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Aircraft Performance Improvements-A Practical Approach

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ABSTRACT

An aircraft is designed based on various wind tunnel testing, computational analysis, previous design experience etc. In most of the aircraft programs the design objective could not be met with the first prototype design itself. Before the induction into the service the aircraft could have undergone many design improvements in order to meet the desired performance. These performance improvements can be achieved by improving the original design in the area of aerodynamics, structure (weight reduction), propulsion and systems (like flight control system, avionics, fuel system etc.). This could be by modifying the original design or introducing new concepts in the design. Due to the obsolence of many technology and growing demand many aircraft program undergone an upgradation program and meets the higher performance demands. Many successful modifications were retrofitted in all their earlier aircrafts and followed in other aircraft programs also.

Keywords: Aircraft, aerodynamics, performance improvement program, PIP, propulsion systems

1. INTRODUCTION

Performance Improvement Program (PIP) is inevitable in almost all the aircraft programs worldwide. Always there is a scope for improvements. An attempt has been made to bring out and consolidate the successful aircraft modifications in other countries. And this paper brings out the many modifications envisaged in our country's prestigious indigenous aircraft programs Tejas and HJT-36 also. Even though the modifications are in the field of aerodynamics, structure, propulsion and other systems the general modifications are pertained to aerodynamic configuration change and propulsion, i.e. engine upgradation. The weight reduction methods followed in many aircraft programs also brought out in this paper.

2. SUCCESSFUL AIRCRAFT PERFORMANCE IMPROVEMENT METHODS WORLDWIDE

Due to the increasing pollution, cost and demand there is a need to improve the aircraft airframe and its power plant. From the first flight of Wright brothers in 1903 to Airbus 380, the aircraft industry underwent various technology challenges. During this phase there was lot of improvements in the airframe, propulsion and other systems. The following are some of the design changes or inventions which makes great impact in the aircraft performance improvements.

2.1 Winglets in Boeing-737

The unmodified 737 model wing, originally designed in the early 1970's, is derived from wings developed at a time when aircraft flew at low Mach numbers, and a primary goal was to produce low skin friction drag. At high Mach number, such as those achieved by the 737 model aircraft, strong shock waves form on the upper wing surface of the unmodified wing. This causes the following deficiencies: a) relatively high lift-induced drag; b) rapid increase in drag with increased Mach number (early drag rise); c) early onset of wing buffet at typical cruise Mach numbers; and d) appearance of pronounced nose-down pitch at relatively low Mach numbers.

The winglet at the wing tip along with the flaps and aileron droop reduces these deficiencies. Winglets are small lifting surfaces attached to the outboard end of an airplane wing, commonly at or near to a vertical angle from the wing structure. Winglets function to relocate the tip vortex of an airplane wing further outboard and above the unmodified location. In flight, the substantially inward pointing load carried by the winglets relocates the wing tip vortex.

Due to pressure differentials between wing surfaces at a wing tip, air tends to flow outboard along the lower surface of a wing around the tip and inboard along the wing upper surface. When winglets are added, the relocated wing tip vortex caused by the winglets produces cross-flow at the winglets, which often are perpendicular to the flow across the wing surfaces. The side forces created by such cross-flow contain forward components which reduce drag.

Performance improvements obtained as a result of winglet additions are reduced drag and increased wing buffet margin. Wing buffet occurs when lift on a wing is so great that it causes flow separation and wing stall, and subsequently limits the boundary for the aircraft. The reduction in drag (~3%) brings increased aircraft fuel mileage at all altitudes, while the increased buffet margin allows the aircraft to fly at higher altitudes where fuel mileage is increased.

A conservative target of only a 3 per cent reduction would equal 100 liter of fuel saved per hour. The amount of fuel saved is equivalent to 215 kg. of CO_2 emissions, which are also eliminated. Accordingly, a commercial aircraft averaging 3000 h per year (the industry average) would save around 92 crore and reduce CO_2 emissions by 645,000 kg. per aircraft, per year. The aerodynamic efficiency of unmodified and modified (with winglets) Boeing 737 is shown in Fig. 1.

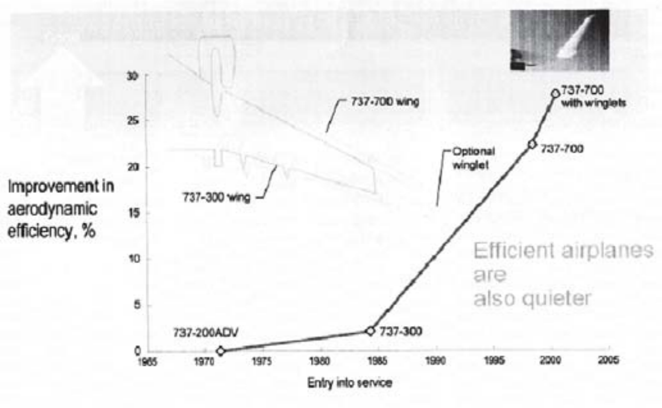

Figure 1. Winglet benefits in boeing 737.

2.2 Generalized Geometric Solution

2.2.1 Vortex Generators (VGs)

One of the most widely applied concepts for flow control is vane-type, passive vortex generators that transfer high-energy fluid outside the boundary layer to the surface region inside the boundary layer. First introduced in 1947, vortex generators consist of a row of small plates or airfoils that project normal to the surface and are set at an angle of incidence to the local flow to produce an array of streamwise trailing vortices. These devices are used to energize the boundary layer such that boundary-layer separation is eliminated or delayed, and this can be used to enhance wing lift, improve control effectiveness, and/or tailor wing buffet characteristics at transonic speeds. The flow separation over a flat plate is shown Fig. 2.

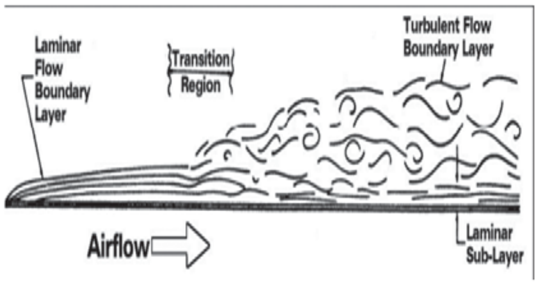

Figure 2. Boundary layer in a flat plate.

Vortex generator energize this sublayer and suppress flow separation. Hence delayed the onset of stall.

Many commercial transports utilize vortex generators to enhance wing aerodynamic performance over an enlarged flight envelope. Air travelers can readily view vortex generators that are normally arranged in a spanwise direction on the upper surface of the wing or the empennage of modern transports; single vortex generators can also be found on the sides of the fore and aft sections of the fuselage and on engine nacelles.

The vortex generators installed in wing is shown in Fig. 3.

Figure 3. Vortex generators in wing.

2.2.2 Micro vortex Generators (MVG)

Although aircraft designers have made wide use of relatively large vortex generators (VGs) to solve numerous flow control problems, the relative size of the auxiliary vanes can unfavorably impact the performance of aircraft. Conventional VGs usually produce residual drag through conversion of aircraft forward momentum into unrecoverable turbulence in the aircraft wake. Therefore, the design and implementation of a passive, effective VG configuration that prevents flow separation for critical flight conditions yet imposes little or no drag penalty on the aircraft is a formidable challenge to the aerodynamicist.

Micro Vortex generators (MVGs) are used to produce streamwise vortices that more efficiently transfer momentum within the boundary layer. The resulting optimization to a sub-boundary-layer scale provided a major breakthrough in the fundamental understanding of the nature of vortex generator flow control and potential applications. The optimised MVGs dramatically enhanced aerodynamic performance including a 10 per cent increase in lift, a 50 per cent decrease in drag, and a 100 per cent increase in lift-to-drag ratio.

For commercial transport aircraft, these positive aerodynamic effects could lead to improved landing performance with the simpler (more economical) single-flap design and, more importantly in many instances, to reduced approach noise (i.e., less engine power to achieve the same lift). Another practical benefit of using the MVGs for high-lift applications is that they are small enough to be stowed with the flap at cruise and hence do not increase the cruise drag.

2.3 Engine-pylon Redesign in MD-11

The powerful computational capabilities of rapidly evolving modern computers and computational fluid dynamics (CFD) methodologies have provided civil aircraft designers with unprecedented flexibility to assess the impact of configuration variables and conduct fundamental studies of fluid phenomena.

MD-11 incorporated a number of advanced technologies, including redesigned airfoil sections with more trailing-edge camber, winglets, and an advanced horizontal tail that included an integral trim tank. Initial flight tests of the MD-11 indicated an unacceptable range shortfall of over 400 nmi. The flow separation region occurred on the outboard side of the juncture between the engine pylon and the lower surface of the wing. Several computational tools used to identify the problem, assess the effects of geometric changes to the pylon, and arrive at the new pylon design.

After analyzing pressure distributions, suction peaks, and the effects of geometric modifications, redesigned the pylon fairing that significantly reduced adverse pressure peaks and eliminated flow separation at cruise conditions. A very significant drag reduction of about 0.75 percent was achieved. The fairing was installed in an all-new MD-11 aircraft and was retrofitted to existing aircraft.

2.4 Deep-Stall Avoidance in DC-9

In the "T-tail" configurations, the horizontal tail was moved to the top of the vertical tail for enhanced efficiency and reduced weight. By arranging the vertical and horizontal tails in a T, designers could locate the horizontal tail in a relatively benign flow field. In this location, the flow downwash from the wing would not reduce the stabilizing effects of the horizontal tail at the relatively low angles of attack associated with cruise conditions. This advantage was also obtained during the landing approach, when the downwash effects became even stronger because of the deflected wing trailing-edge flaps. In addition to placing the horizontal tail in a region of less downwash, the T-tail position provides more tail length (with a swept vertical tail); thereby less tail area is used for the required tail contribution to stability. Also, the end plating effect on the vertical tail makes the vertical tail more effective and permits a reduction in vertical fin size. As a result of the increased efficiency of the horizontal and vertical tails, the surface areas could be reduced relative to a tail size for the conventional low-tail configuration and thereby result in a significant weight savings.

But the problem in T-tail configuration is that at high angles of attack near and above those associated with wing stall, the low-energy wakes of the stalled wing and fuselage-mounted engine nacelles impinged on the horizontal tail and significantly reduced its stabilizing effect. Also, the low-energy wakes severely reduced the effectiveness of the horizontal tail as a longitudinal control. These characteristics manifest themselves as an critical poststall condition in which the angle of attack of the aircraft would increase to very large values in response to the loss of stability, and the pilot would be unable to recover from the condition because of the loss of horizontal tail control effectiveness.

In T-tailed DC-11 aircraft an under-wing leading-edge fence ("vortillon") which is short for vortex generating pylon that provided additional flow energy at the tail for nose-down recovery at and slightly above the stall angle of attack. The final modifications developed to prevent the DC-9 from entering a dangerous deep stall included the vortillons (which assisted in immediate poststall recovery, but had little effect at the deep-stall condition), an increase in the span of the original horizontal tail, a stick shaker, visual and aural stall warnings, and a standby power system that provided full nose down elevator capability for deep-stall recovery. (The original aerodynamic tab system was not capable of providing sufficient elevator angle at very high angles of attack.) These modifications, which were incorporated prior to the first flight of the DC-9 on February 25, 1965, proved effective in preventing deep stall for the DC-9 throughout its service life.

2.5 Discontinuous Leading Edge for Spin Resistance

Several approaches might be used to increase the spin resistance of aircraft. For example, commercial civil transports have successfully used pilot stall-warning systems, such as stick shakers, for many years to provide an awareness of stall proximity. Some T-tail transports have used automatic stick pushers to actively prevent inadvertent stalls to avoid entry into potentially dangerous deep-stall conditions. High-performance military fighters successfully use complex control system feedbacks and schedules which permit strenuous maneuvers at high angles of attack. Another approach involved restricted control surface deflections and limited center-of-gravity travel. Finally, research prior to the 1970s had indicated that the selection of wing airfoils and wing stalling characteristics had significant potential for improved spin resistance; and several aircraft programs within the civil sector indicated that canard-type configurations could be designed to be inherently stall proof. For a typical canard configuration, the canard tail surfaces are mounted forward on the fuselage and are designed to stall before the aft-mounted main wing. The mechanism of canard stall (and the associated loss of canard lift and the effectiveness of canard-mounted elevators) results in an inherent limiting of angle of attack to values lower than that required to stall the main wing (passive stall and spin resistance). Each approach to improve the spin resistance of an aircraft involves consideration and trade-offs of various levels of complexity, cost, and compromise in the performance and utility of the aircraft.

Certain stalling characteristics (especially abrupt leading-edge flow separation) produce sudden, asymmetric wing drop and highly autorotative rolling moments, which can result in rapid rolling and yawing motions that precipitate spin entry. Wing leading-edge devices such as slots, slats, and flaps can significantly improve the autorotative resistance of unswept wings at stall. Separate leading-edge slat segments to control the shape of the lift curve, eliminate the sudden drop in lift curve at stall, and produce a "flat-top" lift-curve shape to angles of attack far beyond the stall.

Finally a “discontinuous” leading-edge configuration in which the airfoil of the outer wing panel was extended and drooped was tested. The results shows that wing stall progression started at the trailing edge of the midspan position and progressed forward as angle of attack was increased to stall. However, the increase in lift-curve slope beyond stall was caused by the fact that the outer wing panel continued to produce lift to extreme angles of attack. The leading-edge discontinuity produced vortical flow that prevented the low-energy stalled flow of the inner wing from progressing spanwise and stalling the outer wing. Thus, the discontinuity worked as an aerodynamic fence to prevent outer panel stall.

The basic airplanes entered spins in 59 to 98 per cent of the intentional spin-entry attempts, whereas the modified aircraft entered spins in only 5 percent of the attempts and required prolonged, aggravated control inputs or out-of-limit loadings to promote spin entry. A Cessna 172 research aircraft with outer wing leading-edge-droop is shown in Fig. 4.

Figure 4. Cessna 172 research aircraft .

2.6 Composite Structure for Performance Improvements

Since its inception at the beginning of the 20th century, aircraft have undergone dramatic structural and performance improvements, impacting the dynamics of the aerospace sector along the way. Throughout the early years of development, materials such as wood and canvas constituted the basic building blocks of aircraft. The emergence of aluminum in the 1920s provided the first notable breakthrough in advanced material technology. Aluminum has remained the principal material for aircraft to date, however, it is gradually giving way to advanced composites as the material of choice for next generation aircraft. This has been evidenced by the extensive use of composite material in the Airbus A380 and the Boeing 787.

Composites are superior to aluminum in terms of strength and stiffness and are extremely light-weight. The resulting fuel efficiency gained by an aircraft is becoming increasingly important. Other positive attributes include excellent fatigue and corrosion resistance and good impact resistance. With respect to design, composites render a consid¬erable amount of structural flexibility, leading to significant reduction in part counts. Overall, the emergence of composites has reduced aircraft weight by almost 10 to 40 per cent, and design costs by 15 to 30 per cent. While strength and weight are critical and desirable characteristics, composite material will also compete with other advanced metals in both performance and cost for aerospace applications.

The surfaces of stealth aircraft are made of composite material that absorb or deflect radar signals, providing a significant warfare advantage. In addition to weight reduction for aircraft components (projected to be from 10 to 30 per cent), it was anticipated that a significant reduction in component parts (40 to 60 per cent) such as fasteners could be obtained. The increasing usage of composite in civil and military fighter aircrafts is shown in Fig. 5.

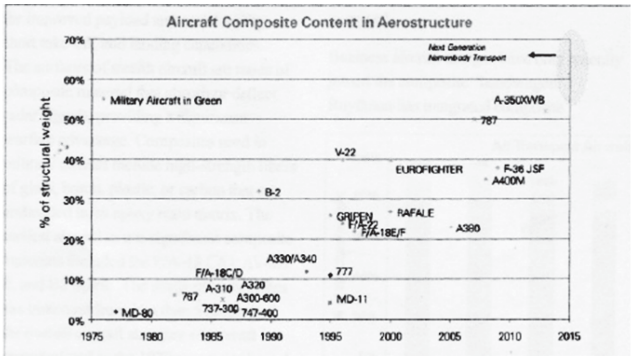

Figure 5. Increase in composite usage.

2.7 Performance Improvements by Relax Static Stability

In a conventional wing-tail stable aircraft the C.G is always ahead of the aerodynamic centre. Hence the net aerodynamiclLift is the difference of wing and tail generated lift. The net lift available is less. This is shown in Fig. 6. In the unstable aircraft, the C.G is behind the aerodynamic centre. The net aerodynamic Lift is the addition of wing and tail generated lift. This is aerodynamically more efficient for the highly agile fighter aircraft. Here the instability is controlled by a Digital Flight Control Computer with higher band width actuators. This concept is known as Relax Static Stability (RSS) and shown in Fig. 7. Due to the higher lift generation capability at lower Mach numbers and lower trim drag at higher Mach numbers the aircraft performance can be improved considerably.

3. PERFORMANCE IMPROVEMENT METHODS IN TEJAS

LCA is a tailless delta wing multirole combat aircraft designed and developed jointly by Aeronautical Development Agency (ADA) and Hindustan Aeronautics Limited (HAL). The design of LCA configuration has been chosen in order to meet the Air Staff Requirements (ASR). Approximately 1000 sorties on various LCA prototypes have been completed to asses the LCA performance in air/ground. It is seen that most of the performance parameters are deviating from the requirements. Hence an active performance improvement program has been taken up by ADA with the intiation from CEMILAC to explore the various design improvements in order to meet the ASR requirements. The following are some of the important improvements undertaken in Tejas.

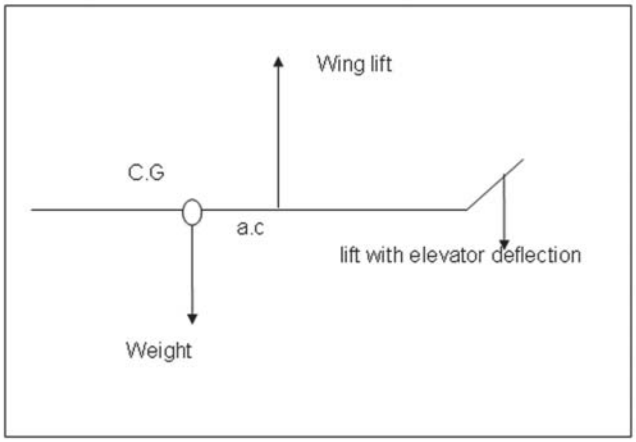

Figure 6. Stable aircraft force balance.

3.1 Main Landing Gear (MLG) door as an Air Brake

The Air brakes in Tejas provided at the rear spinal part of the fuselage to decelerate aircraft at higher speeds. Due to this rear location in addition to the deceleration it gives an uncommanded pitch up and directional stability reduction. Various improvement methods like perforated airbrake, updation of aero data set and fine tuning of control law gains were tried. Still the problem is not rectified completely. The Fig. 7 shows the airbrake in Tejas.

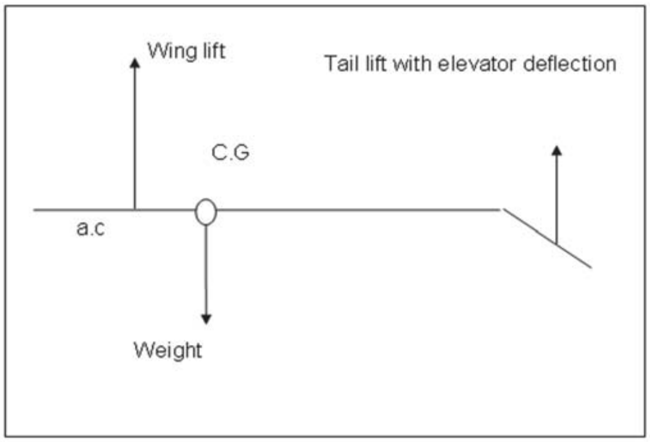

Figure 7. Unstable aircraft force balance.

The reduction of directional stability with various Air Brake position is shown in Fig. 8.

A study taken up to utilize the main landing gear follow up door as an airbrake. Due to its location close to the centre of gravity it will not give any pitch up moment about extensive wind tunnel testing has been carried out. The results were encouraging. The location of main landing gear door in Tejas is shown in Fig. 9.

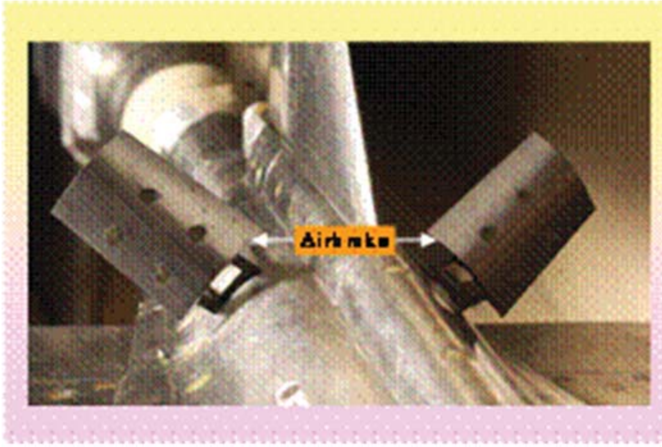

Figure 8. Air brake in Tejas.

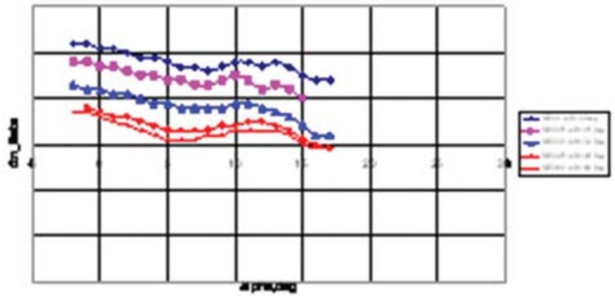

Figure 9. Cn-beta variation with airbrake.

The increase in drag coefficient and directional stability with MLG door is shown in Figs. 10 and 11 respectively. From the figures it is seen that the MLG door meets the drag requirement for the deceleration similar to Air Brake at 60? deflection. And the directional stability is close to that of the Air Brake at retracted condition.

3.2 Reduction of wave drag

One of the major out come of sea level trial of Tejas is that the drag of the aircraft is high such that the aircraft could not reach the supersonic Mach number at sea level. The components contributing for the maximum drag rise has been identified and improvement methods were worked out.

Nose cone extension using a Plug: The major component of drag at higher speed is the wave drag. This can be minimized by following the Whitcomb's Area rule for the aerodynamic configuration design. The cross sectional area variation of LCA along the length of fuselage is shown in Fig 12. Between station X = 5000mm & 6000mm there is a sudden increase in area. By smoothing this sudden rise, the wave drag can be minimized. A possible solution proposed is the extension of nose cone by introducing a Plug. The detailed analysis of this design and its implementation plan is being worked out.

Pylon reshaping: Another area for improvement is identified as the pylon reshaping. The leading edge of all the pylons are blunt and it can be reshaped aerodynamically for the drag reduction. The in-board pylon before modification is

Figure 10. MLG door in Tejas.

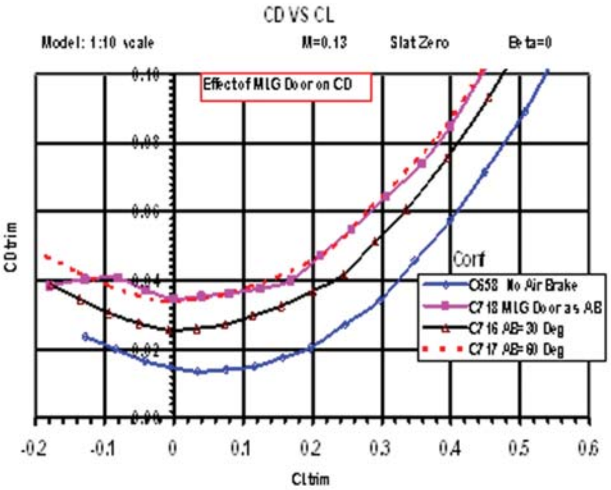

Figure 11. Drag coefficient with MLG door..

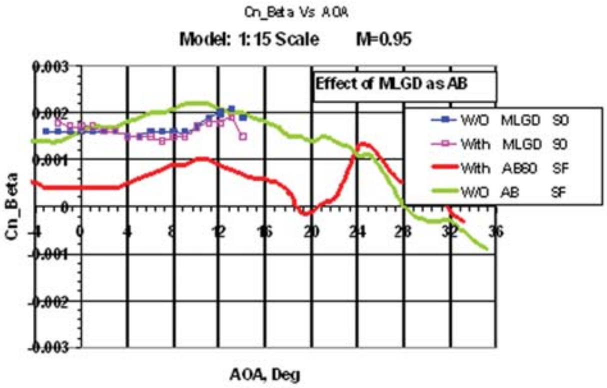

Figure 12. $C_{n\beta}$ with MLG door.

shown in Fig. 13. and Fig. 14 shows the in-board pylon after the modification.

The analysis shows that a drag reduction of 3.7 dm^2 at M=1.2 is possible with this modification. Similar exercise for the mid-board and out-board pylons carried out and the drag reduction predicted as 0.6 dm^2 and 1.54 dm^2 respectively.

Trailing Edge Extension (TEC)

From the Fig. 12 it is seen that there is a sudden variation in cross sectional area at the rear end of the fuselage also. This can be minimized by the modification in the trailing edge using TEC. Fig. 15 and Fig. 16 shows the rear fuselage before and after modification. The drag reduction predicted is around 1 dm^2.

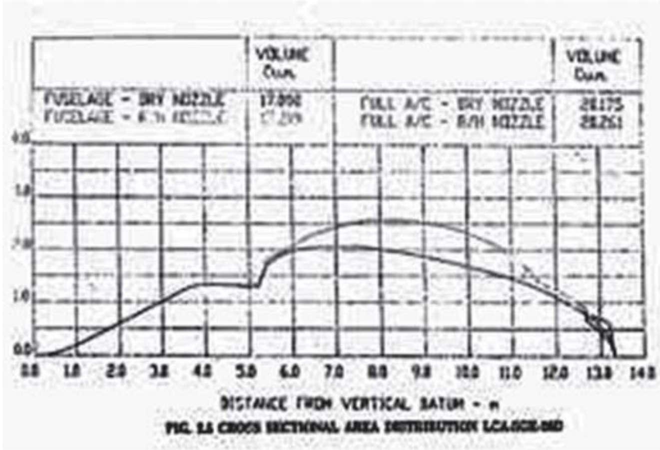

Figure 13. Cross sectional area of Tejas.

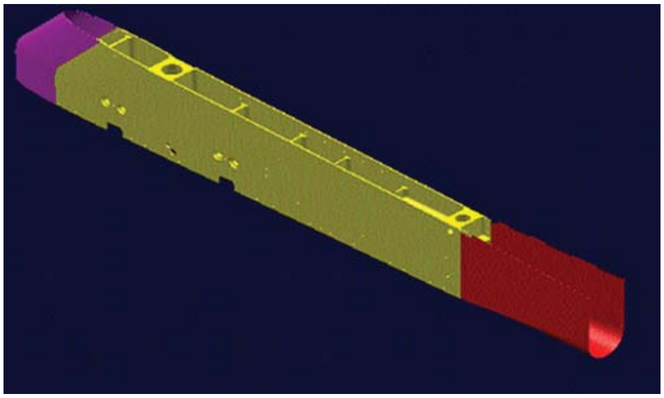

Figure 14. In-board pylon before modification.

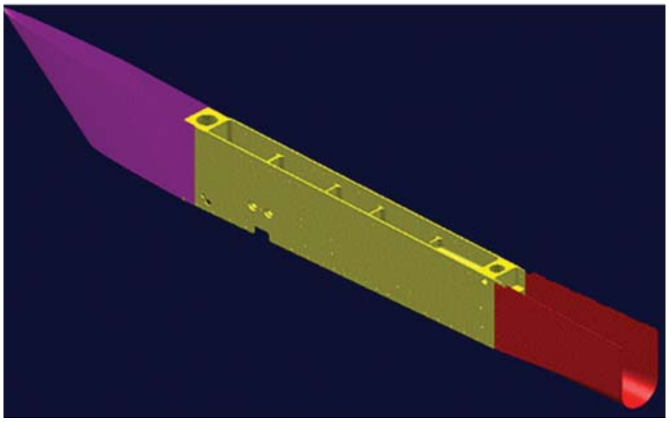

Figure 15. In-board pylon before modification.

3.3 Sustained Turn Rate Improvement using Levcon

Leading Edge Controller (Levcon) is an secondary control surface located at the leading edge of the wing and the fuselage. The Levcon is initially planned in LCA Navy for the low landing speed capability and other cruise performance. An important requirement of a fighter aircraft is the Sustained Turn Rate (STR). The fighter variant of Tejas is not meeting the STR requirement of ASR. The STR is a strong function of the aerodynamic efficiency. From the wind tunnel results it was found that the Levcon produce higher L/D (Fig. 17). A detailed study to implement Levcon in fighter and identification of other design constraints is under progress.

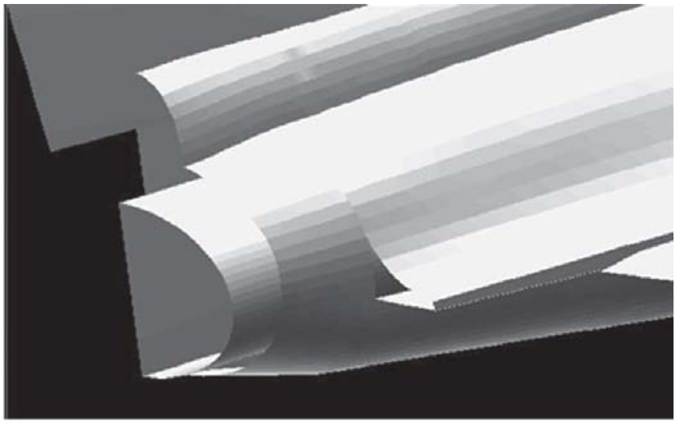

Figure 16. Tejas rear fuselage before modification.

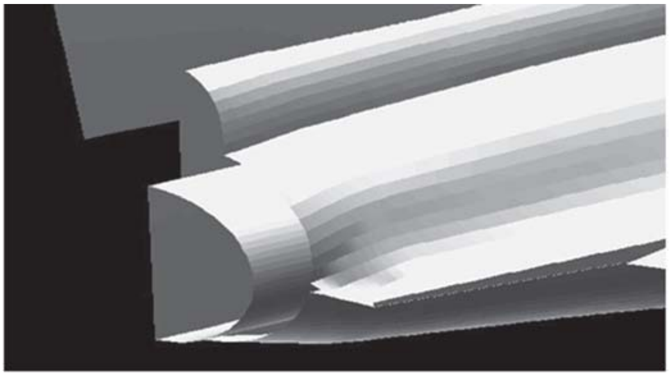

Figure 17. Tejas rear fuselage after modification.

3.4 Performance Improvements by Weight Reduction

Converting metal components into composite: Weight reduction is an important activity in an aircraft program to improve the performance. Use of high performance composite material can considerably reduce the weight of the components and preserving the structural integrity. The airframe of Tejas has already undergone one cycle of weight reduction prior to Prototype Vehicle series, which resulted in a weight saving around 350 Kg. It is felt that some of the components like slat doors, casing & mounting of LRUs and rear fuselage bulkheads and pylons can be converted into composite. This will give further weight reduction.

Co-cured co-bonded wing: LCA wing components have been manufactured separately and joined together using rivets, fastener and sealant. In the proposed co-cured co-bonded wing, the bottom skin, ribs and spars are cured together. This has advantage from reduced part count as well as weight saving. The weight saving is mainly due to the elimination of sealants, fasteners and associated components. Further, the wing is expected to have improved stiffness, leak proof and better lightning protection.

3.5 Active/Passive fuel proportioner

The typical C.G travel (˜3%) due to the fuel consumption in Tejas is given in Fig. 18.

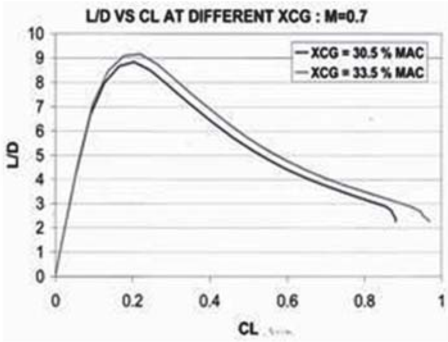

Figure 18. L/D improvements by levcon.

When the aircraft in its mid weight (wing tank empty) condition, the aircraft C.G is most forward. The aircraft is more stable. The maneuvering capability is limited. Hence a passive fuel proportioner introduced in Tejas by varying the diameter of the fuel pipe. With this modification the maximum fuel travel is within ±0.5%. In future the better C.G management is planned by the Active Fuel Proportioner using the motorized valves.

A study has been carried out to find the advantage of the passive fuel control by moving the C.G aft from the earlier forward position. The C.G at 30.5% MAC and 33.5% MAC are considered for the analysis. Fig. 19 shows the amount of elevon required for trimming the aircraft. This shows the lesser down elevon required for the aft C.G configuration.

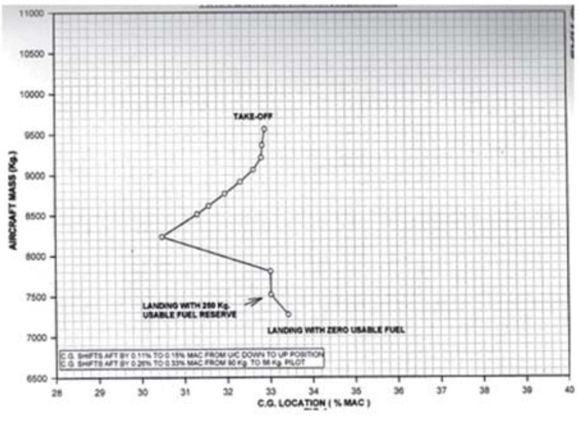

Figure 19. Typical C.G variation.

The (Lift/Drag) ratio for these two C.G configurations is shown in Fig. 20. It is very clear that moving C.G aft gives increase in L/D. This will improve the performance parameters considerably.

4. PERFORMANCE IMPROVEMENTS IN HJT 36

Hindustan Jet trainer (HJT-36) is our indigenous intermediate

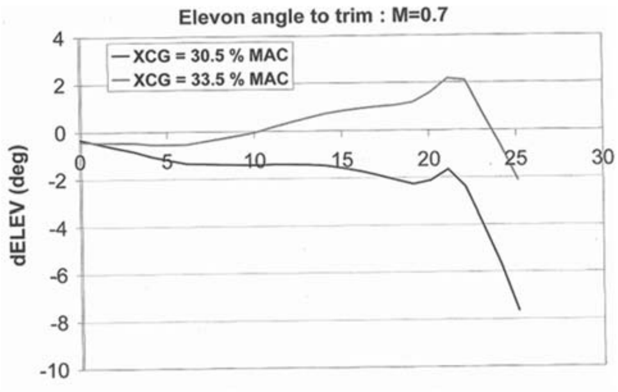

Figure 20. Trim elevon for forward and aft C.G condition.

trainer aircraft designed and developed by HAL to replace the ageing Kiran aircraft. It is a single engined, tandem cockpit aircraft with advance feature like glass cockpit and zero-zero ejection seat. It took around 20 months from the metal cutting to its first flight. The following are some of the performance improvement activity carried out in this aircraft. The HJT-36 is shown in Fig. 21.

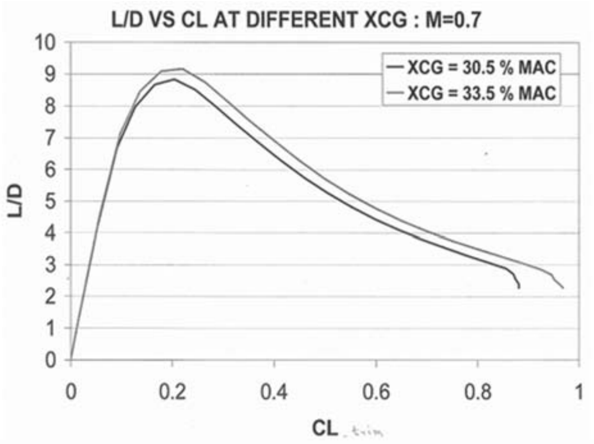

Figure 21. L/D for forward and aft C.G condition.

4.1 Strakes for Spin Resistance

The spin tunnel testing of IJT-36 shows that it can enter in to flat spin. Flat spin is more stable and hence difficult to recover. Being a trainer aircraft it should have the capability to recover from spin. This is possible by building inherent spin resistance capability in the aircraft. The modification done in HJT-36 to achieve this is the introduction of 'Nose strakes'. Nose strakes helps in breaking the asymmetric vortex shredding at the nose cone region.

Figure 22. HJT-36.

This reduces the large side force experienced by the aircraft which was the cause for the flat spin. Now with reduced side force and spin rate the aircraft can be recovered from flat spin with the less pilot work load.

4.2 Engine Upgradation

The maximum speed and other performance of an aircraft mainly depend on the thrust/power generated by the engine. HJT-36 currently uses LARZAC4H20 engine, weighing 365kg and thrust rating of 1440 kgf. This is insufficient to reach the maximum speed of 750 kmph (max. designed speed) which is currently achieved only in dive. In order to meet this performance requirement, an engine AL55I is fitted in HJT-36. This engine weighing 355kg and thrust rating of 1760 kgf. The performance assessment with the new engine is under progress.

5. CONCLUSION

The important parameters governs the aircraft performance are Lift, Drag, Weight and Thrust. The required performance can be achieved by improving the aerodynamic configuration, weight reduction and system upgradation (like engine, fuel system etc.). This paper brought out the major design changes/inventions demonstrated for the improvement of aircraft performance in major aircraft programs.

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