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Effect of freestream-jet plume interaction on aerodynamic coefficients with different flared aft-bodies

S.L.N. Desikan [a,*], K. Suresh [b], R. Saravanan [a], N. Chandrasekar [b], M.M. Patil [a], S. Pandian [c]

[a] Experimental Aerodynamics Division, Vikram Sarabhai Space Centre, Thiruvananthapuram 695022, India
[b] Wind Tunnel and Instrumentation Division, Vikram Sarabhai Space Centre, Thiruvananthapuram 695022, India
[c] Aeronautics Entity, Vikram Sarabhai Space Centre, Thiruvananthapuram 695022, India

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ABSTRACT

Experiments were carried out on a blunt-cone-cylinder geometry with various flared aft body configurations to understand the effect freestream (M = 5)-jet plume (M = 2.65) interaction on aerodynamic coefficients. Supersonic jet plume of varying pressure ratios (P_j/P_∞ = 0–130) were simulated and the model angle of attack (α) is varied from 0 to 4°. The complex freestream-jet plume interaction was captured through Schlieren flow visualization while the forces and moments are measured through conventional strain gauge balance. The introduction of supersonic jet plume resulted in reduction of aerodynamic coefficients in all the cases. The change in aerodynamic coefficients depends primarily on the extent of Plume Induced Flow Separation (PIFS) due to freestream-jet plume interaction and the aft body configurations. A reduction of 37–46% in axial force coefficient (C_A), 20–23% in normal force coefficient (C_N) and 31–72% in pitching moment coefficient (C_m) were observed due to freestream-jet plume interaction. In cylindrical aft body, separation due to freestream-jet plume interaction was found to be dominant whereas it is less pronounced in flared aft body configurations. Among the tested configurations 14 and 16° flared aft body configurations show more stability compared to cylindrical and other flared aft body configurations under jet plume-on and off conditions.

1. Introduction

During ascent phase of a launch vehicle, it is a customary to provide solid motors for initial thrust. The plumes from the solid motors at altitudes become highly under-expanded depending on the pressure ratio interacts with them and with freestream. Thus, the flowfield becomes more complex in nature both on the launch vehicle surface and at the base. As a result, vehicle experiences differential pressure on the surface (windward as well as leeward side) and change in pressure distribution at the base region. The former is caused by Plume Induced Flow Separation (PIFS) and the latter is due to suction effect. The consequences are change in center of pressure, stability and thrust of the vehicle. Hence, the vehicle requires suitable control forces to overcome stability related issues due to the movement of center of pressure and other challenges such as loss in roll rate, and unsymmetrical lift [1–11].

In some cases, particularly at transonic region, these effects may lead to buffeting associated issues which may even lead to catastrophic failure. Generally, stability of the vehicle can be achieved either by increasing the angle of attack (α) or the body length. However, controlling the vehicle will be limited by the extent of freestream-jet plume interaction. Another important characteristic of freestream-jet plume interaction is the suction effect which produces reverse flow at the vehicle base, moves towards the base [12–15] and eventually stagnates at the base leading to change the drag/thrust characteristics of the vehicle. Thus it is very important to understand the contribution of PIFS on launch vehicle aerodynamics

PIFS in general, depends on many parameters such as freestream Mach number, Reynolds number, aft body configurations, jet plume pressure ratio, etc. With increasing jet plume pressure ratio (P_j/P_∞), PIFS is a strong function of Mach numbers [16] and a weak function of Reynolds numbers [17,18]. At low Mach numbers, flow separation due to freestream-jet plume interaction is small and depends on both jet plume pressure ratio (P_j/P_∞) and the shape of the aft bodies.

It is understood that limited literatures (experimental/numerical) are available to understand the effect of freestream-jet plume

* Corresponding author.
E-mail addresses: desikan_sln@yahoo.com, sln_desikan@vssc.gov.in (S.L.N. Desikan), suresh_balakrishnan@vssc.gov.in (K. Suresh), saravanan_ram@vssc.gov.in (R. Saravanan), n_chandrasekar@vssc.gov.in (N. Chandrasekar), mm_patil@vssc.gov.in (M.M. Patil), s_pandian@vssc.gov.in (S. Pandian).

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Nomenclature

α	angle of attack, deg
C_A	axial force coefficient
X_{CP}	center of pressure
ρ	density, kg/m^3
D	diameter, mm
F	force, N
D_e	free-jet diameter, mm
M	jet plume Mach number
P_j/P_∞	jet plume pressure ratio
m	moment about nose, N m
C_N	normal force coefficient
C_m	pitching moment coefficient about nose
P	pressure, bar
S_{ref}	reference area, m^2
R_e	Reynolds number
δ	semi plume angle, deg
P	static pressure, bar
T	temperature, K
M_1	tunnel Mach number
V	velocity, m/s

Subscript

X, Y, Z	coordinate system
∞	freestream
j	jet plume
0	total condition
01	tunnel stagnation condition

Acronyms

AF	axial Force, N
NF	normal Force, N
PIFS	plume induced flow separation
SF	side force, N

interaction and associated PIFS on launch vehicle aerodynamics [2,4,7,16,19–25]. Generally, aerodynamic coefficients are altered due to change in the surface pressure distribution caused by flow separation through freestream-jet plume interaction. Once the jet plume size is increased to the large extent (high values of P_j/P_∞), there is a possibility of change in the type of flow separation and the flow may even become transitional in some cases. Under these circumstances, separation point may move out of the model. At low angles of attack (<2°) separation due to freestream-jet plume interaction show a characteristics of laminar separation [19]. On the other hand, increasing the angle of attack (>2°) changes the local Reynolds number, leads to large flow separation in leeward side while windward side experiences comparatively small flow separation [16,19,33]. In some cases, the flow may be completely attached [22]. The extent of flow separation also depends on the type of aft body configuration. In the case of flared aft bodies, the extent of flow separation decreases with increase in the flare angle [22]. As the angle of attack increases, a small region of separation exists on the windward side and some recovery of the flare effectiveness is also observed. The effect of angle of attack demonstrate that the stability of the vehicle is less pronounced at low angles of attack (<2°) and recovery in stability could be seen beyond $\alpha = 2°$ [22]. The aerodynamic coefficients (C_N and C_m) under jet plume-off condition is found to be linear for small angles of attack whereas under jet plume-on conditions, substantial reduction in normal force and destabilizing moment is observed [2,33]. However, more stability is observed by increasing the angle of attack under large jet plume pressure ratios. Another important point reported is the movement of center of pressure [2]. The center of pressure movement for finned aft body is found to be gradual whereas the flared and the cylindrical aft bodies show abrupt change [19]. Hence it is very important to study the changes in aerodynamic coefficients on a typical model with flared aft bodies in the presence of jet plume.

Generation of aerodynamic data in the presence of jet plume is a daunting task especially in wind tunnels where design of scaled model, facilitation of jet plume nozzle and routing of jet plume to the model, accommodation of strain gauge balance, isolation of load measuring and non-measuring parts, elimination of jet reaction force, etc. are the bottle necks [26–28]. The use of strain gauge balances for this purpose can be either conventional [4] or ring balances [29–33]. However, they require proper isolation which means, they have to measure aerodynamic forces and moments only due to freestream-jet plume interaction alone. However these balances have their own merits and de-merits. In order to use the conventional strain gauge balance, model design is a bottle neck while, cumbersome calibration procedure is required for ring balances. Other parameters [34] to be simulated to correlate wind tunnel data to the flight are the plume boundary, plume trajectory and the plume entrainment. However, simulation of all these parameters together in a wind tunnel is not possible and hence, requires judicial approach.

In the present experimental investigations, effect of freestream-jet plume interaction on aerodynamic coefficients for different flared aft bodies are studied and compared with cylindrical aft body. The studies include a novelty in the design approach to accommodate conventional strain gauge balance in the model to measure forces and moments only due to freestream- jet plume interaction by isolating load measuring and load non measuring parts, eliminating jet reaction and grounding effect. Forces and moments are measured through a conventional strain gauge balance and the complex flowfield of freestream-jet plume interaction such as PIFS, and jet plume shock structures are studied through Schlieren flow visualization.

2. Model details

Fig. 1 shows schematic representation of the geometries and a typical model photograph tested in Hypersonic Wind Tunnel, Vikram Sarabhai Space Centre. The overall length of the model is 8D where, D is the diameter (32 mm) of the model, R is the nose radius (100 mm) and the cone angle is 40°. The aft cylindrical portion is replaced with a flare of 10, 12, 14 and 16° to study the flare effect on aerodynamic coefficients due to freestream-jet plume interaction. In all the cases the length of the model is not altered and only the base area is changed. A strut used to support the model through a sting acts as a passage to facilitate the compressed air to the jet plume nozzle. This jet plume nozzle is a false nozzle i.e., a separate convergent divergent nozzle is fabricated and kept inside the aft body (cylinder/flare) through shrink fit to avoid grounding effect [26,27]. The model design is well established for single and twin jet configurations [27,28]. The maximum and minimum clearance of 3.5 mm (at the nozzle exit plane) and 1.3 mm (just upstream of the convergent portion of the supersonic nozzle) is provided between the external shape and the false nozzle