

CFD ASSESSMENT OF AERODYNAMIC DEGRADATION OF THE TU-154M PLANE

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Abstract

The purpose of this work is to determine the change in the aerodynamic forces and moments of a TU-154M plane exposed to a left wing loss of 5.5m and 10m respectively with and without interaction of the right aileron and right outer interceptor surface. This is done through the computational fluid dynamics technique (CFD) using validated CFD++ software by Metacomp Inc. and by use of a detailed model of the TU-154M aircraft. Results presented here correlate well with the manufacturers data for the plane in cruise and landing modes, thereby confirming the models and method and bringing a level of assurance that the CFD is being solved consistently. The lost lifting force associated with a wing loss of 5.5m is found to be less than 8.6% of the original lifting force. Including the effect of the increased airflow at the inner portion of the wings caused by the engine flow will further reduce the loss associated with the loss of the wing tip. The results of this work are important in understanding the case of the crash of the presidential plane in Smolensk in April 2010. The results undermine the official explanation and support a hypothesis of a significantly higher wing loss than claimed in the official accident investigation report. The hypothesis is furthermore supported by the recording of two distinct and large drops in the vertical acceleration signal separated with about 120 m flying distance as logged by the planes QAR data recorder.

Keywords - CFD, wing damage, roll, Smolensk Catastrophe, TU-154.

Streszczenie

W pracy ustalono zmiany w siłach i momentach aerodynamicznych działających na samolot TU-154M wywołane utratą odcinka lewego skrzydła o długości odpowiednio 5.5 m i 10 m zarówno w przypadku zadziałania jak i bez zadziałania prawej lotki i zewnętrznej powierzchni prawego interceptora. Obliczenia wykonano w technice komputerowej mechaniki płynów (CFD). Wykorzystano zwalidowane oprogramowanie CFD ++ firmy Metacomp Inc. przy użyciu szczegółowego modelu samolotu TU-154M. Uzyskane wyniki dobrze zgadzają się z danymi producenta samolotu zarówno w konfiguracji rejsowej jak i w konfiguracji do lądowania. Potwierdza to słuszność przyjętych modeli i metody obliczeń i zwiększa poziom pewności, że uzyskane rozwiązanie CFD jest prawidłowe. Stwierdzono, że utrata 5.5 m skrzydła powoduje spadek siły nośnej mniejszy niż 8.6 % oryginalnej siły nośnej skrzydła. Uwzględnienie efektu zwiększonego przepływu powietrza na części skrzydła przylegającej do kadłuba wywołanego działaniem silnika dodatkowo zredukuje spadek siły wywołany utratą końcówki skrzydła. Wyniki pracy są ważne dla zrozumienia przypadku katastrofy prezydenckiego samolotu w Smolensku w kwietniu 2010. Podważają one oficjalne wyjaśnienie przyczyny katastrofy i potwierdzają hipotezę o znacząco większej utracie skrzydła, niż stwierdzona w oficjalnym raporcie z badania wypadku. Hipoteza ta jest ponadto poparta przez zarejestrowanie dwóch wyraźnych i dużych spadków przyspieszenia piono-

wego rozdzielonych dystansem 120 m lotu samolotu, jakie zarejestrował rejestrator QAR samolotu.

Słowa kluczowe – CFD, zniszczenie skrzydła, beczka samolotu, Katastrofa Smoleńska, Tu-154M.

1. INTRODUCTION

On the 10th of April 2010 a Tu-154M plane crashed into the ground close to the Smolensk Airfield killing all 96 people on board including the Polish president, the top NATO generals of the Polish Air Force, navy and army. In the final report by the Russian Interstate Aviation Committee (MAK Report, [1]), it is claimed, that the crash was a result of the 150° left roll of the plane in low height caused by the loss of 5.5 m of the left wing tip after its collision with a 30 - 40 cm thick birch tree about 5 m above the ground and about 340 m prior to the site of crash. The measured roll angle is recorded by the planes data recorders (black boxes) the first 1.6 seconds after loss of the wing area until the system reaches some (unexplained) cut-off limitation of about 62°. The measured speed of roll is linked to the lost wing area, and from this the estimated wing loss can be found. Loss in wing area on one side during normal flight of a symmetric plane will result in the loss in lifting power of this side and a moment of rotation about the planes length axis driving a roll of the plane. Two models for calculating the final trajectory and roll angles for this case have been published (Kowaleczko 2013 [2]), (G.A.Jørgensen 2013 [3]). These are very different in nature. Both models predict similar results of plane roll, when presented for the same input in form of the associated loss in lifting force or more correct the driving moment of roll caused by the loss of the left wing tip. In the CFD work of Kowaleczko the associated loss in the lifting force at 8° angle of attack was first estimated to be 14 % [4] then later reduced to 12.5 % of the initial lifting force. This work was based on an highly inaccurate model of the TU-154M plane geometry not including the correct double slotted flap configuration, wrong twist of wing etc. and showed a 44 % higher change in the lifting force ratio than found here for the angles of attack of interest. By correcting the main discrepancies of the model used by Kowaleczko the results found by him match those found in this work [4].

In the early work of the author this loss was estimated to be about 8%-9% based on two different methods including a correction of the main errors in the model of the TU-154M plane used in the CFD work of Kowaleczko [4]. In the work presented here and based on a very detailed model of both the TU-154M and TU-154B this loss is found to be less than

8.6%. The work presented here clearly supports the hypothesis of a significantly higher loss of total wing length than claimed in the official report.

2. MODEL DESCRIPTION

2.1. Geometry

The standard notation for describing the motion of, and the aerodynamic forces and moments acting on, a flight vehicle is indicated in Fig. 1. The variables x , y , and z represent coordinates, with origin at the center of mass of the vehicle.

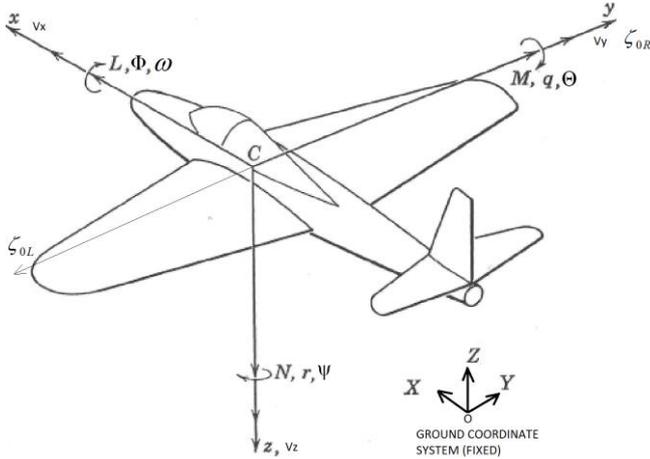


Fig. 1. Definition of the coordinate system. The figure is borrowed from [5].

The x -axis lies in the symmetry plane of the vehicle (Nelson 1989, [6]) and points toward the nose of the vehicle. The z -axis also is assumed to lie in the plane of symmetry, perpendicular to the x -axis, and pointing approximately down. The y -axis completes a right-handed orthogonal system, pointing approximately out the right wing. The variables u, v , and w represent the instantaneous components of linear velocity in the directions of the x -axis, y -axis, and z -axis, respectively. The variables F_x, F_y , and F_z represent the components of aerodynamic force in the directions of the x -axis, y -axis, and z -axis, respectively. The variables p, q , and r represent the instantaneous components of rotational velocity about the x -axis, y -axis, and z -axis, respectively. The variables L (or CM_x), M , N represent the components of aerodynamic moments about the x, y , and z axes, respectively. The variables Φ, Θ, Ψ , represent the angular rotations, relative to the equilibrium state, about the x, y , and z axes, respectively (roll angle, pitch angle and yaw angle). Thus

$$\omega = \frac{d\Phi}{dt}, \quad q = \frac{d\Theta}{dt}, \quad r = \frac{d\Psi}{dt}. \quad (1)$$

3D models of the TU-154 plan are created in Creo™ Release 2.0 and imported into CFD++ by Metacomp. Minor corrections are added by Metacomp to make the model water tight. In some instances, the geometry is slightly altered to enable quality mesh generation. The alterations made to the models are extremely small and prevent mesh singularities that would affect the CFD simulation. Where possible the geometry is based on the data given by B.Bextnp et Al. [7]. Additional data is found in TU-154 by Dmitriy Komissarov [8]. According to Komissarov the Tu-154M features double-slotted flaps and redesigned LE slates deflected 22° with no gap between the inner/outer wing

sections, where the Tu-154B features triple-slotted flaps. One piece ailerons are located outboard of the flaps. The outer wing spoilers are flight spoilers and assist the ailerons for roll control. The hinge line is located ahead of the leading edge so that a gap appears when the spoilers are deployed, hereby optimizing the airflow and preventing pressure fluctuations. Each outer wing has two prominent boundary layer fences. The fences are attached in line with the inboard ends of the No2 LE slat sections and the outer ends of the outboard flaps. The wing utilizes TsAGI high-speed airfoils, P-56M₂-12 at the roots, P-35M₃-11 at mid-span and P-35M₃-10 at the tips. In the absence of these airfoil coordinates and based on the overall description of the airfoil main parameters found in T.N.Nnrym, the NACA 23012 airfoil is chosen for the root section, the Boeing B737b-il (11%) airfoil is chosen for the mid span and the Boeing B737b-il (10%) airfoil is chosen for the tip section. The wings have zero sweepback inboard of the main landing gear fairings. Sweepback at quarter-chord is 35° , the anhedral angle $1^\circ 10'$, incidence at root is $+3^\circ$ and -1° at the tip giving a total wing twist of 4° , aspect ratio 7.85, taper 3.5 and MAC 5.285 m. The plane has a cantilever swept T-tail featuring symmetrical airfoils. Sweepback at quarter-chord is 45° , aspect ratio 1.0, taper 1.88 and thickness/chord ratio 11%. The symmetrical airfoil S9032-il (11 %) is chosen for the tail profile (both root and tip). The plane in cruise mode is modelled without landing gear and with retracted flaps and slats. See Fig. 2 and Fig. 3.



Fig. 2. Top view of the 3D model of the TU-154 in cruise mode.



Fig. 3. Bottom view of the 3D model of the TU-154 in cruise mode.

In landing mode the plane is modelled with deployed landing gear. One version is modelled as the Tu-154B with triple-slotted flaps and rounding of the wing tips (see figures Fig. 4, Fig. 5 and Fig. 6),

Note the extended slats towards the tip whereas the Tu-154M is modelled with double slotted fowler flaps and the slats are extended further outboard compared to the TU-154B with a more square wing tip (see figures Fig. 7 - Fig. 9).

2.2. Pilot interaction

The effect of no pilot counteraction (free stick) is examined by setting both the right wing outer interceptor and the right aileron to their neutral positions. The effect of

any pilot counteraction of the roll of the plane is examined by setting both the right wing outer interceptor and the right aileron to their full travel (45°) and (20°) respectively.

2.3. Flight conditions

Each plane mode is evaluated for two or three angles of attack from $\alpha = 3^\circ$ to $\alpha = 13^\circ$. The free stream air temperature is $T = 275\text{K}$, the free stream air pressure $p = 99325\text{ Pa}$ and the free stream velocity $V = 75\text{ m/s}$. The reference area is set to $S = 180\text{ m}^2$ for easy comparison to the manufacturers data. The reference length is set as the Mean Aerodynamic Chord $L = 5.285\text{ m}$.



Fig. 4. Top view of a 3D model of the TU-154B in landing mode.



Fig. 7. Top view of a 3D model of the TU-154M in landing mode.



Fig. 5. Bottom view of a 3D model of the TU-154B in landing mode. Note the triple slotted fowler flaps.



Fig. 8. Bottom view of the 3D model of the TU-154M in landing mode. Note the double slotted fowler flaps.



Fig. 6. Close view of the triple slotted fowler flaps of the TU-154B in landing mode.



Fig. 9. Close view of a 3D model of the TU-154M in landing mode. Note the double slotted fowler flaps and extended slats towards the tip.

3. COMPUTATIONAL METHOD.

3.1. Numerical methodology used

Steady state viscous simulations are conducted using Reynolds Averaged Navier Stokes equations (RANS) methodology. This approach allows a quick and reliable estimate of the pressure distribution on the body as well as the skin friction in order to evaluate the various forces and moment coefficients. The turbulence closure model used is Spalart-Allmaras (SA). The solution is driven to a steady state by relaxation using a pseudo time step. Convergence is accelerated via multigrid.

3.2. Generation of Grid

All meshes discussed in this report have been generated by Metacomp's Multipurpose Intelligent Meshing Environment (MIME) pre-processing package. The geometry considered is somewhat complex and maintains several parts of the actual aircraft (fairings, flaps, slats, fences). The total number of cells in the mesh for the various modes varies between 35 million to 56 million volume cells (see Fig. 10 and Fig. 11). To enhance accuracy, curvature refinements as well as several local refinement boxes were used to ensure proper quality of the meshes.

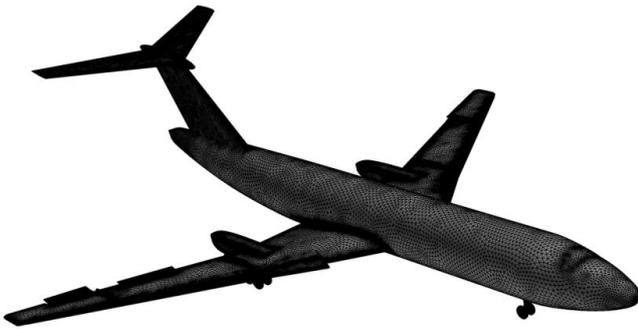


Fig. 10. One example of the grid generated by Metacomp's Multipurpose Intelligent Meshing Environment. The total number of volume cells vary between 35million and 56 million.



Fig. 11. Close look at the region of the aileron and outer interceptor of the right wing in the case of full pilot interaction.

3.3. Problem setup in CFD++

CFD work is performed using **validated** CFD++ software by Metacomp Inc. A steady RANS simulation is done to evaluate the flow around the body of the aircraft and using the one equation Spalart-Allmaras turbulence closure. The ratio of turbulent to laminar viscosity is set to 2.0. Steady state solution is obtained using the implicit solver and ramping the Courant Friedrichs Lewy number (CFL) from 1 to 120 in 100 steps. Residual convergence is very good on the clean geometry (no flaps, no slats), and the residuals drop by more than 6 orders of magnitude in the first 600 iterations.

3.4. Alpha shift

For the case of the plane in landing mode with 36° flaps, and 22° slats extension the overall lifting curve slope and shape correlates extremely well with the manufacturers data, but a small alpha shift of $\Delta\alpha=+2^\circ$ is required to bring the CFD results and manufacturers data completely in line. A plane in landing mode produces a large amount of lift and circulation which can be affected by the presence of wind tunnel walls. Since the AoA for a 3-D finite wing is reduced because of the induced AoA. It is the effect of this induced AoA that is different from tunnel to free flight and thus can cause a shift in alpha. Such alpha shift is therefore not uncommon when comparing CFD results with wind tunnel data or actual flight data, and it is without importance to the conclusions drawn here.

4. RESULTS

4.1. Lifting coefficient and moment of roll

The overall lifting coefficient found in this work for the plane in cruise and landing configurations correlates well with the manufactures data for the TU-154, thereby confirming the models and method and bringing a level of assurance that the CFD is being solved consistently. See Fig. 13.

The dimensionless pressure coefficient at the plane boundary is shown in Fig. 12.

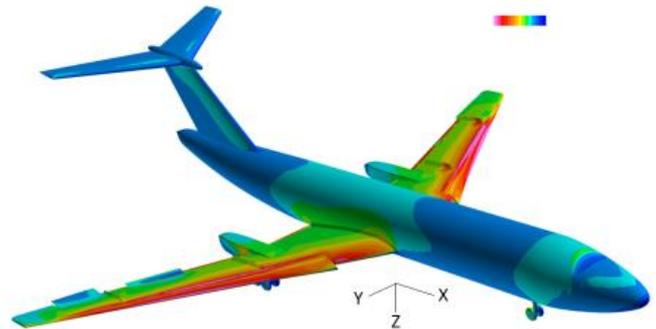


Fig. 12. The dimensionless pressure coefficient C_p for the TU-154M plane in landing mode.

The local lift coefficient CL as a function of the span coordinate y is shown in Fig. 15 and data are presented in table 1 for the TU-154M plane in cruise mode for $\alpha = 3^\circ$ and $\alpha = 13^\circ$ and in landing mode for $\alpha = 5^\circ$ and $\alpha = 15^\circ$. An alpha shift of $+2^\circ$ is observed for the plane in landing mode for both the TU154M and TU154B2 planes. No "normalization techniques" are required to bring these data in agreement with the reference data for the TU154M. Results presented here correlate well with the manufacturers data for the plane in cruise and landing modes, thereby confirming the models and method and bringing a level of assurance that the CFD is being solved consistently. The total lost lift power of the wing is found to be less than 8.6% for the TU154M for (angle of attack, AOA or α) AOA's between 5° and 15° . See Fig. 14. This is significantly lower than the 12.5% to 14% earlier claimed by Kowaleczko. The required average moment necessary to obtain a roll of the plane as logged by the plane's flight data recorders is earlier found by Jorgensen to be about $CM_{x_{req}} = 0.68$ [3, 4]. In case of no pilot interference the expected moment of roll is $CM_x = 0.297$ or 44% of the required value, as seen in Tab. 2. In the case of full pilot interaction (full right aileron and outer interceptor)

the expected moment of roll drops to $CM_x = 0.117$ or only 17 % of the moment required to obtain the logged roll rate. In this case the pilots are nearly able to counteract the entire loss of the wing tip of 5.5 m. A wing loss of about 10 m can generate the required moment of roll for AOA's

between 10° and 15° (see Tab. 1 and Tab. 2). Increasing wing losses will generally result in increasing AOA's in order to obtain the necessary lift with the reduced remaining wing area, thus driving the moment of roll up.

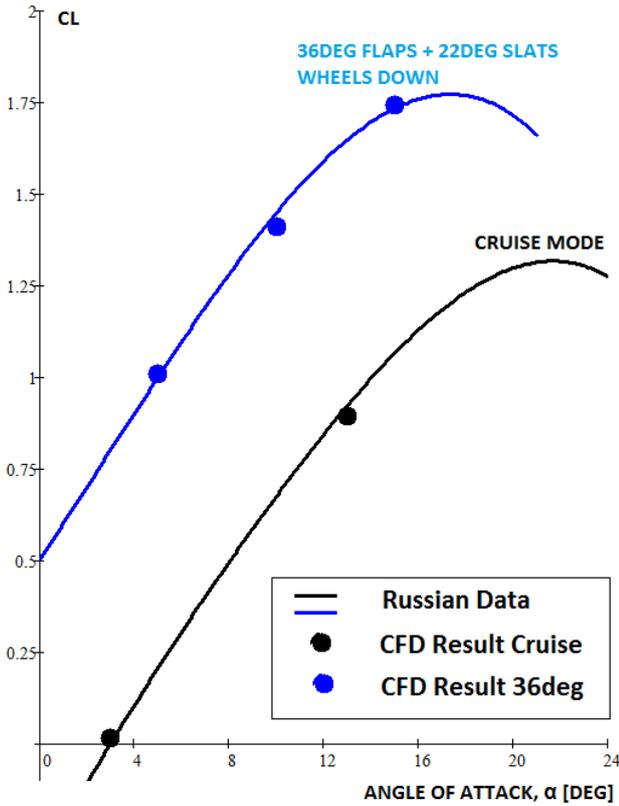


Fig. 13. The overall lifting coefficients found in this work (circles) and compared to the Russian TU-154M data (lines) [7] of the undamaged plane. The very fine correlation of both cases with and without flaps/slats confirm the model and method and brings a level of assurance that the CFD is being solved consistently.

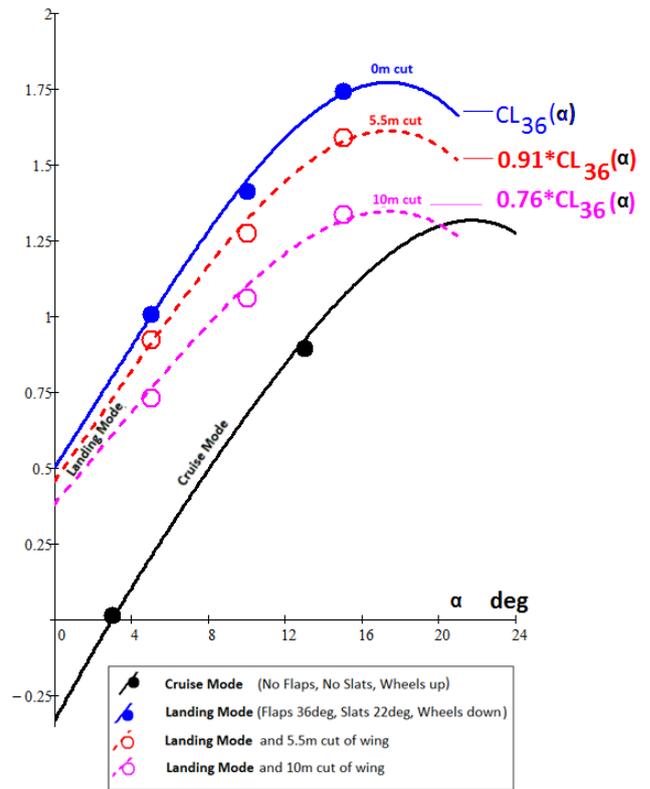


Fig. 14. Same as figure 13 but including the overall lifting coefficients of the damaged wing. The loss of lift associated with a wing loss of 5.5 m is less than 8.6 %. The resulting moment of roll is less than half the value required to obtain the roll as recorded by the planes black boxes. For a loss of 10 m wing the moment of roll reaches a value, that perfectly explains the recorded roll angle of the plane [9].

CL(Y) Full length and Length Loss of Left Wing of 5.5m

CL(Y) With and Without Aileron and Outer Interceptor

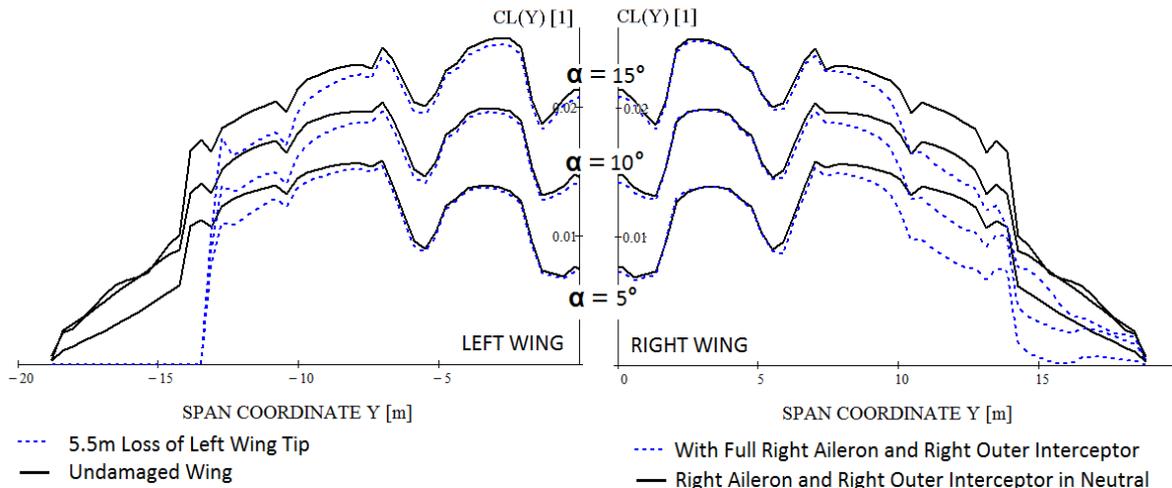


Fig. 15. The lifting distribution found in this work. The integral of area below each curve equals the total lifting coefficient for the examined case. The full black lines correspond to the lift distribution of undamaged wing in neutral for three different angles of attack (5° , 10° , 15°). The dotted lines on the left side correspond to the same for the case of a loss of 5.5m wing length. The dotted lines on the right side correspond to the same for the undamaged wing with outer interceptor and outer aileron at full extent. Note the large similarity between the two sides, i.e. applying full interceptor and full right aileron could to a large degree cancel the rotational moment of the loss of 5.5m wing tip. This effect is quantified in tab.1.

Tab. 1. The overall lifting coefficient found in this work, CLCFD++, the value found by [7], CLREF, the angle of attack, α , and the shift in α , α shift for both configurations without flaps/slats (cruise) and with 36° flaps and 22° slats (landing).

Mode	α	α - shift	CL Ref	CL CFD++
	[deg]	[deg]	[1]	[1]
Cruise	3	0	0.002	0.016
Cruise	13	0	0.922	0.896
Landing	5	2	1.001	1.009
Landing	10	2	1.449	1.413
Landing	15	2	1.733	1.742

Tab. 2. The overall lifting coefficient, CL, and the moment of roll about the X-axis (CMx) is shown for the undamaged wing (Lost span = 0m) and for a lost span of 5.5 m and 10.0 m respectively for three angle of attacks with and without full pilot interaction (by right aileron and right outer interceptor). Note that for a wing loss of 5.5 m the pilots can nearly counteract the rolling moment, i.e. prevent the rolling of the plane.

α	Lost span	Loss	CL	CMx	CL	CMx
			Free stick		Full (A+I)	
deg	m	%	1	1	1	1
5	0	0	1.009	0	0.920	-0.212
10			1.413	0	1.322	-0.217
15			1.742	0	1.676	-0.155
5	5.5	9	0.923	0.214	0.832	0.001
10			1.276	0.339	1.181	0.117
15			1.592	0.371	1.515	0.194
5	10	24	0.733	0.550	0.693	0.347
10			1.061	0.729	0.906	0.468
15			1.337	0.835	1.112	0.598

The results clearly show, that a pilot interaction with full right aileron and full right interceptor would almost entirely counteract the moment of roll associated with a wing loss of only 5.5 m, i.e. the plane would only roll a minimum angle and such loss would not lead to a crash [9] as claimed in [1]. The actual values are listed in Tab. 1 and Tab. 2.

The results presented in this work do not include the effect of the increased flow close to the fuselage as a result of the large engine thrust of motors at high speed. The effect of the increased flow around the inner portion of the wings is to increase the lift produced in this region, and thereby shifting more of the entire lift away from the tip and towards

the root of the wing. With other words the loss of lift associated with a loss of say 5.5 m of the wing tip will be even lower than the 8.6 % found in this work when including this effect. *The 8.6 % is therefore a very conservative maximum value, and further work including the motor effect could be done to reveal whether this loss is even below 7%.*

4.2. Critical speed after wing damage

From the results found in this work and presented in Fig. 14 and Tab. 2 the planes critical speed (speed of stall) can be found for both cases "no-pilot interaction" and "full pilot interaction" for a wing loss of $\Delta L = 5.5$ m.

The basic lifting equation can be written as [7]

$$F_{z,\max} = Cl_{\max} * S * \frac{\rho_{air} V^2}{2}, \quad (2)$$

Where S is the aero dynamical reference area ($S=180$ m² for the TU-154 [7]), $\rho_{air}=1.272$ kg/m³ and V is the speed of the plane relative to the air.

4.2.1. Case of no pilot interaction (right aileron and outer interceptor in neutral).

The maximum lifting coefficient Cl_{\max} for a wing loss of $\Delta L = 5.5$ m is for the case of no pilot interaction found from Fig. 14

$$Cl_{\max_{\Delta L=5.5m,NP}} = 0.91 * Cl_{\max_{\Delta L=0}} \quad (3)$$

or

$$Cl_{\max_{\Delta L=5.5m,NP}} = 0.91 * 1.77 = 1.611, \quad (4)$$

where $Cl_{\max_{\Delta L=0}} = 1.77$ is the maximum lifting coefficient of the undamaged wing [7] and the index "NP" denotes "No Pilot Interaction" in contrast to "FP", "Full Pilot Interaction".

The total required lift of the plane can be written as :

$$F_Z = M_{tot} * g * G, \quad (5)$$

By inserting (4) and (5) in (2) the critical speed of the TU-154M after a wing loss of $\Delta L = 5.5$ m can and be found as

$$V_{Critical,NP}(G) = \sqrt{\frac{M_{tot} * g * 2 * G}{\rho_{air} * S * Cl_{\max_{\Delta L=5.5m,NP}}}}, \quad (6)$$

where G is the factor of vertical acceleration. $G=1$ corresponds to a horizontal flight. $M_{tot} = 78.600$ kg is the estimated total weight of the plane [1] at the time of crash.

For horizontal flight ($G=1$) the critical speed can hereby be found as

$$V_{Critical,NP}(G = 1.0) = 233km/hr. \quad (7)$$

From (8) it is shown, that the plane speed of $V=275$ km/hr even would allow for a vertical acceleration of $G=1.25$, i.e. the pilots could continue the started upwards acceleration similar to what they had prior to the wing loss, simply by pulling a little more nose and thereby increasing the angle of attack keeping this below the critical angle of $\alpha_{critical} = 17.4^\circ$.

$$V_{Critical,NP}(G = 1.25) = 260km/hr, \quad (8)$$

4.2.2. Case of full pilot interaction (full right aileron and full right outer interceptor).

In a similar fashion the critical speeds can be found for the case of full pilot interaction using full right aileron and full right outer interceptor, again in the case of a wing loss of $\Delta L = 5.5$ m. Here the reduction, χ , of the total lift coefficient caused by the activation of the right aileron and outer interceptor must be taken into account. A good estimate of χ can be found from the values of CL with and without pilot interaction for the loss of $\Delta L = 5.5$ m for $\alpha=15^\circ$ found in this work and listed in table 2

$$\chi = \frac{1.515}{1.592} = 0.952. \quad (9)$$

Then the maximum lifting coefficient for the case of full pilot interaction can be found as

$$Cl_{\max_{\Delta L=5.5m,FP}} = 0.91 * 1.77 * 0.952 = 1.533 \quad (10)$$

The critical speed in case of full pilot interaction is found as

$$V_{Critical,FP}(G) = \sqrt{\frac{M_{tot} * g * 2 * G}{\rho_{air} * S * Cl_{\max_{\Delta L=5.5m,FP}}}}, \quad (11)$$

$$V_{Critical,FP}(G = 1.0) = 239km/hr, \quad (12)$$

$$V_{Critical,FP}(G = 1.25) = 267km/hr. \quad (13)$$

From (12) and (13) it is shown, that the pilots with a wing loss of just 5.5 m could continue the started upwards acceleration similar to what they had prior to the wing loss **and at the same time** nearly counteract the roll by pulling full right aileron and outer interceptor and a little more nose angle and thereby increasing the angle of attack still keeping this below the critical angle of $\alpha_{critical} = 17.4^\circ$.

5. CONCLUSION

Accurate 3D Models of the Tu-154M have been developed and CFD results based on these models are done using validated CFD software (CFD++). The CFD results show very good correlation to the Russian published lifting data of the Tu154M for both cruise configuration, as well as landing configuration, hereby verifying the models and CFD method and bringing level of assurance, that the CFD is being solved consistently.

The loss in total lifting power associated with a wing loss of 5.5 m is less than 8.6 % for the Tu-154M. This loss correlates very well with CFD results of the work performed by Kowaleczko, *when correcting his results for the many discrepancies between the 3D model used in his CFD work and the actual Tu-154M as described in ref [4].*

Including the effect of the increased flow over the wing roots caused by the influence of the three tail engines will tend to even further reduce the loss associated with the loss of the wing tip to below 8.6 %. Further work is required to show if the actual loss including this effect is below 7 %.

For a wing loss of 5.5 m and free stick (no pilot interference), the main moment driving the roll is less than 50 % of the moment required to achieve a roll of the plane as logged by the planes flight data recorders.

For full use of the right aileron and right outer interceptor, the main moment driving the roll is less than

20 % of the moment required to achieve a roll of the plane as logged by the planes flight data recorders.

A wing loss of effectively $\Delta L = 10$ m provides the required roll moment to get good correlation to FDR data, and leaves no possibility for the pilots to avoid a crash.

The stall speed of Tu-154M with wing loss of 5.5 m is 233 km/hr for neutral aileron and interceptor, and 239 km/hr for full right aileron and full right interceptor. Both speeds are well below the actual plane velocity of about 275 km/hr, i.e. the plane could easily be flown and even accelerated upwards while keeping far from the stall limit.

With a wing loss of just 5.5 m the pilots could - in the time they had control over the plane - continue the started upwards acceleration similar to what they had prior to the wing loss and at the same time nearly counteract the roll by pulling full right aileron and outer interceptor and a little more nose angle and thereby increasing the angle of attack keeping this well below the critical angle of $\alpha_{critical} = 17.4^\circ$.

6. CONCLUDING REMARKS

The results found in this work confirm that a loss of 5.5 m of the left wing of the TU-154M plane in Smolensk can not bring the plane to crash as claimed in the official reports.

The moment of roll caused by the asymmetric wing as a result of a loss of 5.5 m of the left wing is found to be less than half the value required to obtain the speed of roll of the plane as recorded by the planes flight recorders (black boxes). This confirms earlier work in this field [3].

In the time the pilots had control of the plane they could with such wing loss even accelerate upwards and at the same time apply the full use of the right aileron and right outer interceptor without stalling.

Full use of right aileron and right outer interceptor would to a large degree counteract the rolling moment associated with the asymmetric wing.

7. ACKNOWLEDGMENTS

The CFD work was strongly supported by Metacomp inc., to whom I am very great full. Metacomp has a large experience within the field of CFD analysis. They work

together with several major aircraft industries using Metacomp's validated state of the art software CFD++. I would also like to acknowledge Senior Mech. Eng. Jan Andrzejewski for on going support and technical discussions.

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