Effect of Installation of Long Cylindrical External Store on Performance, Stability, Control and Handling Qualities of Light Transport Aircraft

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***Abstract*—**This paper presents the effect of installation of cylindrical external store on the performance, stability, control and handling qualities of light transport category aircraft. A pair of long cylindrical store was installed symmetrically on either side of the fuselage (port and starboard) ahead of the wing and below the fuselage bottom surface running below pilot and co-pilot window. The cylindrical store was installed as hanging from aircraft surface through specially designed brackets. The adjoining structure was sufficiently reinforced for bearing aerodynamic loads. The length to diameter ratio of long cylindrical store was ~20. Based on academic studies and flow simulation analysis, a considerable detrimental effect on single engine second segment climb performance was found which was later validated through extensive flight testing exercise. The methodology of progressive flight envelope opening was adopted. The certification was sought from Regional airworthiness authorities and for according approval.

***Keywords*—**Second segment climb, maximum operating speed, cruise performance, single engine and twin engine, minimum control speed, and additional trim required.

I. Introduction

A light transport aircraft certified under commuter category as per FAR 23 with medium MTOW was used as platform for the integration of cylindrical stores. The aircraft is a high wing monoplane powered by two turboprop engines with constant speed and thrust reversible propellers. Preliminary estimation of basic aerodynamic parameters like CL, CD, CM were carried but using tools of Computational Fluid Dynamics (CFD). CFD studies were also focused on establishing effect of unsteadiness introduced due to cylindrical store at moderately high angle of attack on flow over static pressure ports. CFD studies suggested that there would be no appreciable effect on flow over static pressure port but indicated appreciable changes in basic aerodynamic parameters. This necessitated detailed analysis of the aerodynamic effects of such modification and its validation through extensive flight testing. Aerodynamic parameters predicted through CFD were used to forecast effect on aircraft performance & stability and subsequent control requirements post installation. Owing to criticality of store installation and quantum of effect on basic aerodynamic parameters, methodology of progressive flight envelope opening was adopted. The analysis was carried out for three AUW configurations. i.e. most light Take-Off weight, moderate operating Take-off weight and overweight Take-Off. First analysis was carried out with most light weight Take-off and these results were validated through flight testing.

Based on satisfactory validation of results, analysis was performed for subsequent higher AUW configurations i.e. Moderate operating Take-off weight and Overweight Take-Off.

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II. Aerodynamic Parameters of Long Cylindrical Stores

The data from CFD simulation studies was analyzed to calculate most critical performance parameter for twin turboprop aircraft i.e. Single engine second segment climb gradient. Single engine second segment climb performance analysis was carried out with two flap configurations i.e. Flap up & Take off Flap setting [1].

III. Parameters Determined

The aircraft performance, stability and control parameters which were determined to establish effect of installation of cylindrical store on aircraft were:

1) Single engine second segment climb gradient
2) Effect on cruise performance (Twin engine and Single engine)
3) Effect on maximum operating speed (VMO)
4) Effect on longitudinal stability.
5) Effect on longitudinal trim (In straight and level flight, climb and descent)
6) Effect on lateral and directional stability
7) Effect on minimum control speed in air (VMCA)
8) Effect on rudder deflection required in OEI condition
9) Effect on longitudinal instability i.e. Phugoid oscillation during high speed cruise and low speed cruise and 3 deg angle of descent.
10) Effect on Dutch roll oscillation (DRO)
11) Effect on steady heading side slip (Twin engine and Single engine)
12) Effect on spiral stability.

Some of these parameters were determined only through qualitative assessment during flight testing, while the critical parameters were calculated through classical and empirical methods on the ground and subsequently validated throughout the flight envelope by extensive flight testing.

IV. Methodology Followed

A. Single Engine Second Segment Climb Gradient

For a twin turboprop aircraft, single engine second segment climb gradient is most critical performance parameter which should be met under all take-off conditions at different altitude and temperature. The definition of second segment is understood as the flight phase from point of clearing screening height to height of at least 400 feet above the take-off surface. In second segment flight phase, propeller of inoperative engine is in wind-milling condition, maximum continuous power on live engine, landing gear must be in retracted configuration, flaps in take-off position and aircraft must have attained take off safety speed [1]. Take off safety speed is the minimum speed to be attained with one engine inoperative at screening height. Climb gradient is defined as the ratio of rate of climb in fpm to climb speed in knots. It is always expressed as percentage. For light transport aircraft, minimum gross climb gradient required during second segment is ~2.4% (as per FAR guideline for this class of aircraft).

For three postulated AUW configurations and for flap UP and take off flap setting, climb gradient degradation post installation considering aerodynamic loads on cylindrical store from CFD studies data were calculated. The methodology followed was to estimate decrement in excess power due to predicted additional drag of long cylindrical store. Estimates based on CFD studies suggested that gross climb gradient requirement of 2.4% would be only be met with least AUW configuration in both flap UP and take-off flap settings but with of moderate and Overweight Take-Off AUW requirement of 2.4% would only be met with take-off flap setting. Flight test for validating results was recommended.

B. Effect on Longitudinal Stability and Longitudinal Trim

The requirement was to estimate the detrimental effect of long cylindrical store on longitudinal stability as there is a change in planform area ahead of centre of gravity of aircraft. The slope of pitching moment vs angle of attack (dCM /dα) was estimated using classical methods. Though change in longitudinal static stability index was marginal, flight testing was recommended to validate the expected changes in handling qualities of aircraft. Additional longitudinal trim requirement due to long cylindrical store was estimated by balancing the incremental pitching moment induced by cylindrical store through pitching moment produced by additional horizontal tail deflection. The estimates were made for take-off flap setting and cruise cases. These results were subsequently validated through flight testing.

C. Effect on Maximum Operating Speed (VMO)

The decrement in VMO was determined by obtaining the maximum operating speed of aircraft at which drag experienced by aircraft inclusive of cylindrical store equals to that of clean a/c at VMO. The process involves iteration for VMO at regular step intervals followed by calculation of drag for the two cases. This process was reiterated, till decrement in drag due to decrease in speed becomes equal to additional drag due to cylindrical store.

D. Effect on Twin Engine and Single Engine Cruise Performance

Cruise performance was estimated by calculating pounds of fuel consumed for flying one nautical mile i.e. pounds per nautical mile (PPNM). Flight operating manual data was used to determine fuel consumption and timed cruise at maximum range speed was used to determine fuel consumed for commuting a fixed distance without and with cylindrical store.

E. Effect on Lateral and Directional Stability

The effect on lateral directional stability becomes critical in case of one engine inoperative condition and cross wind conditions. The directional stability of long cylindrical store was measured in terms of rate of change of yawing moment coefficient per degree angle of yaw. $Cn\psi$ = (volume) / (28.7* Sw*b) where, Sw = reference area, b = wing span, Volume = Volume of both cylindrical store.

The effect on directional stability was very small but assessed in flight for any abnormal behavior in handling qualities of aircraft.

F. Effect on Additional Rudder Deflection Required during One Engine Inoperative (OEI) Condition

Long cylindrical store was mounted symmetrically on either side of the fuselage ahead of the wing and below the fuselage bottom surface. The direction of rotation of propeller being counter-clockwise, propeller slipstream becomes skewed towards starboard, which makes starboard engine critical. Starboard engine failure case was examined assuming that both cylindrical stores are operating in free stream. The methodology followed is to assume same minimum control speed in air (VMCA) as per limits of flight operating manual and then estimating additional rudder deflection required to generate same amount of yawing moment through rudder to counteract OEI condition with cylindrical store.

V. Results and Discussions

a) Single engine second segment climb gradient: The calculations of second segment climb gradient based on CFD data indicated that it meets minimum gross climb gradient requirement of 2.4% for least AUW configuration in flap-up & flap in take-off setting kg but with moderate and overweight Take-Off AUW configuration, this requirement is met in only in take-off flap setting configuration. The cylindrical store is predicted to decrease single engine second segment climb gradient by ~0.3% than the regulatory requirement. In order to offset this decrease, it is recommended to decrease AUW by ~2.5-2.8% at all altitude and temperature limits for least AUW to overweight take-Off AUW configuration.
b) The classical methods of determining longitudinal static stability index using CFD data indicated a marginal decrement in static stability. Additional longitudinal trim requirement necessitated additional horizontal tail AOA varied from ~0.37% (nose up) during take-off to 1.5% (nose down) during cruise.

c) The effect on maximum operating speed (VMO) was found to be 1.0 %.
d) The effect on twin engine cruise was observed to be an increase of average PPNM by 4.5 %. The effect on single engine cruise was observed to be an increase in average PPNM by 3.4%.
e) Additional rudder deflection required to counter yawing moment generated during single engine failure at minimum control speed in air was expected to be ~ 0.43%.

VI. Flight Testing Evaluation and Validation

The initial validation of results was obtained by flying the aircraft at least AUW configuration and with both forward centre of gravity and rear centre of gravity definition. After validating results with flight test results obtained with least AUW configuration, tests were repeated for moderate operating AUW and overweight AUW configurations.

A. Twin Engine and Single Engine Cruise Performance

Flight test results have suggested degradation in fuel consumption (pounds per nautical mile) of 4.8% below FAR regulations with the cylindrical store. The degradation in performance can be attributed to engine performance degradation with continued usage of aircraft.

Single engine cruise performance was degraded by 3.7% with critical engine feathered. These results were annotated in performance section of flight operating manual supplement.

B. Single Engine Climb Performance

Single engine second segment climb gradient [5, p 109] was carried out with and without cylindrical store in take-off flap setting and FWD CG position. All test points were carried out at altitudes approaching flight operating manual derived Weight Altitude Temperature (WAT) limits at similar OAT. With RH engine running and LH engine feathered, the degradation in average gross climb gradient was observed to be ~0.3% than the requirement.

C. Minimum Controllable Speed in Air (VMCA) and Maximum Operating Speed (VMO)

Aircraft speed when dropped from V2 to VMCA, adequate rudder control was available and aircraft heading could be maintained with bank angle less than 5 deg. Degradation in VMO was less than 0.5% and is considered within acceptable limits of cruise performance degradation (airspeed degradation limit due to engine performance degradation with continued usage).

D. Effect on Longitudinal Stability and Trim

Positions of elevator, rudder and aileron trims were noted in level flight in FWD and AFT CG configuration between stalling speed to maximum operating speed at regular intervals without and with cylindrical store installed. Aircraft was observed to be trimmable throughout the speed range. A very slight nose up shift in longitudinal trim was experienced with cylindrical store installed, but this shift remained well within trim able range of elevator. Baulked landing was simulated to test trimmablity in climbing flight. It was assessed in landing flap setting, undercarriage UP and maximum power setting both in FWD and AFT CG configurations. Trimmablity during descent was assessed with power setting for 450 fpm rate of descent both in FWD and AFT CG. Aircraft was observed to be trimmable well with in elevator capability [4, p 63] for both climb and descent phase of flight.

E. Effect on Longitudinal Instability (Long Period i.e. Phugoid)

Phugoid motion in high speed cruise condition was initiated from base conditions of aircraft trimmed for level flight at ~ 85% of maximum operating speed wherein speed was increased in a gradual descent to maximum operating speed in order to excite longitudinal motion [2, p. 172]. A plot depicting variation of speed with time is shown at Fig. 1. The aircraft exhibited positive static stability in both without and with cylindrical store. The average time period of Phugoid oscillation was 55 sec. There was a slight reduction in amplitude with negligible change in cycle time of Phugoid with cylindrical store installed.

Phugoid in landing configuration, low speed, and shallow. angle of descent was also carried out. Phugoid was initiated from base condition of aircraft trimmed for shallow. angle of descent at ~45% of maximum operating speed, wherein speed was increased to 50% of operating speed in gradual descent to excite Phugoid oscillation. A plot depicting variation of speed Vs time is shown at Fig. 2 as in [2]. The aircraft exhibited positive static stability for bot without and with cylindrical store. The Phugoid had an average time period of 30 sec. There was negligible reduction in amplitude and cycle time with cylindrical store.

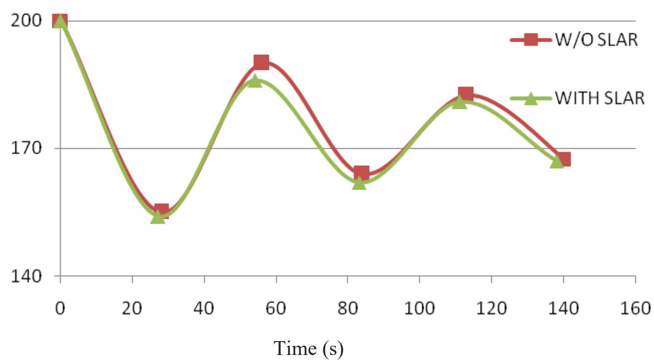

Fig. 1 Comparative plot for Phugoid motion in clean configuration (Time Vs Speed variation)

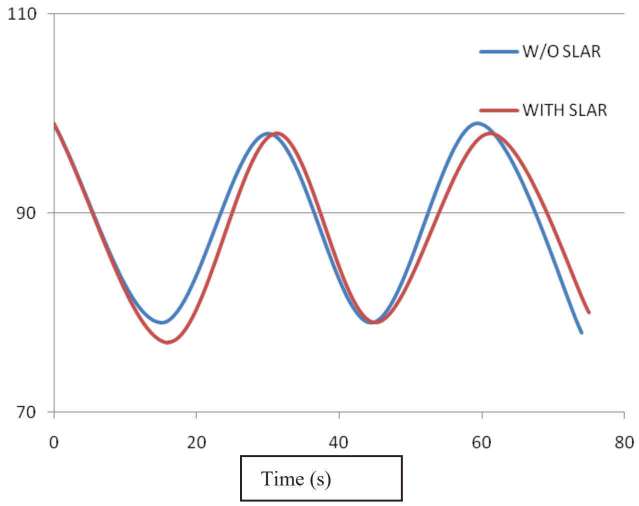

Fig. 2 Comparative plot for Phugoid motion in landing configuration (Time Vs Speed variation)

F. Effect on Lateral and Directional Stability

Twin engine steady heading side slip (TESHSS) and single engine steady heading side slip (SESHSS) was carried out to assess lateral and directional stability characteristics as in [3, p. 282]. TESHSS and SESHSS were carried out in aft CG by applying ½ rudder travel to both sides at 1.3 times of stalling speed. Aircraft bank angle up to 10 Deg. could be achieved without any signs of rudder tramping or overbalancing. Full rudder was also applied to both sides and no signs of tramping or overbalancing were observed.

Dutch Roll Oscillations (DRO) were initiated in AFT CG by giving doublet input using rudder at speeds 45%, 50% & 60% of maximum operating speed in flap UP, flap-01 and flap-02 setting for both without and with long cylindrical store installed. DRO characteristics were predominant in yaw, with yaw to roll ratios between 1:2.5 and 1:3.5. In all cases damping was experienced within 2-3 oscillations.

G. Effect on Spiral Stability

Spiral stability was assessed at 90% of maximum operating speed in without and with cylindrical store configuration and aircraft displayed neutral to very slight convergent spiral stability characteristics.

VII. Recommendations

After validating results with flight test results obtained at least AUW, moderate operating weight & overweight AUW configuration were also carried out. The results obtained showed similar trends to arrive at final recommendations for aircraft fitted with cylindrical store.

In order to offset degradation of ~0.3% in second segment climb gradient, a reduction of ~2.5- 2.8% in AUW was recommended from flight manual derived AUW as per WAT limits. This may also be considered as reduction in payload due to cylindrical store installation on aircraft

Other recommendations regarding degradation in performance were separately annotated in supplement of flight operating manual

References

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