc. The actuator disk is an internal boundary condition that imposes an addition of flow field quantities to the flow through pressure jump that works according to the general momentum theory [17].

The substitute wing is rectangular and it has the wingspan of b=60 m and chord which is equal to mean aerodynamic chord of an example aircraft. This model omits aspect ratio and sweep of the wing. An additional simplification is a rectangular distribution of pressure jump.

The pressure jump can be computed by the following equation:

$$\frac{T}{A} = \frac{mg}{A} = \Delta p \tag{1}$$

where: T – lift force [N], A – wing area [m^2], m – mass [kg], $g = 9.81$ – gravitational acceleration [m/s^2], Δp – pressure jump [Pa]

In this case, the pressure jump is $\Delta p = 6901.6$ Pa. The analysis was carried out in a non-stationary mode. The duration of the pressure jump was defined as the time in which the aircraft covers a distance equal to its mean aerodynamic chord. Time of pressure jump during the 2D simulation is $\Delta T = 0.07$ s. Then, the pressure jump is turned off.

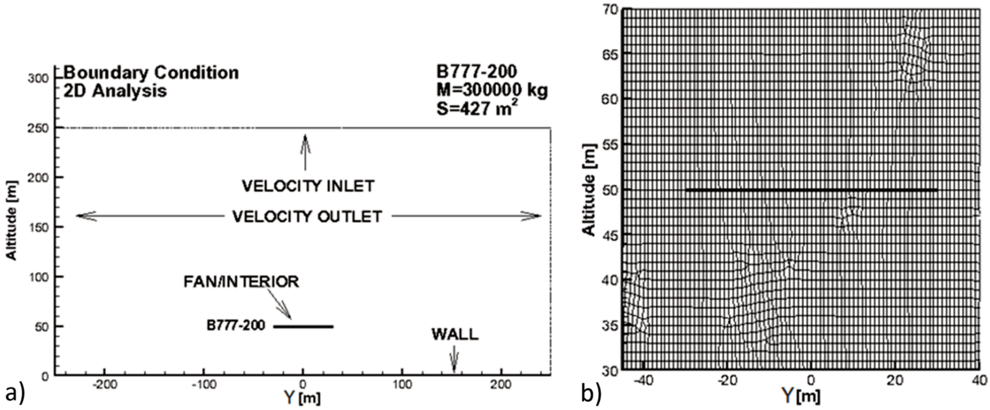

Fig. 4. a) The 2D computational domain dimensions, boundary condition and b) mesh around the Boeing 777 [Bugała, 2016]

The simplified finite wing model uses the Whitcomb-IL airfoil geometry and has a rectangular planform and a blunt tip. The 3D wing simulation does not contain a fuselage or tail. The wing has the same span as for the 2D simulation and is set to the angle of attack sufficient to produce a similar lift force. Figure 5 shows the simplified finite wing computational domain dimensions, its boundary conditions and mesh density on the symmetry surface. An increase of mesh density has been set on the area, behind the wing, containing wingtip vortex. The results of this simulation were used to compare 2D results and 3D simplified wing.

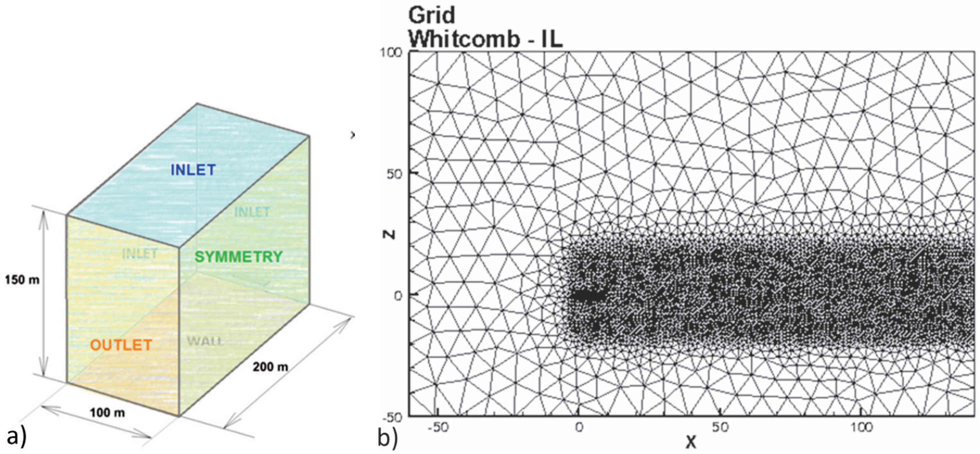

Fig. 5. a) The simplified finite wing computational domain dimensions, boundary conditions and b) mesh on symmetry surface [Bugała, 2016]

3. RESULTS

As an output of this work, an analysis of wake vortex of the B 777 airplane was conducted. The evaluation of the results in the wake may be made by an assessment of the simulation quality with regard to aerodynamic parameters. In order to validate the reliability of CFD results, the lift and drag coefficient analysis has been conducted. The comparison between the CFD results and the experimental data [19] of the lift and drag coefficient against angle of attack is presented in Figure 6. As shown in Figure 6, the simulation quality is sufficient and the relative error does not exceed 10%.

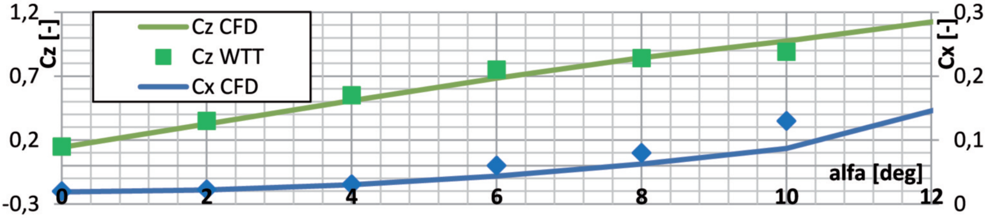

Fig. 6. The comparison between the CFD results and the wind tunnel test (WTT) data [19] of the lift and drag coefficient against angle of attack [Bugała, 2016]

Figure 7 shows the near wake vortex behind the airplane. Figure 8 presents the velocity magnitude distribution on ZY planes located 80 m mean aerodynamic chord. It can be observed in Figure 7 that not only wingtips but also nacelles, horizontal stabilizers and the fuselage are sources of vortices which heavily influence one another. This phenomenon can be seen comparing the maps of vertical velocity, as shown in Figure 8, with results for the simplified wing in Figure 10. The two wingtips wakes are merged together on one side, thereby establishing one area of lower velocity with the minimum in the middle. For the isolated wing, the area with lower velocity has two minima. The analysis did not take into account the effects of slats and flaps.

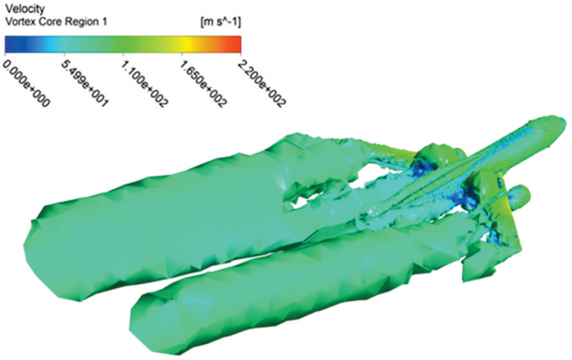

Fig. 7. Near vortex wake of the Boeing 777-200 [Bugała, 2016]

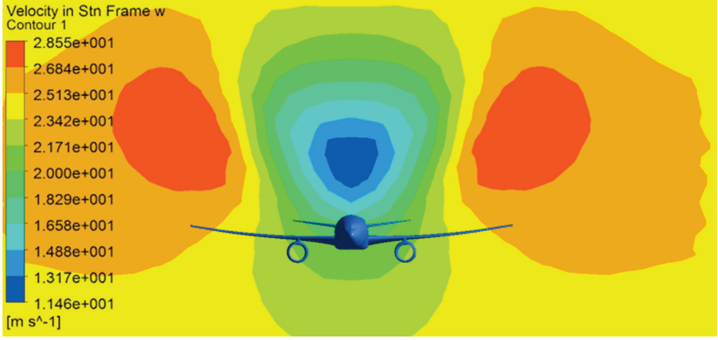

Fig. 8. Vertical velocity magnitude for a plane placed 80m behind mean aerodynamic chord [Bugała, 2016]

In the next part of this work, a 3D analysis of a simplified wing is presented. Figure 9 shows a core of vortex. Figure 10 presents the maps of vertical velocity in cross-sections at a distance of 20 m, 80 m and 136.2 m from mean aerodynamic chord. In Figure 9, it can be seen that the main source of vortices is the wingtip. The cross-section at a distance X=80 m introduced to compare the results with the 2D analysis.

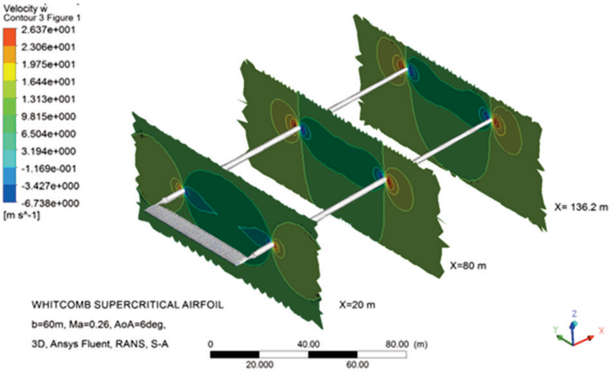

Fig. 9. Maps of vertical velocity [Bugała, 2016]

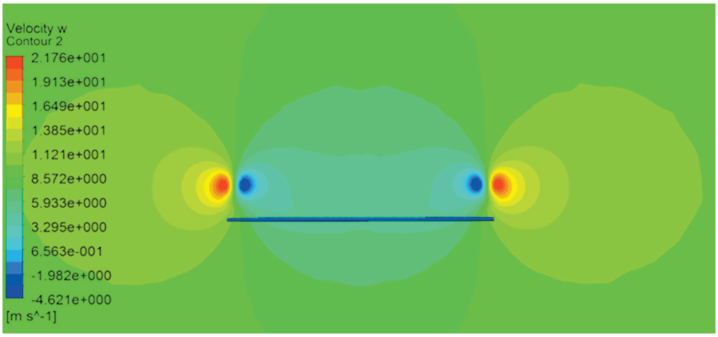

Fig. 10. The core of the vortex in 3D isolated wing case and vertical velocity magnitude for a plane placed 80 m behind mean aerodynamic chord [Bugała, 2016]

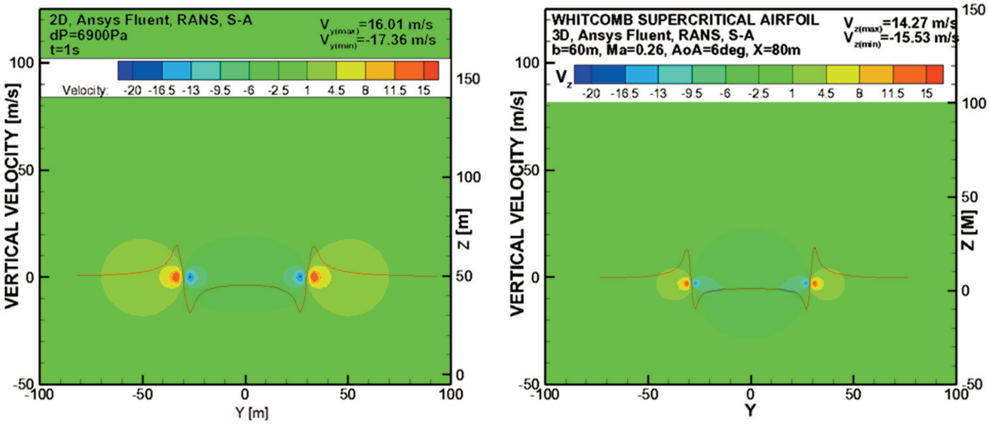

Fig. 11. Maps of vertical velocity, for 2D and 3D analysis respectively, overlayed with graphs of vertical velocity distribution in a horizontal plane [Bugała, 2016]

Figure 11 presents maps of vertical velocity distribution and graphs of vertical velocity for cross-section core vortex in 2D and 3D analysis. The maximum vertical velocity is 14.27 m/s for 3D analysis, whereas for the 2D analysis this velocity is 16.01 m/s. The comparison of results for the 3D and 2D analysis showed 10.8% difference in the maximum vertical velocity. The spatial distribution of velocities is also very similar in both cases. This means that a simplified 2D analysis is sufficient to evaluate wake vortex and its results error appears to be on the safe side, showing a rather more dangerous intensity of phenomenon than it appears to be in the more advanced 3D simulation.

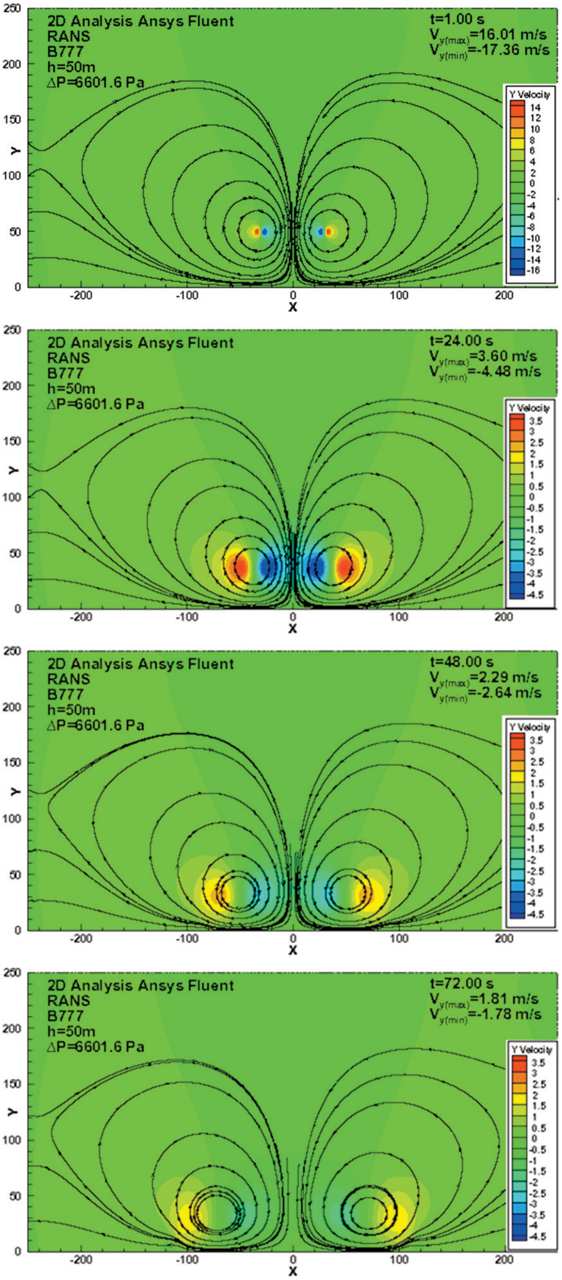

Fig. 12. Maps of vertical velocity and pathlines of flow for wakes interaction [Bugała, 2016]

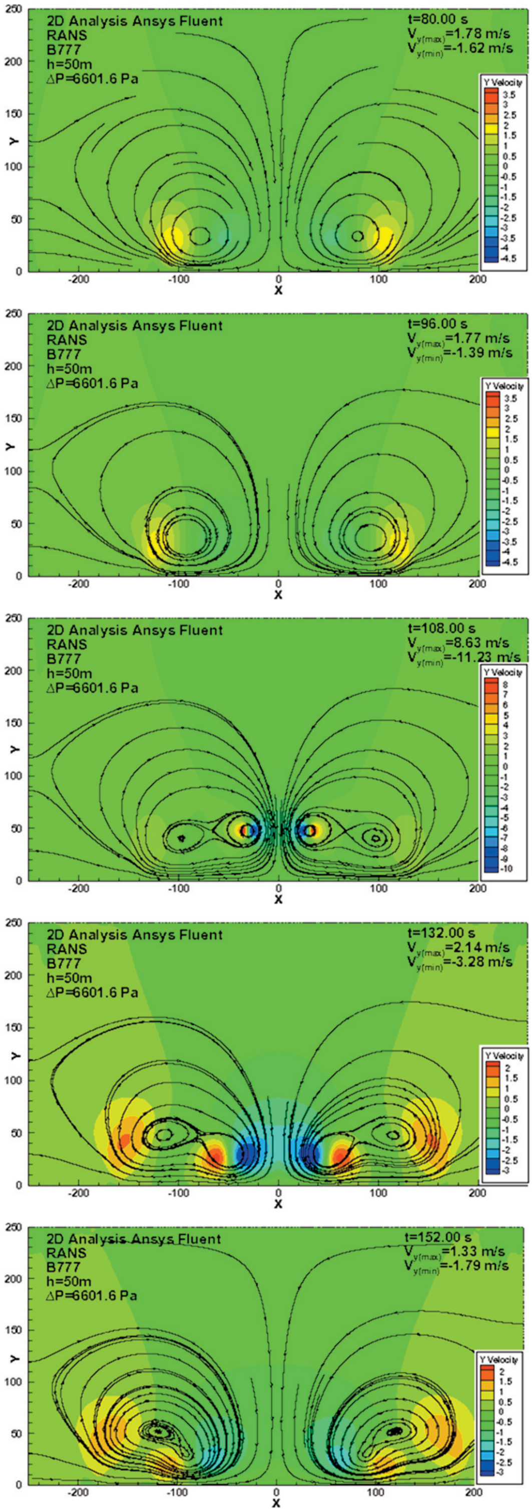

Fig. 13. Maps of vertical velocity and pathlines of flow for wakes interaction [Bugała, 2016]

Another phase of this work was an evaluation of separation between airplanes influence on vortex decay. For this purpose the 2D analysis was conducted. During this simulation an assumption was made that an airplane, the Boenig 777, lands and interval to the next airplane is 106 s. This analysis allows to show vortices in a selected cross-section behind an airplane. Figures 12-14 present maps of vertical velocity distribution and pathlines of flow for vortex interaction in a ground reference frame.

The first 106 seconds of this analysis were a pertain decay of wake vortex of the first airplane. After the first plane's flight, the wake vortices still exist. Each wake vortex reduces and spreads out under the influence of the ground. The maximum and minimum vertical velocity decreases up to 10 times during this time.

Between 106.7 and 107.4 s another Boeing 777 approaches. After 107.4 s, an interaction between vortices can be observed. The second vortex has an impact on the first one. The interaction between wakes consists of spreading out and lifting the old wakes. As shown in the last frame of Figure 14 vortices are quite distant from one another compared to the corresponding frame of 96 s.

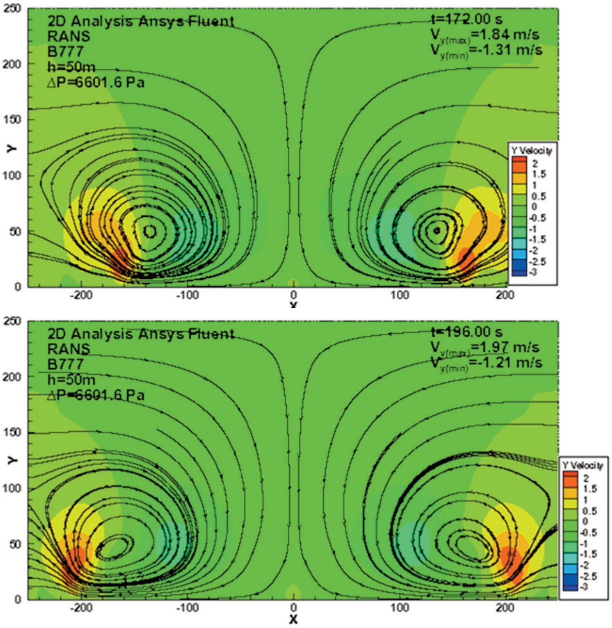

Fig. 14. Maps of vertical velocity and pathlines of flow for wakes interaction [Bugała, 2016]

4. CONCLUSIONS

During the work a set of test cases were calculated in order to obtain the following information:

- for a full commercial airplane, the source of vortices is not only wingtips but also nacelles, horizontal stabilizers and fuselage, and their (vortices) scale in comparison to tip vortexes can be determined,
- all vortices heavily influence one another. Two wingtip airplane wakes merged together on one side, thereby establishing one area of lower velocity with the minimum in the middle,
- comparison of results for 3D wing and 2D analysis showed that a simplified 2D analysis is sufficient to evaluate wake vortex. 2D analysis results error appears to be on the safe side showing a rather more dangerous intensity of the phenomenon than it appears to be in a more advanced 3D simulation,

- after 106 s, when the wake vortex caused by the first airplane still exists, its rotational velocity is reduced gradually and it spreads out under the influence of the ground,
- the fist wake vortex interacts with vorticity caused by the second Boenig 777,
- the interaction between wakes consists of spreading out and lifting wakes.

The results proved the following:

- CFD analysis of vortex decay can be computed at different degrees of advancement: from a simple 2D to an advanced 3D case including full airplane geometry,
- with the development of computational models and an increase in the computing power of current clusters, more cases can be analyzed numerically avoiding scaling and kinematic problems, which is the case in an experimental analysis of the phenomena described above.

Future studies should comprise:

- the size of the separation period and the influence of crosswind and headwind on vortices behaviour,
- possibility of further increase of accuracy with non-rectangular distribution of lift along wingspan, elliptic, obtained using 3D simulations, avilable in literature concerning an aircraft with slats and flaps extended,
- possibility to use a two-stage 3D simulation on moving and stationary domain, where the first one generates wake basing on a real aircraft geometry and the other one is stationary. This is the way to avoid huge meshes in terms of its spatial size and as a result of huge amounts of elements (cells) in computation and a high calculation cost.

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WZAJEMNE ODDZIAŁYWANIE WIRÓW ZASKRZYDŁOWYCH DUŻYCH SAMOLOTÓW

Streszczenie

W ciągu kilku kolejnych lat, problem wirów powstających za ciężkimi samolotami, może wzrastać z powodu rozwoju ruchu lotniczego. Jednak już dziś można zauważyć rosnącą liczbę wypadków spowodowanych interferencją z wirami. To jest powód, dla którego metody opisu wirów powinny stać się przedmiotem badań.

Celem niniejszej pracy jest analiza interferencji wirów powstających za wybranym samolotem pasażerskim. W artykule zaprezentowano charakterystykę zaburzenia powstającego za trójwymiarowym skrzydłem. Niniejsza praca ukazuje wpływ separacji między samolotami na rozpad wirów. Dwu- i trójwymiarowe obliczenia zostały wykonane przy użyciu komercyjnego kodu RANS. Następujące przypadki zostały wzięte pod uwagę: przepływ za pełnowymiarowym samolotem komercyjnym, trójwymiarowa analiza wirów za uproszczonym skrzydłem oraz dwuwymiarowa symulacja rozpadu wirów za lądującymi samolotami z uwzględnieniem separacji. Dla wszystkich tych przypadków zostały przeprowadzone analizy CFD.

Jednym z najistotniejszych rezultatów pracy jest potwierdzenie, że interakcja pomiędzy zaburzeniami polega na rozchodzeniu i unoszeniu się wirów. Uzyskane wyniki pokazują, że obliczenia dwuwymiarowe są wystarczające do wstępnej analizy wirów. Wnioski tych analiz mogą być wykorzystane przez zarządy zatłoczonych, międzynarodowych lotnisk do utrzymania odpowiedniego poziomu bezpieczeństwa.
Słowa kluczowe: CFD, rozpad wirów, oddziaływanie wirów.