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EXPERIMENTAL INVESTIGATION OF DAMAGE WING IMPACT ON THE AIRLINER AERODYNAMIC CHARACTERISTICS

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Abstract

In this paper an experimental wind tunnel investigation was conducted to measure the impact of the aircraft wing damage on the airliner aerodynamic characteristics and its stability after the loss of wing parts. As the presented study referred to the crash of the Polish government Tu-154M aircraft, the loss of 1/3 of the left wing tip along with the loss of left wing control surfaces, i.e. slat and flap was investigated. The issue of the aircraft lateral stability after losing part of its wing was also discussed. Wind tunnel test were carried out in two of the Łukasiewicz Research Network – Institute of Aviation wind tunnels, i.e. in the wind tunnel T-3 (with a 5 m diameter test section) using the aircraft model at the 1:14 scale and also in the wind tunnel T-1 (with a 1.5 m diameter test section), using the aircraft model at the 1:40 scale. In the wind tunnel T-3 the tests were performed at the V_∞ = 75 m/s, which corresponds to Reynolds number Re = 1.67×10^6, and In the wind tunnel T-1 at the V_∞ = 40 m/s, which corresponds to Reynolds number Re = 0.35×10^6. Balance measurements of the wing damage impact on the Tu-154M aircraft models basic aerodynamic characteristics were carried out. Especially, the issue of the aircraft lateral stability after losing part of its left wing was discussed. The test showed that after wing tip loss the lateral balance could be obtained by simultaneous aileron and spoiler deflection or in a condition of the aircraft flight in a sufficiently high sideslip angle.

Keywords: aircraft damage, wing tip lost, wind tunnel tests, lateral balance

1. Introduction

In the history of aviation many air accidents took place during a flight when, as a result of a collision with other objects, a part of an aircraft was damaged or even lost. Damage or loss of a part ofcontrol surfaces usually is a dangerous incident and very often leads to a crash due to the loss of the ability to aircraft control. In the history there were also cases of the air accidents when an appropriate pilot's response, in a case of even serious aircraft damage, ensured a safe aircraft landing. Such a well-documented and repeatedly described case [1] took place in 1965 when, as a result of the explosion of an external underwing engine on the 707-321B, approximately 7.5 m of the right wing tip (i.e. about 1/3 half wing span) was lost. The situation was very dangerous as there were 143 passengers and 10 crew on board. Despite the loss of a large part of the aircraft wing, the pilot managed to land safely.

Equally spectacular accident took place in 1983 when as a result of the collision of two fighters one of them, i.e. F-15D Eagle, lost almost entire right wing. Soon after the collision the F-15D Eagle fell into a spin. Despite such serious damage to the plane, the pilot managed to regain control of the fighter's flight and land safely [2, 3].

A similar accident, as a result of which the F-16c fighter lost almost half of its wing, occurred a few years ago (2014) in the USA [4]. In this case, the pilot also managed to land safely.

The cases of serious air incidents presented above, which resulted in the loss of the entire wing or a significant part of it yet ended with a safe landing, prove that the loss of a part of the aircraft wing does not have to lead to a crash. In such an extremely difficult situation, it is important for the pilot to use all available possibilities of avoiding an air accident.

For these reason the issue of the impact of aircraft damage during a flight on the aircraft aerodynamic characteristics was in the past the subject of many scientific investigations including the wind tunnel tests [5 and 6]. Such tests were not only a source of knowledge of the aircraft performance, but also provide valuable information on the pilot's necessary response in the event of an aircraft damage.

The tests of the aerodynamic characteristics of the Tu-154M aircraft models in the base undamaged configuration and in the configuration with damages left wing tip were already carried out in the past in several wind tunnels, e.g. 2017 in the Military University of Technology (Warsaw, Poland) in a low speed wind tunnel with 1.1 m. diameter test section (model at the 1:50 scale) [7], 2017/2019 in the AEROLAB wind tunnel with 711 mm x 508 mm test section (model at the 1:100 scale) [8], 2018/2019 in the Łukasiewicz Research Network – Institute of Aviation in a low speed wind tunnel T-1 [9] with 1.5 m diameter test section (models at the 1:100 and 1:40 scale), and finally in low speed wind tunnel T-3 with 5 m diameter test section (model at the 1:14 scale). The primary goal of the presented wind tunnel tests results was to determine the impact of the Tu-154M aircraft wing damage on its lift, drag, pitching moment and lateral balance basing on the aerodynamic data obtained from the low speed wind tunnel T-3 as well as from the low speed wind tunnel T-1. Therefore, the two basic aircraft model configurations were tested, i.e. with an undamaged wing and with the left wing top lost.

2. Research Technique

2.1 Wind Tunnels

Wind tunnel test of the Tu-154M aircraft models were carried out in two of the Łukasiewicz Research Network – Institute of Aviation (IoA) wind tunnels, i.e. primarily in the wind tunnel T-3 and also in the wind tunnel T-1.

The T-3 IoA low speed wind tunnel is a close-circuit continuous-flow wind tunnel with a 5 m diameter open test section and length 6,5 m. The maximum air speed in the wind tunnel test section is about 90 m/s, which corresponds to Reynolds number per meter Re = 6.2×10^6. The flow in the test section is relatively uniform with longitudinal turbulence level of about 0.5 percent. Test section airflow is produced by 7-m diameter 8-bladed fan powered by a 5.6 MW AC motor. In Figure 1 the Tu-154M aircraft model fixed to the 6-compnent internal balance with bottom support is presented.

Figure 1 – The Tu-154M aircraft model in low speed wind tunnel T-3.

The T-1 IoA low speed wind tunnel is a close-circuit continuous-flow wind tunnel with a 1.5 m diameter open test section. The range of the air speed in the wind tunnel test section is 15÷40 m/s.

The maximum air speed corresponds to Reynolds number per meter Re = 2.75x10^6. The longitudinal turbulence level is about 0.5 percent. Test section airflow is produced by 2-m diameter 4-bladed fan powered by a 55 HP AC motor. In Figure 2 the Tu-154M aircraft model fixed to the 6-compnent internal balance with bottom support is presented.

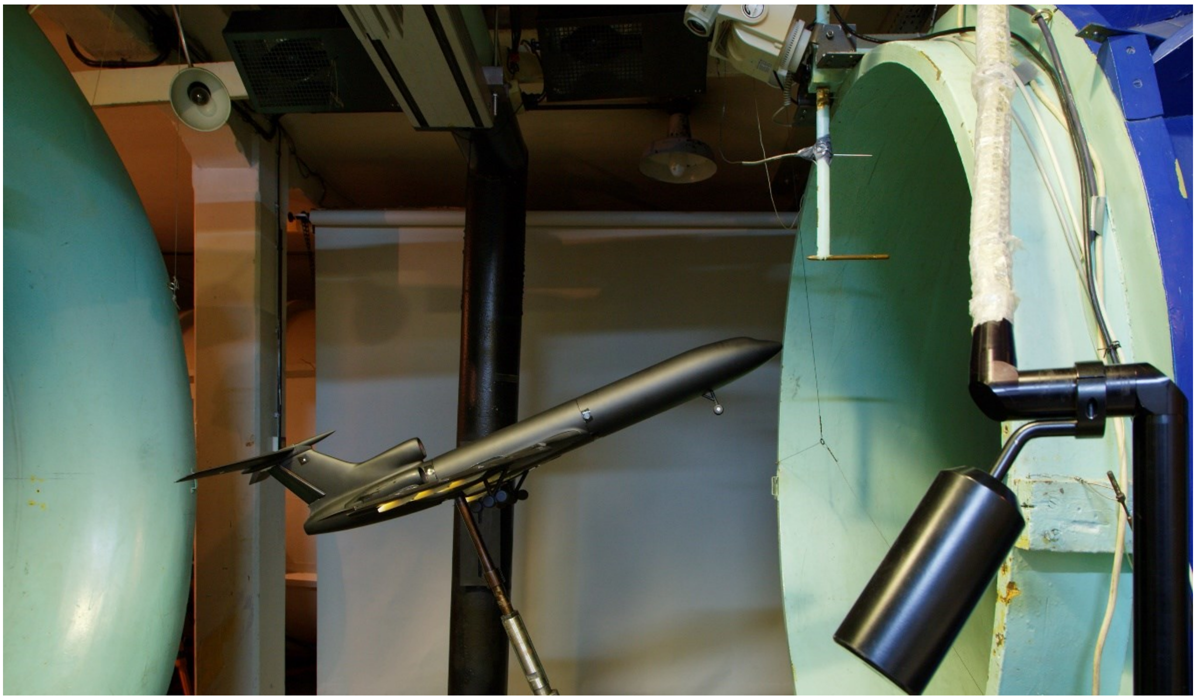

Figure 2 – The Tu-154M aircraft model in low speed wind tunnel T-1.

2.2 Aircraft Models

In the wind tunnel T-3 the Tu-154M aircraft model at the scale 1:14 was tested. It was a model of the following geometric dimensions which were used for the aerodynamic coefficient calculations.

- Wing span b = 2.682 m (reference length for the rolling moment coefficient C_l).
- Wing area S = 0.918 m^2 (reference area).
- Middle aerodynamic chord MAC = 0.377 m (reference length for the pitching moment coefficient C_m).

In the wind tunnel T-1 the Tu-154M aircraft model at the scale 1:40 was tested. It was a model of the following geometric dimensions which were used for the aerodynamic coefficient calculations.

- Wing span b = 0.939 m (reference length for the rolling moment coefficient C_l).
- Wing area S = 0.1125 m^2 (reference area).
- Middle aerodynamic chord MAC = 0.132 m (reference length for the pitching moment coefficient C_m).

Both of the aircraft models (used in the wind tunnels T-3 and T-1) were designed and manufactured (mostly in the rapid prototyping technology) by the Military University of Technology basing on the Tu-154M aircraft outer surface geometry obtained by scanning of the real object. This allowed for accurate mapping of the whole aircraft outer surface including the gaps in control surfaces.

The uncertainty of the measured aerodynamic coefficient were estimated as follows: lift = ±0.004, drag = ±0.007, pitching and rolling moment = ±0.001. The aerodynamic characteristics presented in this study refer to the coordinate system (X0YZ) associated with the direction of undisturbed flow, Figure 3. The position of the center of the coordinate system was defined as follows,

- fuselage symmetry axis,
- 25% MAC i.e. 1.66 m from the model nose.

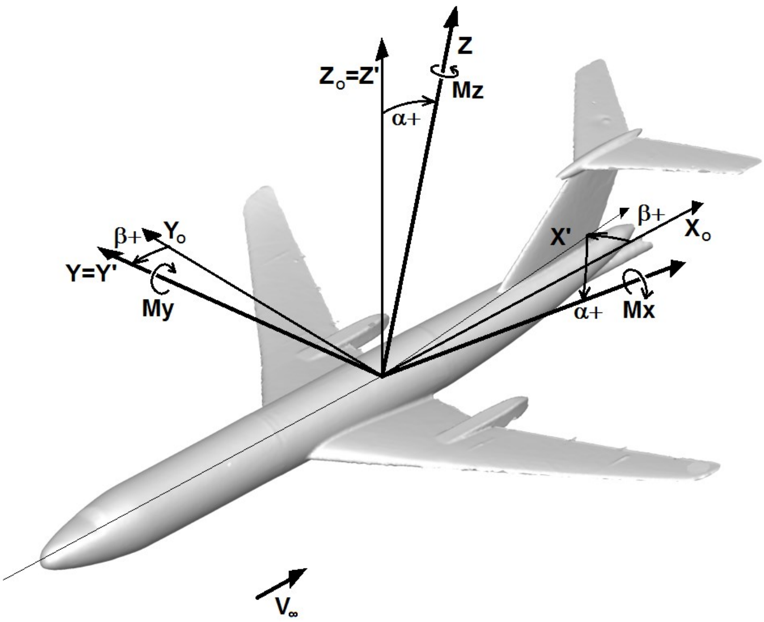

Figure 3 – The measurement coordinate system.

The wind tunnel test presented in this paper were carried out for the two basic Tu-154M aircraft models configurations, i.e. with undamaged wings and with the damage left wing (without approximately one-third left wing tip). Due to different theories concerning the degree of the Tu-154M aircraft left wing tip damage the geometry of models which were tested in the wind tunnels T-3 and T-1, slightly differed each other, as shown in Figure 4 (the given dimension are for a full scale airplane).

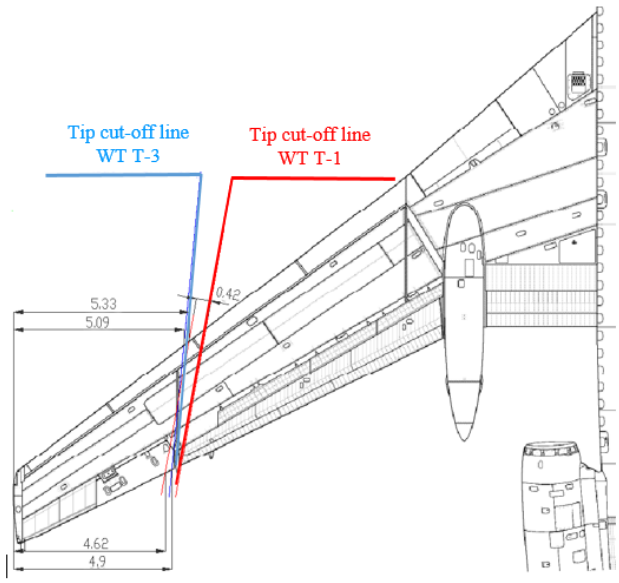

Figure 4 – The wing tip cut-off differences in Tu-154M models tested in wind tunnels T-3 and T-1.

The wind tunnel tests were performed in the wind tunnel T-3 at the undisturbed flow speed V = 75 m/s, which corresponds to Reynolds number (referred to MAC) Re = 1.67×10^6 and in the wind tunnel T-1 at the undisturbed flow speed V = 40 m/s, which corresponds to Reynolds number (referred to MAC) Re = 0.35×10^6.

3. Wind Tunnel Tests Results

In Figures 5 ÷ 11 the impact of the wing tip loss on the Tu-154M aircraft aerodynamic coefficients (drag, lift, pitching, rolling and yawing moments) is presented. The aircraft model was tested in a landing configuration with slats and flap deflected.

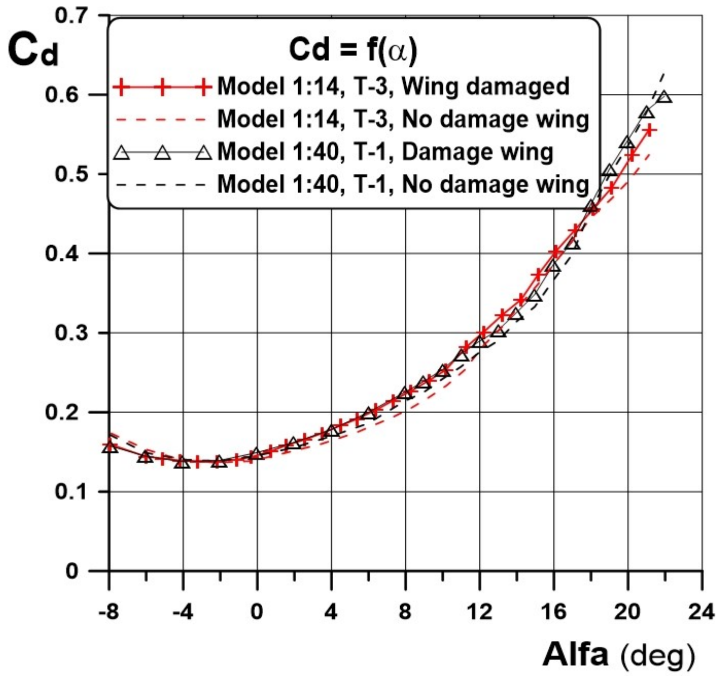

Figure 5 – Impact of the wing damage on the drag coefficient.

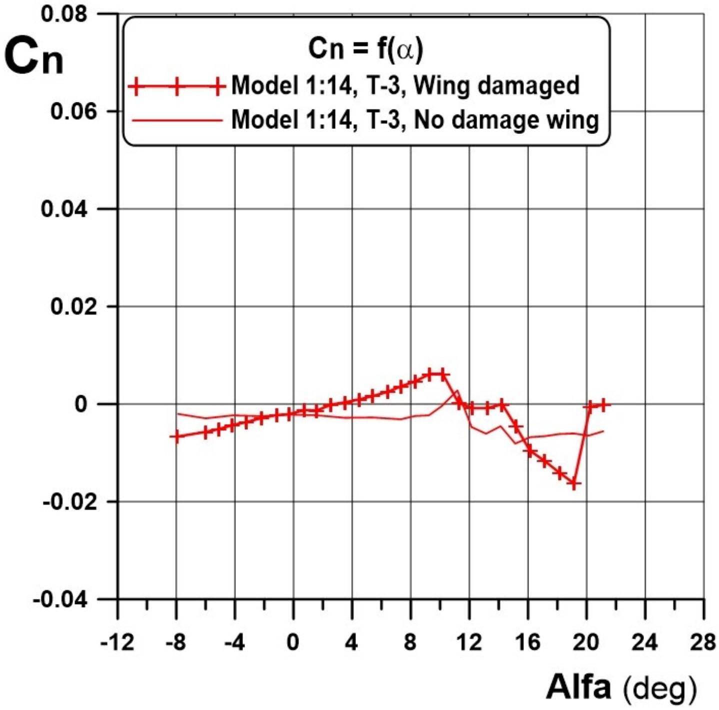

Figure 6 – Impact of the wing damage on the yawing moment coefficient.

Generally, left wing tip damage did not affect the aircraft drag. Although, the aircraft lost its left wingtip so the damaged wing parasite drag was reduced but simultaneously the induced drag increased because of reducing wing aspect ratio (with small lift changes, Figure 7). As a result the total drag of the left wing did not change significantly, which is clearly visible in Figure 6 that presents the impact of the wing damage on the aircraft yawing moment coefficient for the model at the 1:14 scale (wind tunnel T-3).

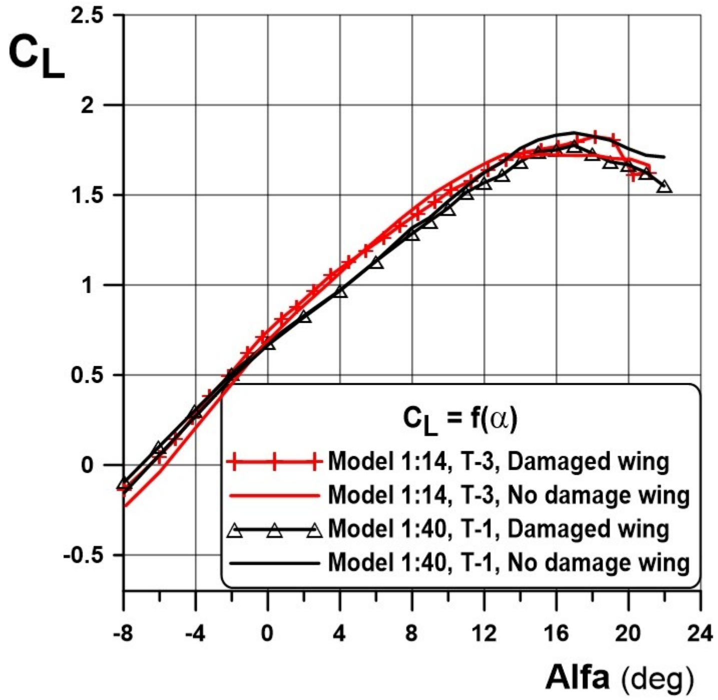

Figure 7 – Impact of the wing damage on the lift coefficient.

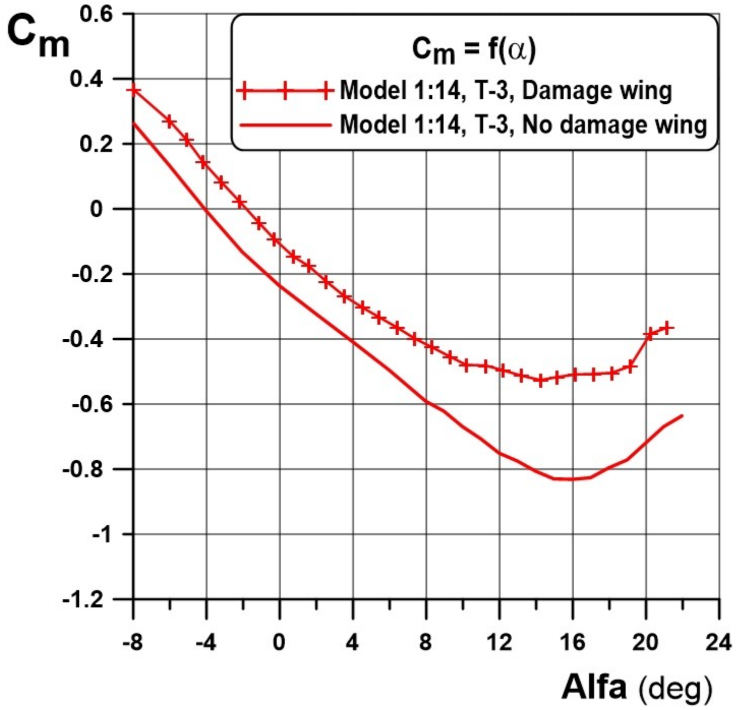

Figure 8 – Impact of the wing damage on the pitching moment coefficient.

Presented in Figure 7 the lift coefficient versus the angle of attack shows that the left wing tip lost reduces the aircraft lift only very slightly (less than 5%).

In Figure 8 the impact of the wing tip damage on the pitching moment coefficient is presented.

The loss of the left wing tip significantly affects pitching moment coefficient increasing its value from $\Delta C_m = 0.1$ at $\alpha = -8^0$ to $\Delta C_m = 0.3$ at $\alpha = 16^0$. As you might suppose the pithing moment increase is caused by the influence of the wingtip vortex, that forms on the left shorter wing, on the horizontal tail. As a result of this affect the horizontal tail angle of attack is reduced causing the lift diminish on horizontal tail.

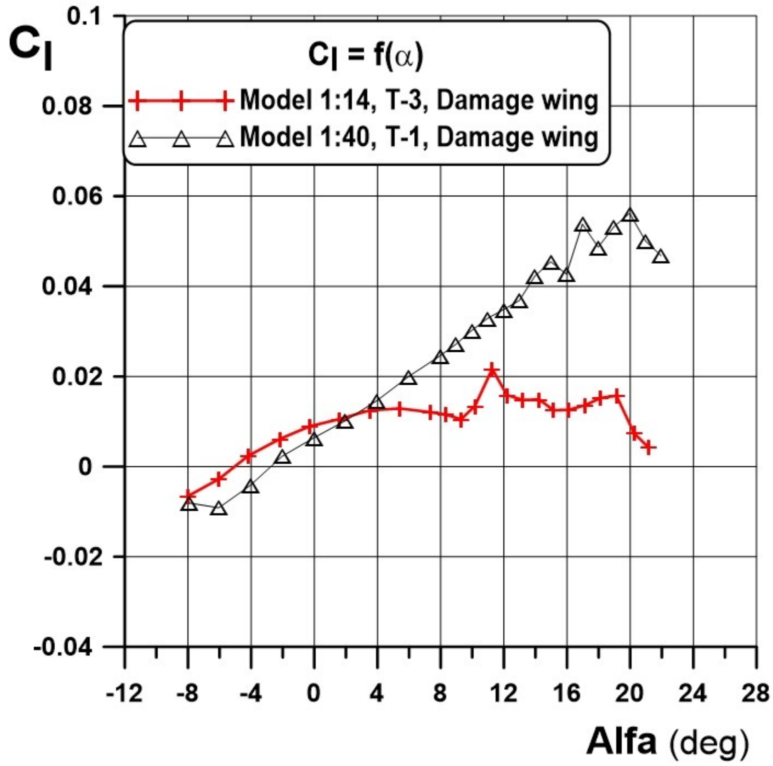

Figure 9 – Impact of the wing damage on the rolling moment coefficient.

In Figure 9 the impact of the wing tip damage on the rolling moment coefficient is presented. As a result of the loss of the left wing tip the rolling moment creates. The value of the rolling moment coefficient increases with the angle of attack and rises up to $C_l \sim 0.02$ for the model at the 1:14 scale tested in the wind tunnel T-3 and up to $C_l \sim 0.055$ for the model at the 1:40 scale tested in the wind tunnel T-1. The differences of the rolling moment coefficient values obtained from T-3 and T-1 wind tunnels, beside other reasons, can be explained by the differences in the modelled left wing damage (Figure 4).

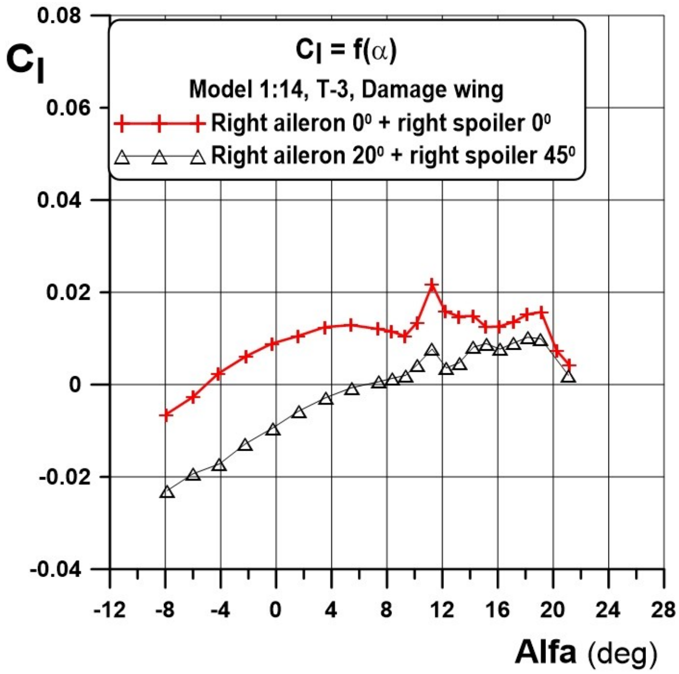

Figure 10 – Impact of the right aileron and right spoiler deflection on the rolling moment coefficient.

In the case of the left wing tip loss, referred to in this paper, it is possible to maintain aircraft lateral balance. This can obtained in two ways, i.e. by simultaneous right aileron and right spoiler deflection or by putting the aircraft into a sideslip on the right wing. In Figure 10 the impact of the simultaneous right aileron upward deflection (at 20°) and the right spoiler deflection (at 45°) on the rolling moment coefficient for the aircraft model tested in the wind tunnel T-3 is presented. In this case it is possible to maintain the aircraft lateral balance in the range of angles of attack up to $\alpha \sim 6.5^o$.

The impact of the Tu-154M aircraft sideslip (β) on its rolling moment coefficient for angles of attack $\alpha = 0^o$ and 12.5^0 is presented in Figure 11. As can be seen the aircraft sideslip in direction of undamaged wing is the most effective way to keep the aircraft lateral balance after a loss one of its wingtip. In the case of the left wing tip damage described in this paper the aircraft sideslip $\beta \sim 1.2^o$ in the direction of the right wing is sufficient to ensure Tu-154M aircraft lateral balance.

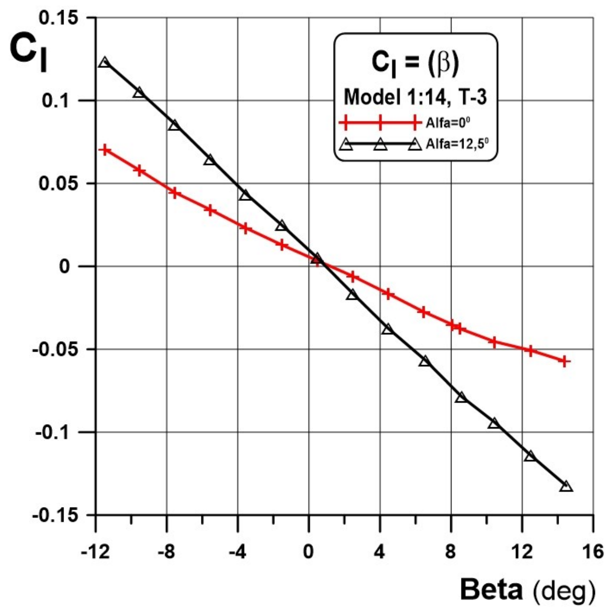

Figure 11 – Impact of the Tu-154M aircraft sideslip on the rolling moment coefficient for $\alpha = 0^o$ and 12.5^0 .

4. Conclusions

In this paper the tests of the aerodynamic characteristics of the Tu-154M aircraft models in the base undamaged configuration and in the configuration with damages of the left wing tip is presented. The wind tunnel tests of the Tu-154M aircraft models were carried out in two of the Łukasiewicz Research Network – Institute of Aviation (IoA) wind tunnels, i.e. primarily in the wind tunnel T-3 and also in the wind tunnel T-1. In the wind tunnel T-3 the tests were performed at the undisturbed flow speed V = 75 m/s, which corresponds to Reynolds number (referred to MAC) Re = $1.67x10^6$ and in the wind tunnel T-1 at the undisturbed flow speed V = 40 m/s, which corresponds to Reynolds number (referred to MAC) Re = $0.35x10^6$. In the wind tunnel T-3 the aircraft model at the scale 1:14 was tested while in the wind tunnel T-3 model at the scale 1:40. The analysis of tests results leads to the following conclusions:

The left wing tip damage (the loss of the approximately one-third wing tip did not affect the aircraft drag. It could be related to the induced drag increased as a result of the reducing wing aspect ratio. Similarly, the left wing tip lost reduces the aircraft lift only very slightly (less than 5%).

The loss of the left wing tip significantly affects the Tu-154M aircraft pitching moment coefficient increasing its value from $\Delta C_m = 0.1$ at $\alpha = -8^0$ to $\Delta C_m = 0.3$ at $\alpha = 16^0$. This impact can be caused by the influence of the wingtip vortex, that forms on the left shorter wing, on the horizontal tail. As a result of the diminishing the horizontal tail angle of attack the lift on horizontal tail is reduced which leads to the aircraft pithing moment coefficient increase.

As a result of the loss of the left wing tip the rolling moment creates of a value up to $Cl \sim 0.02$. In the of this wing damage it is possible to maintain aircraft lateral balance. This can be obtain in two ways, i.e. by simultaneous right aileron and right spoiler deflection or by putting aircraft into a sideslip on the right wing. By maximum right aileron upward deflection (at 20°) and right spoiler deflection (at 45°) it is possible to maintain the aircraft lateral balance in the range of angles of attack up to $\alpha \sim 6.5^o$. Putting the aircraft in sideslip in direction of undamaged wing is the most effective way to keep the aircraft lateral balance after a loss one of its wingtip. In the case of the left wing tip damage described in this paper the aircraft sideslip $\beta \sim 1.2^o$ in direction of right wing is sufficient to ensure Tu-154M its lateral balance.

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