PREDICTION OF INLET DRAG FOR AIRCRAFT CONCEPTUAL DESIGN

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Abstract

Recent efforts to upgrade the aircraft conceptual design program ACSYNT have resulted in a study of methods for inlet drag prediction. These methods enable the drag of four different inlet types (the subsonic pitot, supersonic pitot, supersonic 2-D and supersonic conical inlets) to be predicted over the complete operating range of the inlet. The methods, which have been incorporated into ACSYNT, are presented here, together with sample applications to different inlet geometries.

Nomenclature

A	area
$C_{D_{add}}$	additive drag coefficient
$C_{D_{DF}}$	disturbed flow drag coefficient
$C_{D_{inlet}}$	inlet drag coefficient
$C_{D_{lip}}$	lip wave drag coefficient
$C_{D_{NS}}$	normal shock drag coefficient
$C_{D_{prof}}$	cowl profile drag coefficient
C_{D_s}	cowl suction coefficient
$C_{D_{wave}}$	wave drag coefficient
D_{inlet}	inlet drag force
D	cowl diameter
F_f	force on the forebody
f_f	form factor
f_r	fineness ratio
K_{add}	factor used to determine spillage drag
K	coefficient in lip drag formulation; coefficient in form factor
L	cowl length
L_2	bow shock position
M	Mach number
MFR	Mass Flow Ratio
P	static pressure
$\frac{t}{c}$	thickness-to-chord ratio
q_∞	freestream dynamic head
α	factor used to determine spillage drag
β	factor used to determine spillage drag; exponent in shock expansion method
γ	ratio of specific heats
λ	flow angle at inlet throat
θ	forebody wedge angle (2-D inlet) or cone semi-angle (conical inlet)
ψ	exponent in shock expansion method

Subscripts

c	station at inlet capture face; cone segment
f	forebody
m	station at maximum cowl diameter
s	cowl surface, cowl segment
t	station at inlet throat
t	station at inlet throat
o	total
2	station downstream of normal shock
∞	station in upstream flow

Introduction

ACSYNT (AirCraft SYNThesis) is a computer program developed at the NASA Ames Research Center in the early 1970's for the purpose of aircraft conceptual design, synthesis and optimization. Although this code was originally written for batch-mode operation and required the tedious preparation of lengthy input files, such approaches are outdated in these days of powerful graphics workstations and 3-D graphics standards. Consequently, recent developments by the CAD/CAM laboratory at VPI & SU have greatly enhanced the processes of geometric modeling, data input and graphical post-processing for ACSYNT [1].

It has also become necessary to update the aerodynamic analysis within ACSYNT so that the effects of incorporating new geometric features on the aircraft will be reflected in the performance synthesis. Furthermore, since ACSYNT is a conceptual design code, it is preferable to perform an internal analysis rather than relying on experimental data. However, a judicious choice of methods is required to ensure that the analysis offers a "smooth" (but possibly derivative discontinuous) input to the optimizer. In addition, the aerodynamic analysis should also not place too great a demand on the resources of the workstation, particularly when the code is performing optimization.

Under certain flight conditions, inlet drag can potentially exceed 20 per cent of the total drag of an aircraft. Therefore, it is important to appropriately synthesize the inlet drag together with other propulsion system installation penalties. Propulsion system installation penalties have long been evaluated with the aid of computer programs (see [2], for example). However, such programs are often unwieldy, most require tabulated data proprietary to a specific organization, and they are best operated by propulsion specialists. On the other hand, the present work has enabled the level of the inlet drag analysis *within* ACSYNT to be extended beyond the first-order correction normally used in conceptual design studies, without placing unrealistic demands on the user.

ACSYNT orginally contained a simplified additive drag analysis for a supersonic inlet equipped with a conical forebody [3], combined with a simplistic profile and wave drag analysis of a podded engine nacelle. The present work resulted in the creation of alternative routines which are capable of predicting the drag of four different inlet geometries: a subsonic axisymmetric pitot inlet, a supersonic axisymmetric pitot inlet, a supersonic axisymmetric inlet with a conical forebody, and a supersonic 2-D inlet with a wedge forebody. The subsonic pitot inlet is assumed to be equipped with a cowl profile of the NACA 1-Series family, while the other inlets are all assumed to have parabolic profiles. A further assumption regarding the supersonic inlets equipped with forebodies is that they are two-shock inlets.

Any design analysis must, of necessity, be derived from prior detailed research. The present work has relied extensively on the standard texts on the subject of inlet drag prediction [4, 5], as well as other more detailed papers. The result of this work is a thorough analysis for a range of representative inlet types, covering the full range of operating conditions for each inlet.

Thrust Drag Accounting, Nomenclature and Definitions

To simplify the interaction between the aerodynamics and propulsion modules of ACSYNT, the inlet drag is charged directly to the uninstalled thrust, treating it as a propulsion system installation correction. The inlet drag coefficient is defined as

$$C_{D_{inlet}} = \frac{D_{inlet}}{q_{\infty}A_c} = C_{D_{spill}} + C_{D_{wave}} + C_{D_{prof}} \qquad [1]$$

where $C_{D_{spill}}$, $C_{D_{wave}}$ and $C_{D_{prof}}$ are the spillage, profile and wave drag coefficients for the inlet, respectfully. Each of these coefficients corresponds to the respective drag force, non-dimensionalized by the product of the freestream dynamic head ($q_{\infty} = \frac{1}{2}\gamma P_{\infty}M_{\infty}^2$) and the inlet capture area, A_c. Clearly, these terms may have zero magnitudes, depending on the inlet operating conditions.

Spillage drag is the drag force associated with the excess air spilled around the inlet whenever the engine mass flow demand is less than the maximum which could be accomodated by the inlet at that flight Mach number. In this case, the *mass flow ratio* (MFR), defined as $MFR = \frac{A_{\infty}}{A_c}$ is less than unity (see Figs. 1 and 2). It is common practice to represent spillage drag as a function of the additive drag, which represents the streamwise component of the pressure force acting on the inlet capture streamtube.

The profile drag is the combination of skin friction and form drag, while the wave drag is the increased pressure drag due to the advent of localized or global supersonic flow. These drag coefficients are calculated for the full-flow condition ($MFR = 1$). The deviation from the full-flow drag, known as cowl suction, is implicitly estimated as part of the spillage drag.

Additive Drag

As mentioned above, since spillage drag is commonly expressed as a function of additive drag, the additive drag must be evaluated. Irrespective of the inlet type, the additive drag is defined as

$$D_{add} = \int_{\infty}^{c} (P - P_{\infty})dA \qquad [2]$$

Subsonic and Supersonic Pitot Inlets

In order to evaluate the additive drag given by Eqn. [2] for pitot inlets, a mass and momentum balance is applied across a control volume bounded by a station far upstream, the inlet capture face, and the bounding stream tube (Fig. 1). Assuming that the flow is one-dimensional, this yields the following expression for the additive drag coefficient:

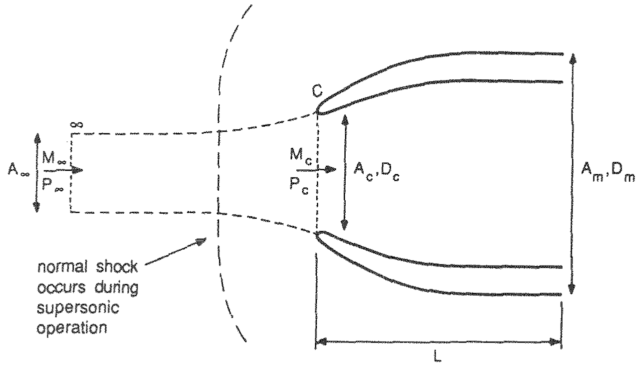

Figure 1. Pitot Inlet Nomenclature

$$C_{D_{add}} = \frac{[P_c\gamma M_c^2 + (P_c - P_{\infty})]A_c - P_{\infty}\gamma M_{\infty}^2 A_{\infty}}{q_{\infty}A_c} \qquad [3]$$

For subsonic operation, an isentropic compression is assumed to occur from far upstream to the inlet plane, enabling the pressure and Mach number at the plane of the inlet capture face, P_c and M_c, to be calculated.

For supersonic operation, a normal shock occurs between the upstream station and the inlet plane. In this case, the pressure and Mach number downstream of the normal shock are used in an isentropic expansion to obtain the conditions at the inlet capture face.

The results of this closed-form expression, for a range of freestream Mach numbers and mass flow ratios, are shown graphically in [6].

Supersonic Forebody Inlets

The evaluation of $C_{D_{add}}$ for supersonic forebody inlets proceeds just as with the pitot inlets. However, in this case, the control volume also has the forebody surface as one of its boundaries (Fig. 2). Therefore,

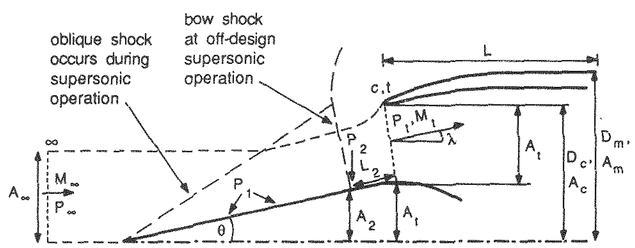

Figure 2. Forebody Inlet Nomenclature

the expression for additive drag is written as

$$C_{D_{add}} = \frac{F_f + [P_t\gamma M_t^2 + (P_t - P_{\infty})]A_t - P_{\infty}\gamma M_{\infty}^2 A_{\infty}}{q_{\infty}A_c} \qquad [4]$$

The additional term in this expression, F_f, is the force on the forebody. This must be evaluated in a manner suited to the freestream Mach number, and here the suggestions of [6] are followed.

1. For *subsonic operation*, the conditions at the inlet throat (which corresponds with the capture plane given that it is a two-shock inlet) are calculated with the assumption of 1-D isentropic flow,

as with the pitot inlet. The forebody force is then

$$F_f = [\,½(P_\infty + P_t) - P_\infty]A_f \qquad [5]$$

This relationship assumes that the mean pressure on the forebody is the arithmetic average of the freestream pressure and the pressure at the throat.

2. For *transonic operation*, the detached forebody shock is assumed to be a normal shock. The conditions at the inlet throat are evaluated by assuming an isentropic compression from the conditions downstream of this detached shock to the throat. The mean forebody pressure is taken to be the average of the pressure immediately downstream of the shock (P_2) and that at the throat, so that

$$F_f = [\,½(P_t + P_2) - P_\infty]A_f \qquad [6]$$

3. During *supersonic operation*, an oblique (for the 2-D inlet) or a conical (for the conical inlet) shock will form from the tip of the forebody. Additive drag can arise in two ways. At off-design Mach numbers, the shock will deflect the bounding streamline and, at mass flow ratios less than unity, a bow shock forms, giving rise to a subsonic portion of the bounding streamline. In the supersonic region of the flow, the forebody pressure is easily calculated for the 2-D case, or obtained from tables [8] for the conical case. The ramp pressure in the subsonic region is assumed to be the average of the pressure immediately downstream of the bow shock and the inlet throat pressure.

Given the pressure at the throat (P_t), the pressure immediately downstream of the bow shock (P_2), and the bow shock position (L_2), the force on the forebody is approximated by

$$F_f = [\,½(P_t + P_2) - P_\infty](A_f - A_2) + (P_1 - P_\infty)A_2 \qquad [7]$$

Due to the obvious differences in the flowfields, separate approaches must be taken to estimate P_t, P_2 and L_2 for the 2-D and conical inlet types. In both instances, the assumption is made that the two shocks intersect outside the streamline that bounds the entering flow.

2-D Inlet: The bow shock is generally assumed to be a normal shock. Hence, the pressure immediately downstream of the bow shock is easily estimated using normal and oblique shock relations. The throat pressure is obtained as before by assuming an isentropic expansion. The bow shock position of must be obtained empirically. Empirical relationships [9, 10] may be used to obtain the bow shock position as a function of Mach number and mass flow ratio, also taking into account the effect of sideplate geometry.

Conical Inlet: The conical flow field presents special problems, since the Mach number in the region downstream of the forebody shock is non-uniform. Following a suggestion in [5], the forebody shock is assumed to be a normal shock occurring at a Mach number which is the arithmetic average of the Mach number on the forebody cone surface, and that immediately downstream of the conical shock — both of which can be obtained from tables [8]. The throat Mach number can then be estimated as before. The forebody shock location must again be obtained from empirical relations, and here [11] is the source.

In the case of the conical inlet, these approximations do not necessarily result in zero additive drag at the inlet design point. To meet this criterion, the flow angle at the throat may be chosen to give an appropriate throat area. However, this approach necessitates an iterative solution because the throat Mach number and pressure are also functions of the throat area. A simpler approximation is to assume a throat flow angle based on geometrical considerations (say $\lambda = \theta$) for estimating the throat conditions, and then use a slightly different throat area to obtain zero additive drag at design point. The minor inaccuracy thus introduced is generally negligible for a conceptual design analysis.

Spillage Drag

Subsonic Pitot Inlet

The formula proposed by [12] is used to obtain the subsonic spillage drag from the additive drag:

$$C_{D_{spill}} = K_{add} C_{D_{add}} \qquad [8]$$

This representation is criticized by [4] because K_{add} is seen to vary with cowl geometry, flow ratio and Mach number. However, [12] presents graphical design correlations for K_{add}, as a product of coefficients derived from data accumulated from NASA and Rolls-Royce experiments on NACA 1-Series cowls. Since the NACA 1-Series cowl is intended primarily for low Mach number operation, transonic and supersonic data is scarce. However, [4] observes that there is minimal additive drag recovery for Mach numbers around 2 or greater, and the spillage drag coefficient varies approximately linearly with Mach number in the transonic range. By fixing the mass flow ratio and allowing the spillage drag to vary from its estimated value at Mach 1 to the additive drag at Mach 2 for that flow ratio, excellent agreement with the sparse experimental data is achieved.

The prediction of the critical mass flow ratio, MFR_{crit}, which is the mass flow ratio below which the subsonic spillage drag becomes significant, is again based on a correlation. This is presented by both [4] and [13] as a function of the cowl geometry.

Supersonic Pitot Inlet

In the absence of extensive data for this slender-cowled pitot inlet, the method suggested by [4] is used.

Before discussing the method of spillage drag estimation, it is useful to divide the additive drag into two components. The additive drag is divided into a *disturbed flow drag* and a *normal shock drag*. The disturbed flow drag is the drag associated with the separation of the flow at the cowl lip. In subsonic flow, this is equal to the additive drag, while in supersonic flow, the disturbed flow drag coefficient is

$$C_{D_{DF}} = \frac{[P_c\gamma M_c^2 + (P_c - P_2)]A_c - P_2\gamma M_2^2 A_\infty}{q_\infty A_c} \qquad [9]$$

where M_2 and P_2 represent the conditions immediately downsteam of the (normal) bow shock.

The normal shock drag is related to the pressure rise across the bow shock, and is the difference between the additive drag and the disturbed flow drag in a supersonic flow. The normal shock drag coefficient may be written simply as

$$C_{D_{NS}} = \frac{(P_2 - P_\infty)(A_c - A_\infty)}{q_\infty A_c} \qquad [10]$$

The spillage drag coefficient is then written as

$$C_{D_{spill}} = \alpha C_{D_{DF}} + \beta C_{D_{NS}} \quad [11]$$

where α and β are coefficients derived from experimental corelations, and suggestions for their values as a function of Mach number and cowl initial slope are presented by [4]. In [4], a suggestion is made that $C_{D_{DF}}$ be neglected for Mach numbers greater than 1.8. However, since this quantity decreases asymptotically to zero as Mach number increases, it was preferable not to introduce a discontinuity into the drag prediction by neglecting $C_{D_{DF}}$. The result does not differ significantly from the original formulation, yet maintains a smooth prediction compatible with the optimization routine of ACSYNT.

Supersonic 2-D Inlet

The spillage drag coefficient for the supersonic 2-D inlet is obtained by subtracting the cowl suction coefficient from the additive drag coefficient. The cowl suction coefficient is obtained from the corelations derived by [9] from the data of [4]. These correlations are presented as functions of cowl thickness-to-chord ratio, cowl lip radius, ratio of inlet capture area to cowl maximum area, mass flow ratio, ratio of inlet capture area to throat area, and throat Mach number for freestream Mach numbers of 0.692, 0.845, 1.093, 1.294, 1.393 and 1.687. The cowl suction coefficients for intermediate freestream Mach numbers are obtained by linear interpolation. For Mach numbers outside the range give, the assumption is made that the cowl suction varies linearly to zero at Mach numbers of 0 and 2.

Supersonic Conical Inlet

In the absence of suitable experimental correlations, a spillage drag model for the supersonic conical inlet was based on the one used for the supersonic pitot inlet, since both inlet types which were assumed to have sharp-lipped cowls with parabolic profiles. Using Eqn. [10] the spillage drag for supersonic operation is given as

$$C_{D_{spill}} = \alpha C_{D_{add}} \quad [12]$$

For transonic operation, the detached forebody shock is assumed analogous to the bow shock of the pitot inlet, even though in reality it will not be a normal shock and it will cause the bounding streamline to deflect. A disturbed flow drag may then be derived which is analogous to that of the pitot inlet as

$$C_{D_{DF}} = C_{D_{add}} - \frac{(P_2 - P_\infty)A_t + (P_\infty M_\infty^2 - P_2 M_2^2)\gamma A_\infty}{q_\infty A_c} \quad [13]$$

By assuming that $\beta = 1$ in Eqn. [10] (the most conservative approach), the transonic spillage drag coefficient is then given by

$$C_{D_{spill}} = (\alpha - 1)C_{D_{DF}} + \beta C_{D_{add}} \quad [14]$$

For supersonic freestream flow, it is assumed that the sharp cowl lip will always result in separation, and that no cowl suction is recovered. In this case then, the spillage drag will be equal to the additive drag.

Cowl Wave Drag

Subsonic Pitot Inlet

The drag-rise Mach number at the full flow condition for the subsonic pitot inlet is given as a correlation by both [4] and [13]. A further correction given by [13] allows the prediction to be adjusted as the mass flow ratio is varied. Subsonic wave drag is also predicted by a correlation from [13], presented as a function of freestream Mach number, drag-rise Mach number and the additive drag estimated both at the freestream Mach number and the drag-rise Mach number.

Even though this inlet type is primarily intended for subsonic operation, a method for estimating supersonic wave drag is still required. Due to the lack of experimental data and complexity of transonic flow solvers, a prediction method was sought that was not necessarily accurate, but would at least indicate to the designer whether the flight Mach number is incurring an excessive cowl drag penalty.

The method recommended by [4] for the wave drag of a blunt circular-arc lip added to a slender cowl, based on Newtonian theory, gives the following lip drag coefficient:

$$C_{D_{lip}} = \frac{(KP_{o,2} - P_\infty)A_{lip}}{q_\infty A_c} \quad [15]$$

where $P_{o,2}$ is the total pressure downstream of a normal shock occurring at the freestream Mach number, and K is a linear function based on the ratio of maximum cowl projected area (A_m) to the area of the inlet capture face (A_c). A correlation for K is presented by [4]. The lip of the NACA 1-Series cowl is taken as that portion of the cowl which has a slope of less than 10°.

Supersonic 2-D Inlet

For supersonic Mach numbers where an oblique shock is assumed to be attached to the cowl lip at the full flow condition, the well-known 2-D shock-expansion method is employed. In this method, the cowl is divided up into discrete segments. Oblique shock relations enable the pressure on first segment to be estimated, and then a Prandtl-Meyer expansion is assumed as the flow turns from one segment to another. Integration of these pressures enables the wave drag to be easily calculated.

For transonic Mach numbers, the cowl is approximated as a wedge, and the transonic similarity laws of [15] are used to derive a drag coefficient. The equivalent wedge angle angle (η_w) for the curved cowl was given by the following weighted average:

$$\eta_w = \frac{(\eta_c + 2\eta_m)}{3} \quad [16]$$

where η_c is the cowl initial slope, and η_m is the cowl slope that would be obtained if the cowl was wedge shaped. This average was derived from numerical experiment, and may have to be adjusted for alternative cowl profile families. However, a linear weighting was also applied to the transonic wave drag to ensure that it blended with the supersonic prediction without discontinuity, and this helps to compensate for for any errors introduced by the assumed equivalent wedge angle.

Supersonic Pitot and Conical Inlets

The modified shock expansion method of [14] is similar to the two-dimensional shock expansion method, except that the pressure after the initial expansion on each cowl segment (P_s) is allowed to fall exponentially to the pressure ,P_c, that would be experienced by a cone of the same local slope for the same Mach number. The simplest variant of the method is termed the *two-step* method, where the pressure distribution on the nth cowl segment is approximated by

$$P_n = P_c + (P_s - P_c)e^{-\beta\psi} \quad [17]$$

where β is a function of cowl radius, distance along the cowl segment, and local cowl angle relative to initial cowl slope; and ψ is a function of local cowl angle, initial cowl angle, $(P_s - P_c)$, the Mach number downstream of the oblique shock, and the Mach number calculated by the Prandtl-Meyer expansion from the initial cowl angle to the local cowl angle. This method gives excellent agreement with the full second-order theory as long as the cowl is curved. If the cowl is conical, however, the parameter ψ is zero, and the method reverts to first order. This was not considered a serious problem for the present work, since the cowl shapes were generally assumed parabolic, and this method was therefore adopted as providing the best compromise between simplicity and accuracy.

Since shock expansion methods depend on the existence of an attached shock at the cowl lip, this method only holds for high Mach numbers (2 or greater) when the cowl slope is high (say 20°). For this reason, the closed-form slender body solution of Willis and Randall for parabolic cowls [4] was used for lower supersonic Mach numbers and this, in turn, has an upper limit of validity when the freestream Mach angle approaches the maximum slope of the cowl. This solution was adjusted using a linear weighting function to ensure that the two solutions matched in the Mach number region of overlapping validity.

In the absence of suitable theory or correlations in the transonic range, the slender body solution was used for Mach numbers close to unity. Subsonic drag rise is approximated by assuming a fixed drag-rise Mach number, and allowing the predicted drag to increase linearly from zero at the drag-rise Mach number to a peak at Mach 1.05. This peak is calculated with the Willis and Randall method for Mach 1.1, and is kept constant for $1.05 \leq M_\infty \leq 1.1$ The result is a transonic behavior which is at least qualitatively close to that observed for slender bodies.

Cowl Profile Drag

In each case, the profile drag coefficient is estimated by combining an appropriate form factor with a suitably estimated skin friction coefficient (C_f), so that

$$C_{D_{prof}} = C_f f_f \frac{A_s}{A_c} \qquad [18]$$

where f_f is the form factor and A_s is the cowl surface area.

Subsonic Pitot Inlet

For the subsonic pitot inlet, a form factor from [12] is used. This is

$$f_f = \frac{1}{K_o}\left[1 + 0.33K\frac{\left(1 - \frac{D_c}{D_m}\right)}{\frac{L}{D_m}}\right]^{1.667} \qquad [19]$$

Here, K is a function of the mass flow ratio and the cowl area ratio $\frac{A_m}{A_c}$ and K_0 is a function of the cowl diameter and length-to-diameter ratios. Both K and K_0 are presented graphically by [13].

Supersonic 2-D Inlet

For the supersonic 2-D inlet, a form factor commonly used for wing sections is employed,

$$f_f = 1 + \frac{t}{c} + 100\left(\frac{t}{c}\right)^4 \qquad [20]$$

where $\frac{t}{c}$ is the cowl thickness-to-chord ratio.

Supersonic Pitot and Conical Inlets

The form factor used for these inlet types is

$$f_f = 1 + 3f_r^{-\frac{3}{2}} + 7f_r^{-3} \qquad [21]$$

where the fineness ratio, f_r is given by

$$f_r = \frac{5}{3}\frac{L}{D_m} + 1 \qquad [22]$$

This was obtained from the original ACSYNT source code and is thought to come from aircraft conceptual design course notes prepared by Professor R. S. Shevell of Stanford University.

Results

The results of applying the methods described herein can, in general, be validated by the data from which they were derived. The question arises, however, as to how well the calculation methods will perform in the prediction of the drag of inlets other than those used as a basis for the development of the correlations.

Test cases consisting of the calculation of the total inlet drag of a supersonic 2D inlet, the total inlet drag of a supersonic conical inlet, and the spillage drag of a supersonic pitot inlet were computed. The first two test cases were run with externally set values of the inlet dimensions and operating conditons. The third case was run as a part of a mission cycle analysis using ACSYNT to simulate the engine mass flow requirements.

The fact that these geometries differ from the simple inlet configurations for which the code has been developed means that it is perhaps unreasonable to expect close agreement, especially in view of the empirical nature of the calculation methods.

2-D Three-Shock External Compression Inlet

An inlet model with varying ramp configurations was tested by [16]. Although nominally a four-shock inlet, in its simplest configuration it performed as a three-shock inlet with ramp angles of 7° and 11°. This inlet was also equipped with a wedge-shaped lower cowl with a 4° wedge angle. The inlet was modeled by treating it as a two-shock inlet with a forebody ramp angle of 7°. This also gave a different inlet throat area than the test configuration.

The results of this calculation are shown in Fig. 3 for freestream Mach numbers of 0.85, 1.2 and 1.39. The results for $M_\infty = 0.85$ show very good agreement with the data, although the predicted gradient of the variation of drag with mass flow ratio is higher than that of the test data. This is to be expected in all cases due to the difference in the throat area between the test and the calculated configurations. The level of the drag prediction is also satisfactory. The two components of the inlet drag which would contribute to this level, the profile and the subsonic wave drag, are therefore in reasonable agreement with the experimental data.

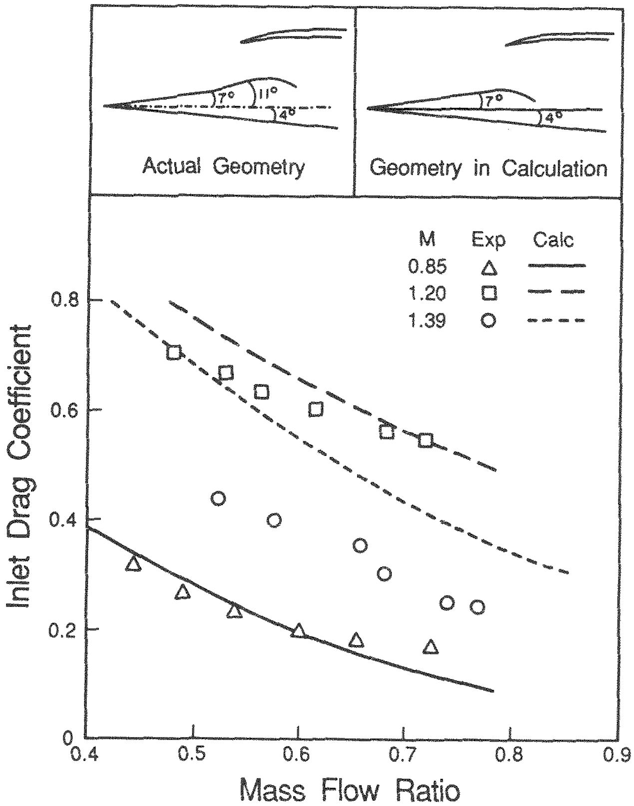

Figure 3. Inlet Drag Coefficient for a 3-Shock, 2-D Inlet

The transonic case ($M_\infty = 1.2$) also exhibits good agreement, in spite of the simplifying assumptions made in the transonic additive drag analysis. As mentioned, the slope of the drag prediction is understandably higher than the data.

The supersonic case ($M_\infty = 1.39$) shows the poorest agreement with the experimental data. Unexpectedly, the slope of the drag prediction matches the data very well, but the absolute level reflects as much as a 40% overprediction. This discrepancy is a probable result of the favorable effect of the mutiple forebody shocks on the spillage drag; an effect which is not captured by the calculation.

Conical Mixed-Compression Inlet

Inlet drag data for tests on an axisymmetric, mixed-compression inlet with a design Mach number of 2.7 and a forebody cone angle of 20° are presented by [17]. These tests were run at freestream Mach numbers of 0.7, 0.9, 1.05 and 2.00. In the calculations the centerbody was moved from its actual position in order to produce an external-compression inlet equivalent to the original mixed-compresion geometry. Figure 4 shows that, for all Mach numbers, the drag is greatly overpredicted. For supersonic flow, this overprediction can be explained in terms of the effect of the compression being mixed, which will reduce the displacement of the bow shock ahead of the inlet capture face. The discrepancy in the transonic case is most likely due to the throat area which could not be faithfully modeled by a two-shock inlet configuration.

Interestingly, scaling the drag prediction by a factor of 0.6 results in an acceptable prediction. This practice is common in conceptual design, and provides the means by which a mixed-compression inlet geometry can be approximated by the simpler two-shock inlet.

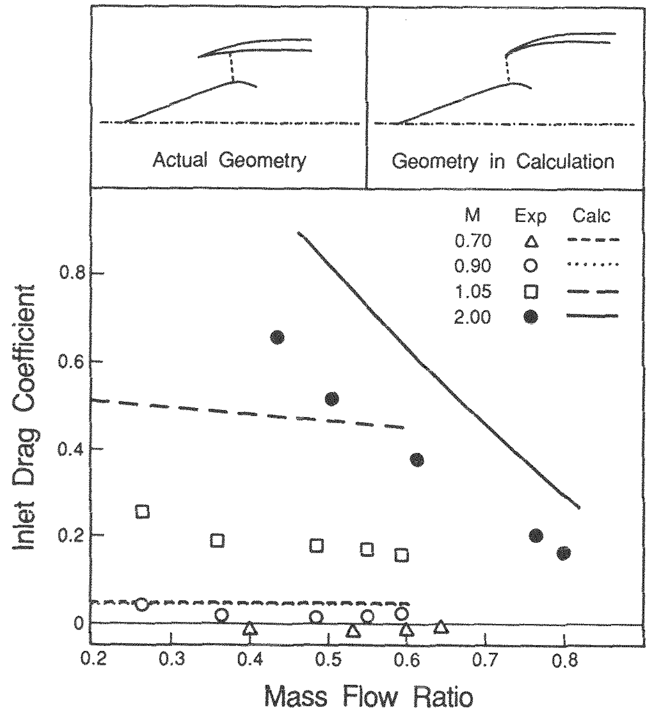

Figure 4. Inlet Drag Coefficient for a Mixed-Compression Conical Inlet

F-16 Inlet Spillage Drag

To test the effectiveness of the new methods within ACSYNT, the F-16 was synthesized, modeling the oval-shaped, chin-mounted inlet as a semicircular supersonic pitot inlet. The resulting spillage drag distributions are shown in Fig. 5 compared to the data of [19].

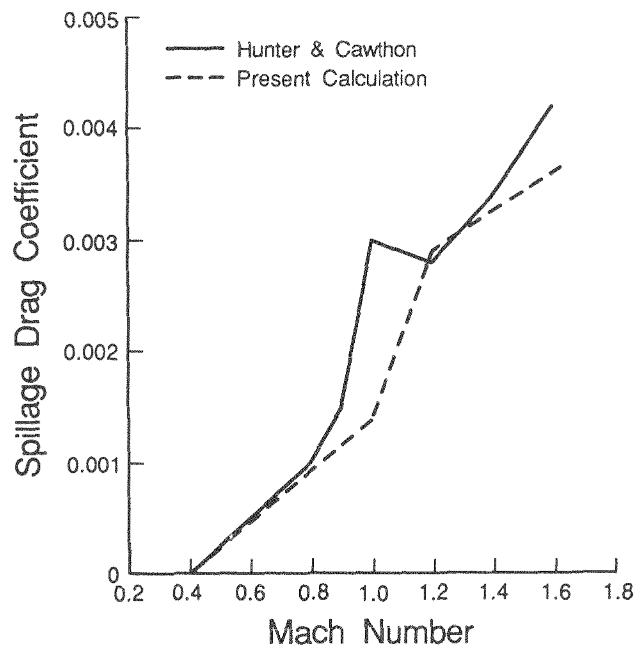

Figure 5. Spillage Drag Coefficient for the F-16 Inlet

The new inlet drag calculations are remarkably successful in modeling the F-16 inlet. The major discrepancy occurs in the transonic region, and it is likely that this is due to a weakness in the spillage drag model for this difficult-to-handle Mach number range. The underprediction in the supersonic region could be due to an error in the inlet sizing, since the predicted trend indicates that the drag coefficient is nearing its design point more rapidly than the data.

Conclusion

Drag prediction methods have been presented for four different inlet geometries, covering the full operating range of the inlet types. These methods are suitable for aircraft conceptual design, and have been demonstrated to exhibit the required trends for predicting the inlet drag coefficient as Mach number and mass flow ratio are varied.

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