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AIRPLANE PERFORMANCE MODELLING THROUGH CFD RESULTS: ASSESSMENT OF A COMPLETE 3-D WING-BODY COMBINATION

SV Abayadeera[1], WMUT Weerasinghe[2], NK Wedage[3], HUGT Piyarathne[4], JI Abeygoonewardene[5], SLMD Rangajeewa[6], RMPS Bandara[7]

[1,2,3,4] Undergraduate, [5,6,7]Senior Lecturer
[1,2,3,4,5,6,7] General Sir John Kotelawala Defence University, Sri Lanka
[5]jabeygoonewardene@kdu.ac.lk

Abstract*: Comprehensive information of fluid and flight dynamics of an aircraft is vital for most aircraft handlers, especially when it comes to more complex aircraft which are capable of flying at wider flight envelopes. In the case of trainer aircraft, it delivers valuable information to both student and trainers. A majority of aircraft manufacturers do no disclose such information to relevant stake holders due to various reasons. As such an information gap exists between handlers and designers as far as the aircraft's aerodynamics is concerned. In this research, an aerodynamic comparison will be done between the most frequently flown configurations of the Chinese built Karakorum-08 aircraft. Selected armament configuration for this research is the 250 Litre Drop Tank attached to the underside of the aircraft with the help of two outboard Pylons. Present work involved in extending the previous work in the area to model a three dimensional surface model and computational mesh of the aircraft including a drop tank and Outboard Pylon using solid modelling software. A 1:48 scaled model was created for the complete aircraft with and without external stores. A CFD tool models the flow physics involved in flight in both configurations, thus rendering performance parameters which are available only through trial and error in the present context. The results provide new insights into the behaviour of the wing-body combination, thus enabling means of enhancing performance and handling qualities of the aircraft for both designers and pilots.*

Keywords: *Aerodynamics, Aircraft Performance, CFD, Flow Physics, Solid Modelling.*

1. INTRODUCTION

The aerodynamic forces acting on an aircraft vary from one armament or external store configuration to another, thereby resulting in changes in aircraft performance and handling qualities as well. These variations can be measured or estimated if the variation of flow properties around the aircraft is known for each configuration. Computational fluid dynamics (CFD) can be used to estimate the flow properties and the coefficients of Lift, Drag, and Moment [1]. An analysis of the CFD results for the different armament configurations of the K-08 wing-body combination can be done to compare the aircraft's performance for each configuration. Such analysis will have to be initiated at ground level since no prior information in this regard has been disclosed to the user.

Most aircraft designers do not publish detailed information on aircraft flow physics. In an effort to bridge the information gap between designers, manufacturers and aircraft handlers with regard to detailed information on flow physics a two dimensional analysis was conducted on a wing of a widely used trainer aircraft having a NACA 64A212 wing body combination. The research was aimed at providing useful information to the operators and engineers of the Karakorum-08 (K-08) such that better understanding of aircraft aerodynamics will yield higher performance. The main source of information about K-08 aircraft was the aircraft operator's manual [2]. Since the information obtained was insufficient for the modelling process, schematics of the first angle projection had to be developed using CorelDRAW software and the diagrams available in the manual.

Many methods of increasing the quality of the mesh and common CFD practices which yield accurate results were found [3]. One of the key steps followed to ensure highest accuracy of the mesh in the presence of limited computational power was maintaining a value of 1 for the aspect ratio of the cells of the grid.

2. EXPERIMENTAL PROCEDURE

Figure 1 shows the main steps which were followed to obtain and analyse CFD data for the three dimensional (3-D) wing body combination.

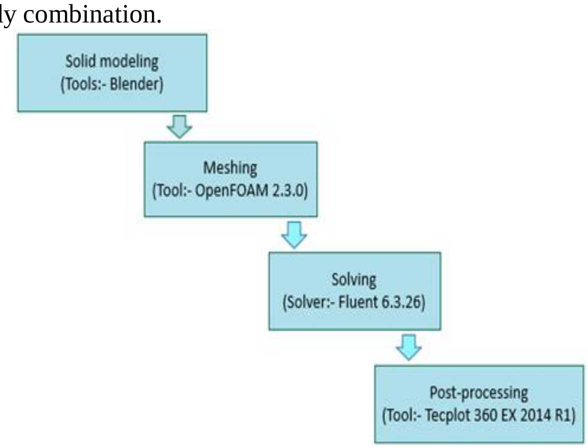

Figure 1: Steps of the experimental procedure followed

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3-D models of the wing-body combination, armaments and pylons were generated using Blender 2.6 and Blender 2.73.6. A scale of 1:48 was chosen for the modelling since scaled down models require less computational power and solving time. This particular scale was chosen as it gives the best compromise between size and detail [4].

Initially the cross sections of the aircraft were developed using drawings which were obtained from the operator's manual. 3-D models of the sole wing-body combination and wing body with the armaments (drop tanks) attached were generated as shown in Figure 2. The cross sections were used as reference to develop the models of the aircraft, armament and pylon.

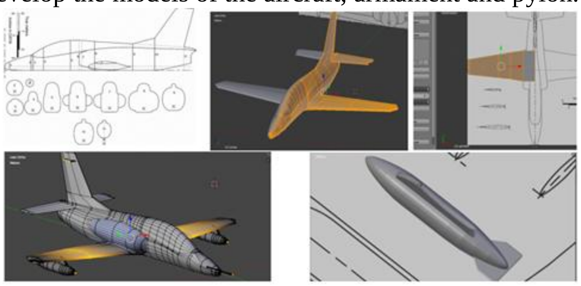

Figure 2: The cross sections and 3-D models

The generated 3-D models were then meshed using OpenFOAM 2.3.0. on a Linux platform as shown in Figures 3 and 4.

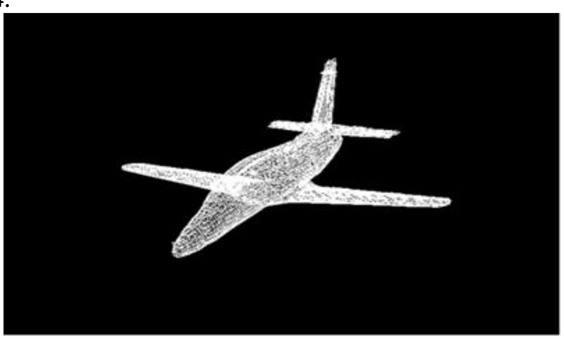

Figure 3: Mesh of aircraft without armaments

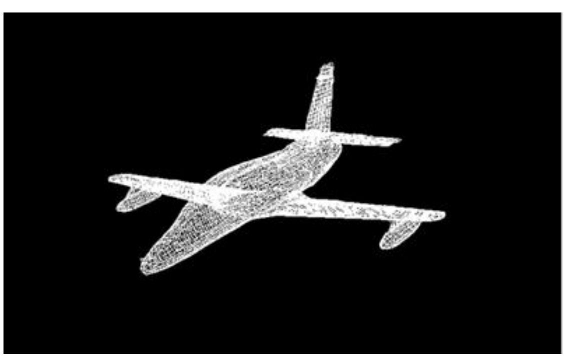

Figure 4: Mesh of aircraft with armaments

These meshes were then imported to ANSYS Fluent and the solving process was carried out. Solving process involves the numerical calculations done to the discretised partial differential equations which govern fluid flow (Navier-Stokes equations) [5].

Simulations were carried out for various angles of attack for the two configurations, namely 0°, 5°, 10°, and 15°. The speed at which the K-08 aircraft commonly operates [6] was used as the speed of the fluid in the simulations. The normal operating altitude of aircraft of 15000 ft was chosen [7]. Other flow properties such as density and viscosity of the fluid were specified as per the International Standard Atmosphere.

A density based solver was used for the numerical solution process as the selected conditions (velocity) produces compressible flow in a 3-D domain. The second order upwind discretisation method was selected and the absolute criterion for the residual monitoring was specified as 1×10-6. Discretization methods of higher orders were not considered as they often do not promote convergence due to the complexity of the numerical calculations. Since this research involved an aerodynamic application where the knowledge about force coefficients is important, force monitoring was activated and the direction vectors were specified according to the angle of attack that was considered.

The coordinates of the centre of gravity of the wing-body combination were determined using the operator's manual and Blender software. These coordinates were specified as the Moment centre about which the moment calculations were computed by the software. K-Omega SST turbulence model was selected as it is used for many aerodynamic applications [8]. K-omega SST is a two equation turbulence model which is suitable for modelling both flows within the viscous layer and flows far away from wall surfaces.

3. RESULTS AND POST-PROCESSING

Table 2 shows the force coefficients that were obtained from the simulations and C_L/C_D values that were calculated using the obtained results.

Table 1: Summary of results obtained from simulations

AOA	Aircraft without Armaments				Aircraft with Armaments			
	c_l	c_d	c_m	$\frac{c_l}{c_d}$	c_l	c_d	c_m	$\frac{c_l}{c_d}$
0°	0.17023	0.06893	0.4185	2.470	0.04234	0.07678	-0.0136	0.551
5°	0.417	0.129	1.329	3.233	0.297	0.132	0.147	2.250
10°	0.528	0.225	1.816	2.347	0.463	0.224	0.249	2.067
15°	0.673	0.333	2.410	2.023	0.630	0.333	0.356	1.892

CFD data should usually be validated before they are accepted [9]. Due to the unavailability of experimental data, theoretical values were used for the validation. A theoretical C_L value was calculated for the 0° AOA case without armaments and was compared with the Simulation value.

Theoretical Value = 0.130
Simulation Value = 0.170
Percentage Difference = 26.6667%

Simulation value for C_L is calculated by considering all surfaces of the model whereas the theoretical value only considers lift from the main wing therefore this difference is

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acceptable. Also the point of grid independency was not reached and a RANS approach was used for turbulence modelling. Thus it is seen that the difference is within computational/ numerical error and the CFD data is acceptable. The figures 5 to 9 depict the graphs plotted to analyse the data.

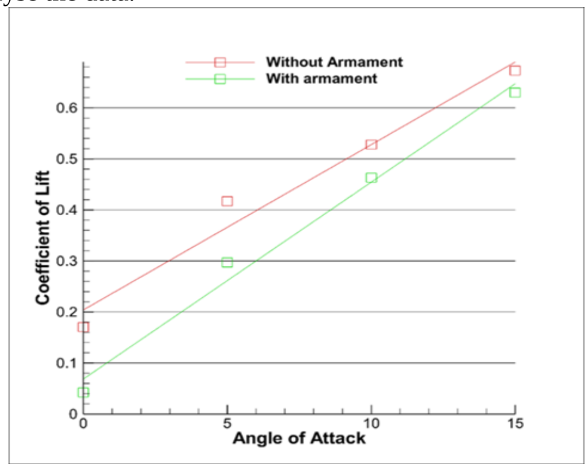

Figure 5: Lift curves of both configurations

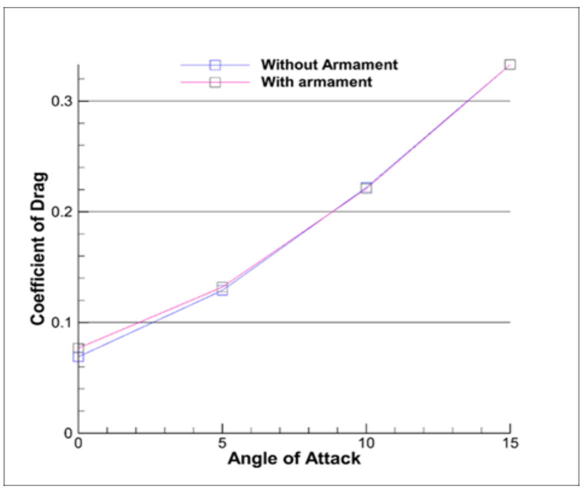

Figure 6: C_D vs. AOA curves of both configurations

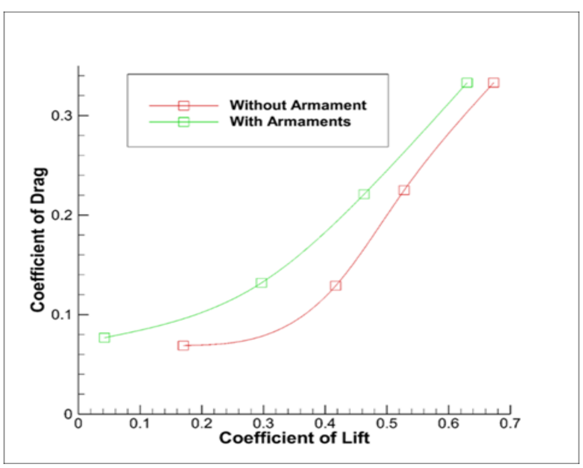

Figure 7: Drag polar curves of both configurations

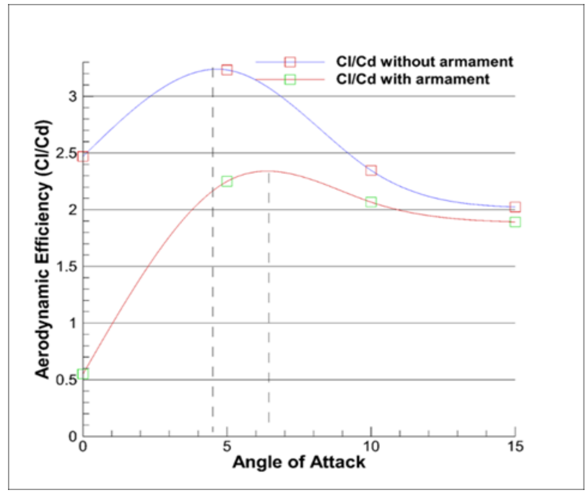

Figure 8: Aerodynamic efficiency vs. AOA

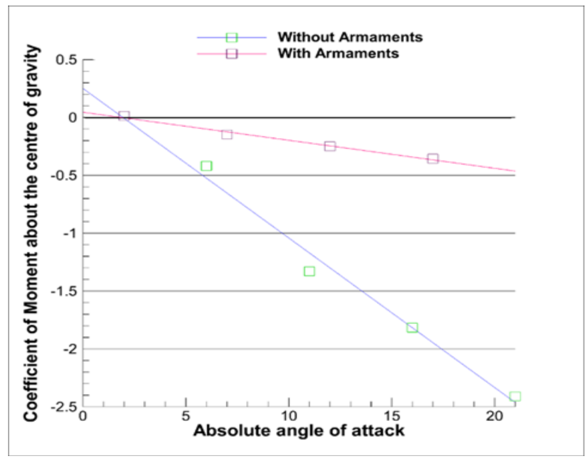

Figure 9: $C_{M,cg}$ vs. AOA for both configurations

The lift curves shown in Figure 5 depict that the lift increases with the angle of attack for both configurations. However the lift for the sole wing-body combination is always higher than that for the wing-body combination with the armaments attached. It is also seen that the difference between the two configurations reduces as the angle of attack is increased.

The C_D vs. AOA graphs shown in Figure 6 also show that the difference between the two configurations reduces as the AOA is increased. It is evident that there are no major differences in the drag values of the two configurations. This is because the increase in skin friction drag and pressure drag caused by the presence of the armament is compensated by the reduction in induced drag due to the reduction in C_L.

The drag polar curves of the configurations shown on Figure 7 can be used to analyse the aerodynamics of the two configurations. These curves can be used for the analysis of performance of the two configurations depending on the analyst's requirements.

C_L/C_D directly provides knowledge about the aerodynamic efficiency of the object being studied. C_L/C_D vs. AOA graphs were plotted for the two configurations and the angles of attack corresponding to the maximum aerodynamic efficiency were found for each configuration as shown in Figure 8. The AOA corresponding to maximum aerodynamic efficiency of the sole wing-body combination was found to be between 4° and 5° while the AOA corresponding to the maximum aerodynamic efficiency for the wing-body combination with armaments attached to it was found to be between 6° and 7°. These graphs also show that there is a large reduction in aerodynamic efficiency at level flight with the armament attached. The percentage reduction is a considerable 77.69%. This highlights the significance of jettisoning the drop tanks once the contained fuel is utilized during critical missions.

The $C_{M,cg}$ (Coefficient of moment about the center of gravity) vs. AOA graphs can be used to evaluate the longitudinal balance and static stability of an aircraft. Criteria for longitudinal balance and static stability states that the $C_{M,cg}$ vs. AOA graph should have a negative gradient and intercept the $C_{M,cg}$ axis (vertical axis) at a positive value (above the origin) [10]. Both criteria have been satisfied by both configurations, therefore both configurations have longitudinal balance and static stability. The graphs shown in Figure 9 also depict that the line corresponding to the sole wing-body combination has a more negative (steeper) gradient and also crosses the $C_{M,cg}$ axis at a higher point than the line corresponding to the wing-body combination with armaments. This clearly shows that the wing-body combination without the armaments has more longitudinal balance and static stability than the wing-body combination with the armaments.

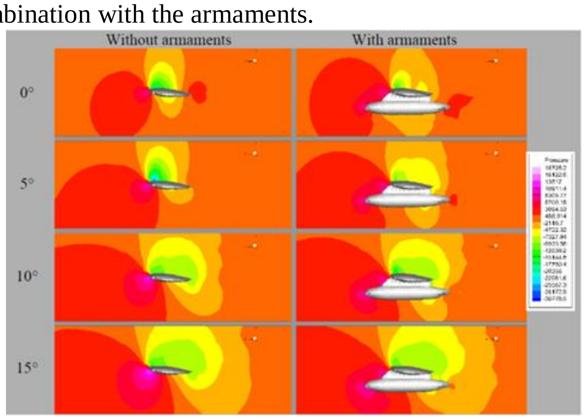

Figure 10: Pressure contours around the armament position

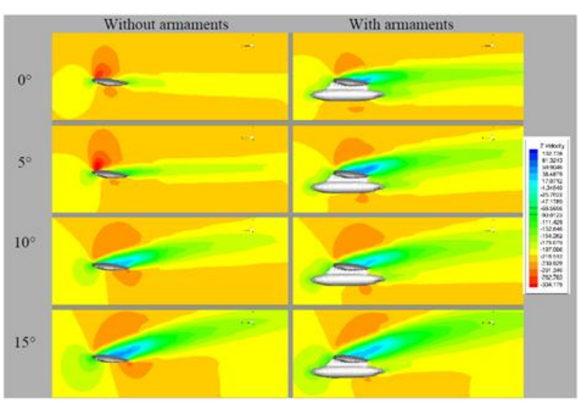

Figure 11: Velocity contours around the armament position

The pressure contours and velocity contours around the armament position were analysed to study the differences in flow caused by the presence of the armament. Figure 10 shows the pressure contours and Figure 11 shows the velocity contours for all the simulations that were carried out. These contours were obtained by slicing at the same position (Outboard pylon position) in all simulations using a post processing tool.

The pressure contours show that the armament causes the area of stagnant pressures upstream of the wing to increase. This causes the pressure drag to increase when the armament is attached. The low pressure areas created above the wing are being disturbed by the presence of the armament. This is the main reason for the reduction in lift caused by the presence of the armaments.

The velocity vectors depict that the velocity of the air over the wing reduces when the armament is attached. Flow reversal due to flow separation takes place regardless of the AOA, when the armament is present. However, for the sole wing-body combination, flow reversal occurs only when the AOA is greater than 10°.

Both velocity contours and pressure contours depict that the differences in the flow properties between the two configurations reduced as the AOA is increased.

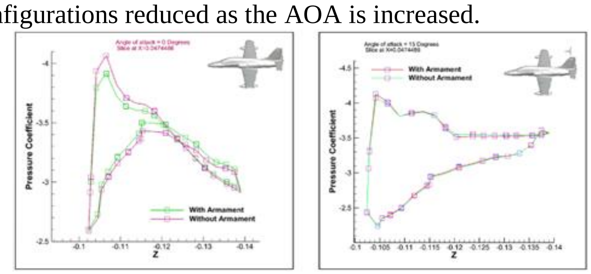

Figure 12: C_P curves at the centre of the wing for 0° and 15° AOA

Figure 12 shows the Coefficient of Pressure (C_P) curves which were drawn by considering a slice at the centre of the wing. The curve on the left side and right side curves correspond to the 0° and 15° AOA simulations respectively. The observations which were made through the contour plots were confirmed once again by the C_P curves. When the AOA is 0°, the curves of the two configurations do not coincide, however when the AOA is increased to 15° the C_P curves drawn for the two configurations coincide. This clearly shows that the effect on pressure coefficient due to the presence of the armament reduces as the AOA is increased.

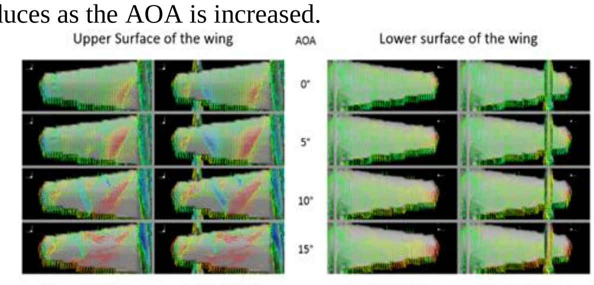

Figure 13: Velocity vectors coloured by the magnitude of spanwise flow

Figure 13 shows the velocity vectors on the upper surface and the lower surface of the main wing. The left half of the image shows the upper surface while the right half shows the lower surface. The velocity vectors have been coloured by the magnitude of the spanwise flow in such a way so that red colour represents flow towards the tip of the wing and blue colour represents flow towards the root of the wing.
Close examination of the upper surface shows that the flows of the two configurations become more and more identical as the AOA is increased. Flow starts to diverge near the armament at low AOA simulations.
Velocity vectors of the lower surface show that the intensity of the red colour near the tip of the wing increases as the AOA is increased. This is due to more pressure leaking from lower surface to upper surface at higher AOA. When the armament is attached the spanwise flow towards the root of the wing reduces. Thus the pylon used to attach the armament to the wing acts as a wing fence on the lower surface. It also reduce the strength of the wing tip vortices.

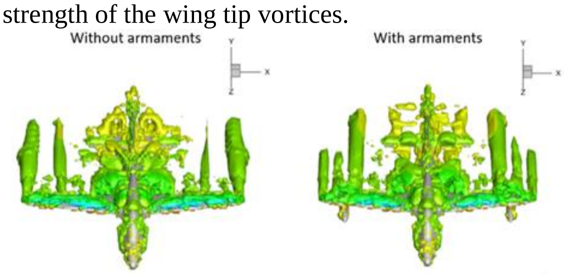

Figure 14: Vortices generated for both configurations

Figure 14 shows the vortices which were generated on both configurations. The vortices were visualised by creating iso-surfaces for rotational velocity about the z-axis (longitudinal axis). The reduction in strength of vortices when the armament is attached is clearly visible. It is visible that an additional vortex originates from the armament position, imposing difficulty in analysing the changes in induced drag. However from the C_D vs. AOA curve it was observed that the drag values of the two configurations do not differ at higher AOA. The skin friction drag and pressure drag will definitely be increased due to the presence of the armament. Therefore if the total drag is to remain the same, the induced drag of the wing-body combination with armaments should definitely be lower than that of the sole wing-body. This can only happen if the strength of the vortices originating from the armament is lower than the strength of the vortices which occur at the tips of the wings when the armament is not present. This is mainly due to a portion of the aircraft's energy being lost as rotational (kinetic) energy in the vortices.

4. CONCLUSION AND RECOMMENDATIONS

In this research performance of the K-08 aircraft was analysed using CFD data. CFD data for the sole wing-body combination, and the wing-body combination with armaments attached to it, was generated. The aerodynamic effect caused by the presence of the armament degraded as the angle of attack was increased. The main effect that the armament had on the wing-body combination was the reduction of lift and increment of drag. The sole wing-body combination was found to have more longitudinal balance and static stability than when external stores were attached.
It was also found that flow reversal due to flow separation occurs regardless of the angle of attack, when the armament is present. The armaments and pylons tend to act as wing fences on the lower surface of the main wings and thus reduce the strength of the tip vortices.
The angles of attack corresponding to the maximum aerodynamic efficiency were found for the two configurations. Use of this knowledge in actual handling of the aircraft would enhance the performance and fuel efficiency.
This research could be extended through numerical and experimental approach. The 3D models which were developed can be 3D printed to produce 3D models that can be tested in a wind tunnel. The wind tunnel data can then be used to validate the computational data.

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