JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 42, No. 6, November–December 2005

Effect of Intake Geometry on Longitudinal Aerodynamics of Airbreathing Vehicles

A. Satyanarayana*
Defence Research and Development Laboratory, Hyderabad 500 059, India
S. Santhakumar†
Indian Institute of Technology Madras, Chennai 600 036, India
S. Panneerselvam‡
Defence Research and Development Laboratory, Hyderabad 500 059, India
and
Sajeer Ahmed§
National Aerospace Laboratories, Bangalore 560 017, India

A wind-tunnel test program was conducted to generate a systematic aerodynamic database for airbreathing vehicles. Generic models consisting of tangent ogival nose, cylindrical body with cruciform intakes or twin intakes were tested at freestream Mach numbers ranging from 0.5 to 3.0. The length and span of intakes were varied. The intakes were two-dimensional with blocked entry. Normal force and pitching moment were nondimensionalized using planform area and distance of centroid (from nose tip) of the planform of the model rather than body cross-sectional area and body diameter, which are traditionally used. When normal-force and pitching-moment coefficients nondimensionalized this way are plotted against angle of incidence, the coefficients of different configurations coalesce for zero roll. In addition, data for different roll angles are found to coalesce when an empirical function of roll angle is introduced in the nondimensionalizing. A prediction method was developed to estimate the normal force and pitching moment of similar body-intake configurations based on this trend.

Nomenclature

A	=	cross-sectional area
A_B	=	body cross-sectional area of the configuration, $=\pi r^2$
A_P	=	planform area of configuration
A_{PB}	=	planform area of body
A_{PI}	=	planform area of intakes alone, $A_P - A_{PB}$
A_R	=	reference area (equal to A_P unless otherwise specified)
C_{dn}	=	crossflow drag coefficient of circular cylindrical section
C_m	=	pitching-moment coefficient about nose, M_p/qA_RX
C_{mNL}	=	nonlinear component of pitching-moment coefficient about nose
C_N	=	normal-force coefficient, $=N/qA_R$
C_{NNL}	=	nonlinear component of normal-force coefficient
c_n	=	local normal-force coefficient per unit length
d	=	body diameter
H	=	height of air intake
l	=	length of model
l_i	=	length of air intake
M	=	freestream Mach number
M_p	=	pitching moment about nose
N	=	normal force
q	=	freestream dynamic pressure
r	=	body radius
s	=	total span of body-intake configuration
W	=	width of air intake
X	=	reference length (equal to x_C unless otherwise specified)
x	=	axial distance from body nose tip
x_C	=	distance of centroid of planform area of model from nose tip
$x_{C\phi}$	=	distance of centroid of planform area of model from nose tip at ϕ
α	=	angle of incidence
η	=	crossflow drag proportionality factor
ϕ	=	angle of roll about body longitudinal axis

Subscripts

Newt	=	Newtonian theory
SB	=	slender-body theory
0	=	equivalent circular body or cross section

Introduction

AIRBREATHING engines are characterized by high specific impulse. It is thus attractive to use airbreathing propulsion for long-range and high-speed missiles. Presence of intakes makes the geometry more complex, and so it is difficult to generate external aerodynamic characteristics of airbreathing missiles by theoretical methods. There is thus a need to generate the data experimentally. A wind-tunnel test databank for twin intake airbreathing missile configurations is given by Hayes.[1] However, only one body-intake geometry was investigated. A methodology presented by Champigny and Baudin[2] can predict only the normal force and pitching moment of intakes in the presence of body. In the present work, an attempt is made to predict these coefficients for body-intake configurations of similar geometry.

An experimental test program was taken up for investigating generic airbreathing vehicle configurations consisting of a body and intakes of different geometries. The objective of the test program is to develop empirical/semi-empirical relations for aerodynamic force and moment coefficients from the experimental database. These relations can be used for predicting the coefficients of any other similar configuration.

Received 13 August 2004; revision received 24 March 2005; accepted for publication 20 June 2005.

*Scientist, Aero Test Facility Division.
†Professor and Head, Department of Aerospace Engineering.
‡Project Director, Hypersonic Technology Demonstrator Vehicle.
§Deputy Head, Experimental Aerodynamics Division.

According to Allen's crossflow theory,[3] the crossflow component of freestream velocity produces a normal force on the aerodynamic configuration. Because of the presence of air intakes, the planform area of an airbreathing vehicle is large, and the intakes contribute more lift. This fact is used in choosing the planform area of the configuration in characterizing the normal force and pitching moment, and it resulted in the unification of the characteristics of different body-intake configurations. Experimental results of body with two intakes and body with four intakes were analyzed using this method for all of the five test Mach numbers. These results are presented in this paper. The methodology adapted in analyzing the test data is described.

Description of the Facility

Tests were conducted in the 0.3 m × 0.3 m Trisonic Wind Tunnel at National Aerospace Laboratories, Bangalore. It is an intermittent blowdown-type tunnel that is capable of operating at Mach numbers ranging from 0.2 to 3.0 and Reynolds numbers ranging from 4×10^6 to 32×10^6 per meter. Fixed geometry replaceable nozzle blocks are available for nominal test-section Mach numbers of 1.4, 1.6, 1.8, 2.0, 2.2, 2.5, and 3.0. Tunnel operating pressures are 26 psia at Mach number of 2.0 and 60 psia at Mach number of 3.0. The model support system has the capability to pitch the model in the range of −10 to +10 deg.

Model Details

A schematic of the wind-tunnel test models is shown in Fig. 1. The configuration had a tangent ogival nose of fineness ratio 3, a cylindrical after body of fineness ratio 12, and four/two intakes. The body of the model was designed so that various intakes can be attached to it. A total of five body-cruciform intake configurations and three body-twin intake configurations were tested. The parameters varied were the intake span and intake length. The dimensions of individual intakes are given in Table 1.

Test Conditions

The tests were conducted at freestream Mach numbers of 0.5, 0.8, 2.0, 2.5, and 3.0 and Reynolds number of approximately 26.9×10^6 per meter. The model angle of incidence was varied from −10 deg to +10 deg (in steps of 2 deg) during tunnel run. Body-cruciform intake configurations were tested at roll angles 0, 22.5, and 45 deg, and the body-twin intake configurations were tested at roll angles 0, 22.5, 45, 67.5, and 90 deg.

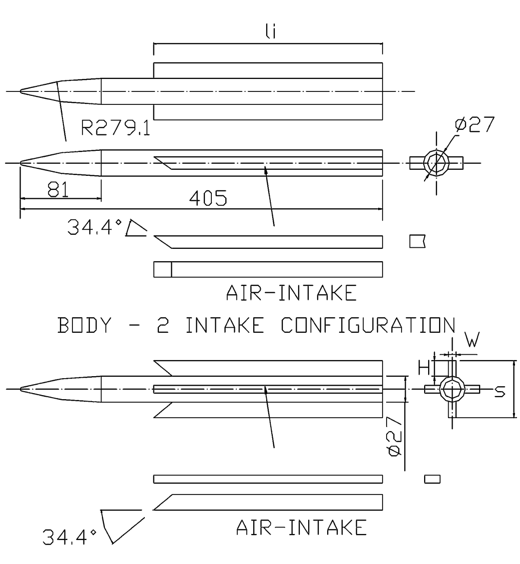

Fig. 1 Model details.

Table 1 Dimensions of the intakes tested[a]

Configuration	l_i	H	W	s/d
Four-intake configurations				
1	240	12.75	6.4	1.94
2	240	17.6	8.8	2.3
3	240	23.0	11.5	2.7
4	189	23.0	11.5	2.7
5	256.5	23.0	11.5	2.7
Two-intake configurations				
6	240	12.75	12.75	1.94
7	240	8.1	8.1	1.60
8	240	17.5	17.5	2.30

[a] $d = 27$. All dimensions are in millimeters.

Table 2 Percentage uncertainty of C_N

	Mach number			
Configuration	0.5	0.8	2.0	3.0
1	2.39	1.27	0.86	0.92
2	2.03	1.04	0.68	0.77
3	1.67	0.88	0.58	0.66
4	2.09	1.06	0.67	0.76
5	1.65	0.85	0.51	0.62
6	2.20	1.13	0.75	0.70
7	3.00	1.53	1.04	0.99
8	1.73	0.90	0.53	0.46

Table 3 Percentage uncertainty of C_m

	Mach number			
Configuration	0.5	0.8	2.0	3.0
1	2.3	1.21	0.69	0.75
2	1.88	0.96	0.53	0.61
3	1.55	0.82	0.42	0.50
4	1.73	0.89	0.46	0.55
5	1.60	0.81	0.39	0.48
6	2.53	1.18	0.63	0.66
7	3.0	1.54	0.86	0.90
8	1.99	0.97	0.51	0.55

Measurements

Aerodynamic forces and moments on the model were measured using a floating frame "ABLE" six-component internal strain-gauge balance of diameter 0.75 in. The percentage of uncertainties of C_N and C_m were computed for test Mach numbers 0.5 to 3.0 for all of the configurations at angle of incidence of 10 deg and roll angle of 0 deg: percentage of uncertainty of $C_N = (\Delta C_N / C_{N \text{ at } \alpha = 10 \text{ deg and } \phi = 0 \text{ deg.}}) \times 100$ and percentage of uncertainty of $C_m = (\Delta C_m / C_{m \text{ at } \alpha = 10 \text{ deg and } \phi = 0 \text{ deg.}}) \times 100$, where ΔC_N and ΔC_m are measurement uncertainties of C_N and C_m, respectively. The percentage uncertainties of C_N and C_m are shown in Tables 2 and 3, respectively. The maximum percentage of uncertainty of both C_N and C_m was found to be ±3% at Mach number 0.5 for configuration 7. The measurement uncertainty is based on planform area and distance of centroid from nose.

Methodology

The normal force measured on three different configurations with different intake spans is shown in Fig. 2. C_N data are calculated by using body cross-sectional area as reference area. We see normal-force increases with increasing span. The normal force on body alone is also shown in the same figure. The increment in C_N caused by intakes was found from the experimental data as follows:

$$C_{N \text{ intakes}} = C_{N \text{ body+intakes}} - C_{N \text{ body}} \tag{1}$$

$C_{N\text{intakes}}$ data are recalculated by changing the reference area to planform area of intakes, and the data are plotted in Fig. 3. Normal-force coefficients of the three intakes are found to coalesce as seen in

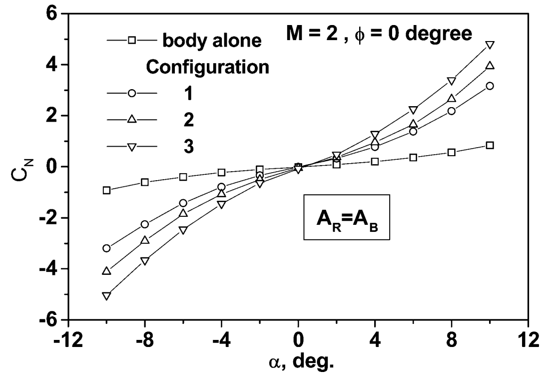

Fig. 2 Effect of intake span on C_N.

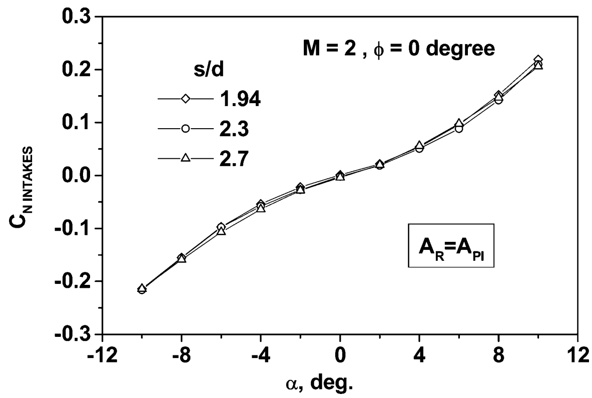

Fig. 3 Intake contribution to C_N in the presence of body.

the figure. This observation paved the way for a prediction method for complete configurations described herein.

The normal force and pitching moment of an aerodynamic configuration can be expressed as[3]

$$C_N = \frac{\sin 2\alpha \cos(\alpha/2)}{A_R} \int_o^l \left(\frac{C_n}{C_{\mathrm{no}}}\right)_{\mathrm{SB}} \frac{\mathrm{d}A}{\mathrm{d}x}\,\mathrm{d}x + \frac{2\eta C_{\mathrm{dn}} \sin^2\alpha}{A_R} \int_o^l \left(\frac{C_n}{C_{\mathrm{no}}}\right)_{\mathrm{Newt}} r\,\mathrm{d}x \tag{2}$$

$$C_m = \frac{\sin 2\alpha \cos(\alpha/2)}{A_R X} \int_o^l \left(\frac{C_n}{C_{\mathrm{no}}}\right)_{\mathrm{SB}} \frac{\mathrm{d}A}{\mathrm{d}x} x\,\mathrm{d}x + \frac{2\eta C_{\mathrm{dn}} \sin^2\alpha}{A_R X} \int_o^l \left(\frac{C_n}{C_{\mathrm{no}}}\right)_{\mathrm{Newt}} rx\,\mathrm{d}x \tag{3}$$

For constant-area cross section, the nonlinear term of Eq. (2) becomes

$$\frac{2\eta C_{\mathrm{dn}} \sin^2\alpha}{A_R}\left[\frac{C_n}{C_{\mathrm{no}}}\right]_{\mathrm{Newt}} A_P$$

and that of Eq. (3) becomes

$$\frac{2\eta C_{\mathrm{dn}} \sin^2\alpha}{A_R X}\left[\frac{C_n}{C_{\mathrm{no}}}\right]_{\mathrm{Newt}} A_P x_c$$

Thus, the nonlinear term in Eq. (2) is proportional to planform area A_P, and the nonlinear term in Eq. (3) is proportional to product of planform area and distance of centroid x_C for constant-area cross section of the model. Choosing planform area and distance of centroid as reference parameters, the nonlinear components of normal-force and pitching-moment coefficients are made independent of planform area and distance of centroid. A method that makes use of this idea for predicting the normal-force and pitching-moment coefficients is given next.

Body with Four Intake Configurations

The potential terms in Eqs. (2) and (3) are estimated using slender-body theory.[3] The cross section of the model at the intake location is approximated as circular for the purpose of obtaining the value of the parameter $(C_n/C_{\mathrm{no}})_{\mathrm{SB}}$, and it is taken to be 1.0 while integrating in the body-intake portion. The base area is the sum of the areas of body cross section and cross section of the four intakes at the base, which is used for calculating the potential terms of Eqs. (2) and (3). The nonlinear term is obtained by subtracting the estimated potential term from measured overall value of force and moment. Thus,

$$C_{N\ \mathrm{NL}} = C_{N\ \text{overall measured}} - C_{N\ \text{potential}} \tag{4}$$

$$C_{N\ \mathrm{NL}} = C_{m\ \text{overall measured}} - C_{m\ \text{potential}} \tag{5}$$

Body with Two Intake Configurations

The potential terms are again estimated using slender-body theory.[3] The cross section of the model at the intake location is approximated as an ellipse with the major axis equal to span and the minor axis equal to body diameter and the parameter $(C_n/C_{\mathrm{no}})_{\mathrm{SB}}$ is taken to be equal to s/d of the respective configurations[3] while integrating in the body intake portion. The base area is the sum of the areas of body cross section and cross section of the two intakes at the base. The entry plane of the intake (refer to Fig. 1) is at an angle of 34.4 deg from the horizontal plane. Because of asymmetry of the intakes with respect to horizontal plane, the model experiences a normal force at $\alpha = 0$ deg. This is the reason for the presence of $C_{N\ \text{at}\ \alpha=0}$ and $C_{m\ \text{at}\ \alpha=0}$ terms in the equations given next. The nonlinear term for body-twin intake configurations is obtained as follows:

$$C_{N\ \mathrm{NL}} = C_{N\ \text{overall measured}} - C_{N\ \text{potential}} - C_{N\ \text{at}\ \alpha=0} \tag{6}$$

$$C_{m\ \mathrm{NL}} = C_{m\ \text{overall measured}} - C_{m\ \text{potential}} - C_{m\ \text{at}\ \alpha=0} \tag{7}$$

$C_{N\ \text{at}\ \alpha=0}$ and $C_{m\ \text{at}\ \alpha=0}$ are measured values.

On changing the reference areas and lengths to A_P and x_C, respectively, it is expected that the nonlinear components of normal force and pitching moment coalesce to a single curve. Consequently the coefficients can be predicted for a new but similar configuration, with intakes of different length or span for example, in the following way. The nonlinear component of coefficient is taken from the collapsed curve and added to the potential term, which is computed to estimate the total coefficient.

Discussion of Results

Body-Cruciform Intake Configurations at Roll Angle = 0 deg

The measured normal-force and pitching-moment coefficients for five body-cruciform intake configurations are given in Figs. 4 and 5, respectively, for Mach number of 0.5. The coefficients were nondimensionalized using body cross-sectional area and body diameter. The variation in C_N and C_m among five configurations is found to be $\pm 20\%$ at $\alpha = 10$ deg. Similar trends are observed for Mach numbers 0.8, 2.0, and 3.0.

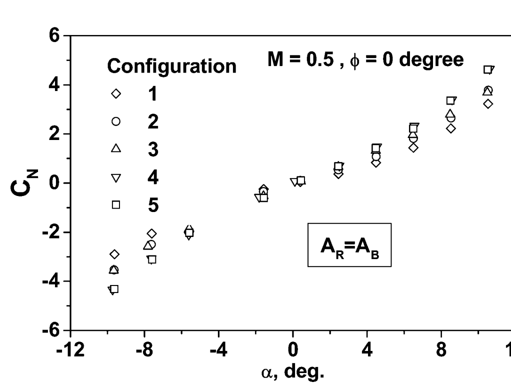

Fig. 4 Effect of intake planform area on C_N.

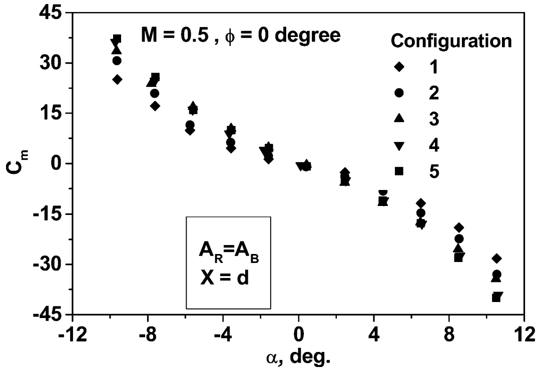

Fig. 5 Effect of intake planform area on C_m.

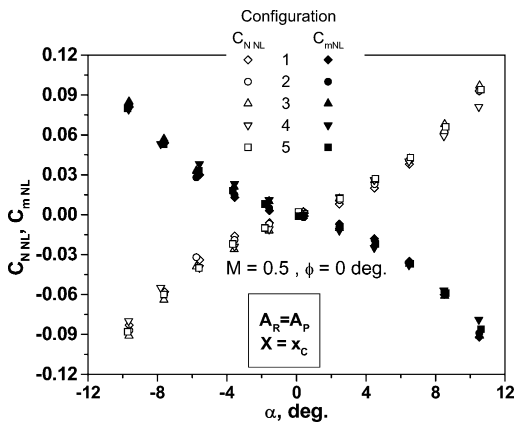

Fig. 6 Effect of intake planform area on C_N and $C_{m\ \mathrm{NL}}$.

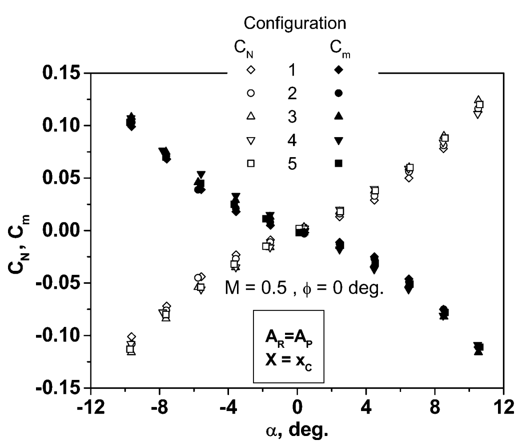

Fig. 7 Effect of intake planform area on C_N and C_m.

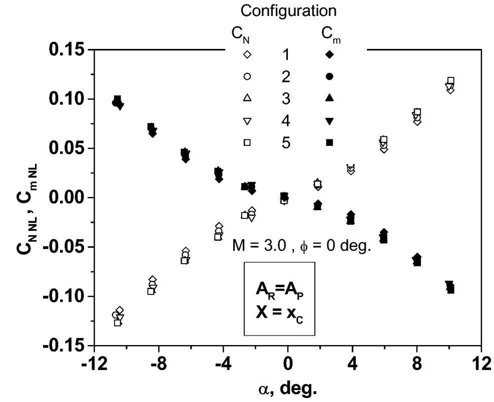

Fig. 8 Effect of intake planform area on C_N and $C_{m\ \mathrm{NL}}$.

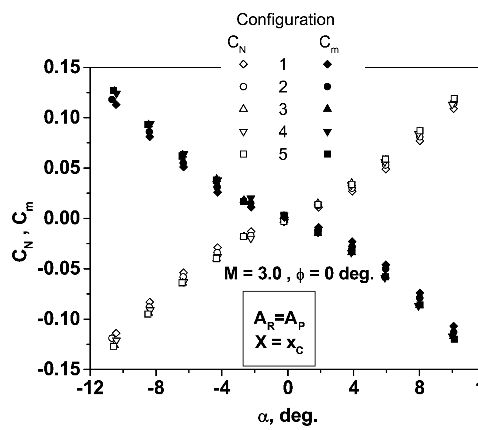

Fig. 9 Effect of intake planform area on C_N and C_m.

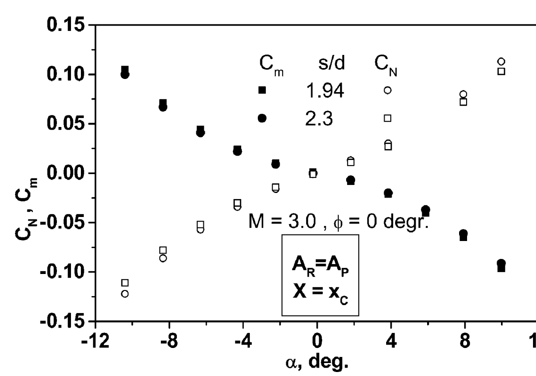

Fig. 10 Effect of intake planform area on C_N and C_m: body intake configurations investigated by Champgny and Baudin,[2] $l_i/d = 8.89$.

Nonlinear components obtained from Eqs. (4) and (5) and nondimensionalized using A_P and x_C are shown in Fig. 6 for a Mach number of 0.5. The coefficients are found to be collapsed. The variation in C_N and C_m among five configurations is found to be $\pm 5\%$ at $\alpha = 10$ deg.

However, the coefficients are found to be collapsed even for the entire force and moment when A_P and x_C are used as reference parameters, as seen in Fig. 7 for the five body-cruciform intake configurations. We expect this to happen if the nonlinear term, which is the term that is dependent on A_P, is dominant. An examination of relative size of the potential and nonlinear terms reveals that the potential term varies from 17 to 23% at a 10-deg angle of incidence for Mach numbers 0.5 and 2.0, respectively.

The nonlinear components of normal-force and pitching-moment coefficients are shown in Fig. 8, and the total coefficients are shown in Fig. 9 for Mach number of 3.0. The variation in the characteristics (both nonlinear and total coefficients) is observed to be about $\pm 5\%$ at $\alpha = 10$ deg for this Mach number also. Similar trends are observed at other test Mach numbers of 0.8 and 2.0. This trend indicates that the values of C_N and C_m of different configurations become independent of intake geometry when normalized with respect to A_P and x_C.

The method is applied to the experimental results of Champigny and Baudin.[2] The incremental effect of intake on normal-force coefficient and location of center of pressure in the presence of body are given in this reference. The body-alone characteristics are predicted using an available missile prediction code,[4] and the characteristics have been summed up componentwise to arrive at the total C_N and C_m for body-intake configurations. The forces and moments were estimated for two different configurations. The length of intakes ($l_i/d = 8.89$) is the same for both the configurations. The values of s/d are 1.97 and 2.3. The coefficients are shown in Fig. 10 for Mach number of 3.0. Unification of the characteristics is observed in this case also.

Body-Twin Intake Configurations at Roll Angle = 0 deg

When the total C_N and C_m were plotted for twin-intake configurations, the data did not coalesce very well showing a spread of about 15%. In this case, a potential term was found to vary from 25 to 39% for $M = 0.5$ and 2.0, respectively. This perhaps explains why the data do not collapse that well.

The nonlinear components of C_N and C_m for Mach number of 0.8 and 2.5 are shown in Figs. 11 and 12 respectively for three different body-twin intake configurations. The variation in the components is observed to be about ±5% at $\alpha = 10$ deg for the three configurations. Experimental results of Hayes[1] after changing the reference area and length to A_P and x_C are also shown in Fig. 12 for Mach number of 2.5.

Body-Cruciform Intake Configurations at Roll Angle > 0 deg

Normal-force and pitching-moment coefficients were nondimensionalized using A_P and x_C as reference parameters. The coefficients of cruciform intake configuration at roll angles of 0, 22.5, and 45 deg were plotted against the angle of incidence. Coalescing of the coefficients was not observed in this case. An empirical function of roll angle was introduced in nondimensionalizing the forces and moments. Planform area of cruciform intake configuration varies with roll angle, ϕ with period of 90 deg. Hence the parameter $(a \cos 4\phi + b)^* A_P$ is used as reference area, and the distance of centroid of planform area at ϕ is used as reference length. The constants a and b are empirically chosen to coalesce the normal-force and pitching-moment characteristics. The values of a and b are found to be 0.25 and 0.75, respectively. The results of C_N and C_m are shown in Figs. 13 and 14 for Mach numbers of 0.8 and 3.0, respectively. The variation in total C_N and C_m is observed to be about ±5% at $\alpha = 10$ deg for the three roll angles. Similar trends are observed at Mach numbers of 0.8 and 2.0.

Body-Twin Intake Configuration at Roll Angle > 0 deg

The parameter $(0.333^* \cos 2\phi + 0.667)^* A_P$ is used as the reference area, and the distance of the centroid of A_P at ϕ is used as

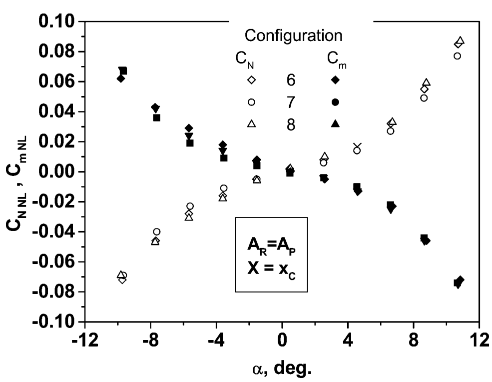

Fig. 11 Effect of intake planform area on C_N and $C_{m\,N}$: $M = 0.8$, $\phi = 0$ deg.

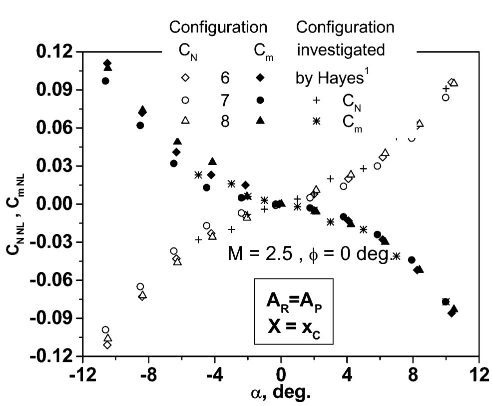

Fig. 12 Effect of intake planform area on C_N and $C_{m\mathrm{NL}}$.

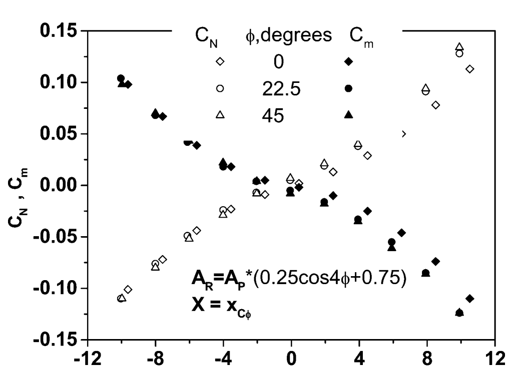

Fig. 13 Effect of intake planform area on C_N and C_m: $M = 0.5$, configuration 1.

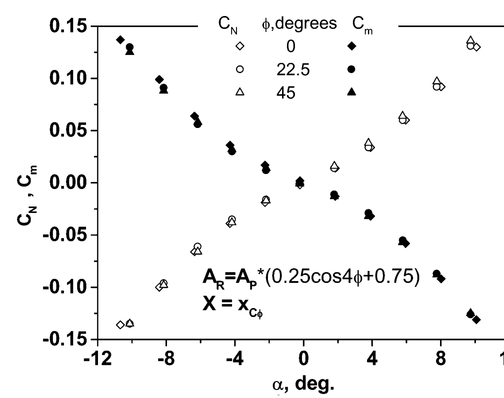

Fig. 14 Effect of intake planform area on C_N and C_m: $M = 3.0$, configuration 1.

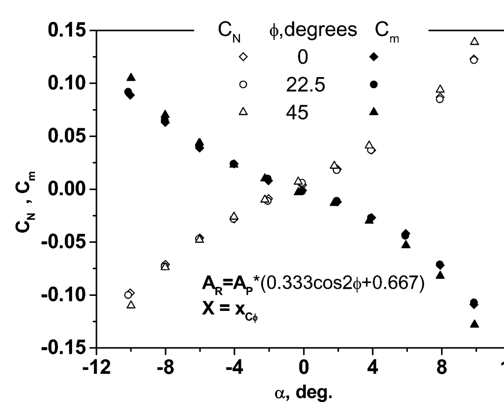

Fig. 15 Effect of intake planform area on C_N and C_m: $M = 0.5$, configuration 6.

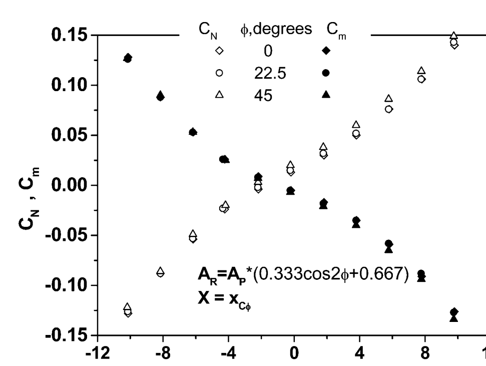

Fig. 16 Effect of intake planform area on C_N and C_m: $M = 3.0$, configuration 6.

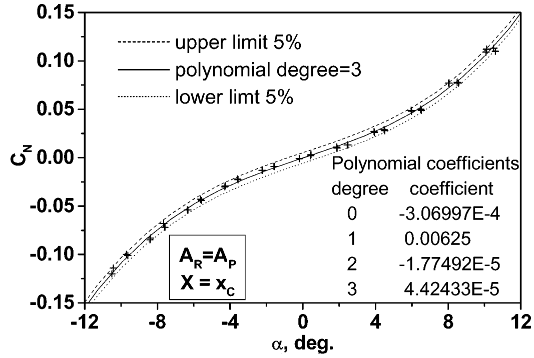

Fig. 17 Effect of intake planform area on C_N: $M = 0.5$, $\phi = 0$ deg, configurations 1–5.

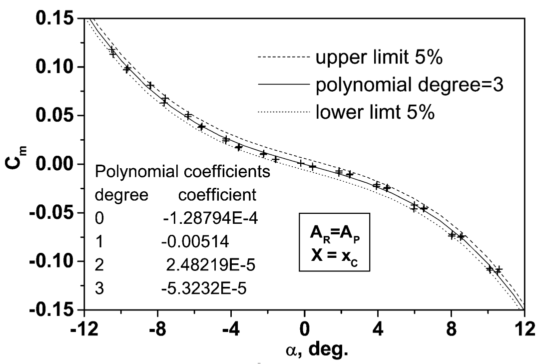

Fig. 18 Effect of intake planform area on C_m: $M = 0.5$, $\phi = 0$ deg, configurations 1–5.

the reference length for coalescing the normal-force and pitching-moment characteristics. The results of C_N and C_m are shown in Figs. 15 and 16 for Mach numbers of 0.5 and 3.0, respectively. The variation in total C_N and C_m is observed to be about ±5% at $\alpha = 10$ deg for the three roll angles. Similar trends are observed at Mach numbers of 0.8 and 2.0 also.

Method of Calculating Normal Force and Pitching Moment of Body-Intake Configurations

Experimental data of C_N are plotted against α for five cruciform body-intake configurations at Mach number of 0.5 and are shown in Fig. 17. A polynomial of degree 3 is fitted to the experimental data. Upper and lower limits are drawn respectively by adding and subtracting a value equivalent to 5% of C_N at $\alpha = 10$ deg to the experimental value. These limits are also shown in the same figure. We see that all experimental points are within these limits. The polynomial fit of degree 3 for C_m for the five cruciform configurations is shown in Fig. 18 for $M = 0.5$ along with 5% upper and lower limits. These polynomials can be used for estimation of C_N and C_m of any other similar body-cruciform intake configuration. The same procedure can be used for finding out the polynomials for body-twin intake configrations.

Conclusions

The normal-force and pitching-moment characteristics of different body-intake configurations coalesce when planform area and distance of centroid of planform area are chosen as reference parameters in nondimensionalizing. Similar trends are observed in the Mach-number range of 0.5–3.0. The method is validated with the experimental results available in the literature. The polynomials obtained by this method can be used for predicting the normal force and pitching moment of similar body-intake configurations.

Acknowledgments

The authors take pleasure in expressing their gratitude to officers and staff of 0.3 m Trisonic Wind Tunnel, National Aerospace Laboratories, Bangalore, for carrying out the experimental work described in this paper. The authors are also thankful to A. S. Narayana, Associate Technology Director, Aerodynamics, Defence Research and Development Laboratory, Hyderabad, for his support and encouragement in preparing this paper.

References

[1]Hayes, C., "Aerodynamic Characteristics of a Series of Twin-Inlet Air-Breathing Missile Configurations, Part II Two-Dimensional Intakes at Supersonic Speeds," NASA TM 84559, March 1983.

[2]Champigny, P., and Baudin, D., "Prevision des Coefficients Aerodynamiques de Missiles Munis de Prises d'Air," AGARD, CP 493, Oct. 1990.

[3]Jorgensen, L. H., "Prediction of Static Aerodynamic Characteristics for Slender Bodies Alone and with Lifting Surfaces to Very High Angles of Attack," NASA TR R-474, Sept. 1977.

[4]Panneerselvam, S., Theerthamalai, P., Balu, G., Sharma, R. K., and Balachandran, N., "Aerodynamic Prediction Code for Rapid Design and Analysis of Missile Configuration," *Journal of the Aeronautical Society of India*, Vol. 40, No. 4, 1988, pp. 229–241.

M. Miller
Associate Editor