Spillage Drag Estimation and Drag-Thrust Accounting for a Missile with Air Breathing Propulsion

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Air intake related aerodynamic aspects of an air breathing cruise missile are analyzed.

A method for thrust and drag accounting is established, and, based on that, a partial simulation model for the thrust and intake spillage drag force of the missile is developed. The model combines wind tunnel data with analytical data.

The intake spillage force has two components, pre entry force and cowl force. The pre entry force can be computed relatively easily, while the cowl force depends strongly upon actual intake geometry and no general method exists. An approximate cowl force is computed based on available data.

The accuracy of the cowl drag results is difficult to predict, as no complete theoretical model is available, and the partial models published cite no accuracy limits. The cowl drag results need further verification through wind tunnel tests or CFD analysis.

However, spillage force results are produced that are in the magnitude of 30% of total drag, which is expected. Also, dependencies on known variables and trends are as expected.

Finally, flight test profiles in order to validate the model are suggested.

Nomenclature

This is not a complete nomenclature, as sparsely used terminology is described in the text. Some terminology frequently reoccurs and is defined here.

Coordinate system

A body-fixed three axis coordinate system is used. For its orientation in relation to the missile, refer to Fig. 1. The axial force X is defined as parallel with and along the negative X_b-axis.

Unless otherwise stated, all and any computations and definitions are made with reference to the axes of the body-fix coordinate system.

A	Area [m^2]
C	with a suffix indicates a dimensionless aerodynamic coefficient
D	Drag - component of R acting along the negative X_w-axis aka relative wind [N]
F	Thrust force or component thereof. Assumed to act along the positive X_b-axis [N]
L	Lift - component of R acting along the negative Z_w-axis [N]
M	Mach number [-]
m_R	Flow ratio, $m_R = A_0/A_1$ [-]
N	Normal force, component of R acting parallel to the negative Z_b-axis [N]
Pt	Total pressure or stagnation pressure [Pa]
p	Static pressure [Pa]
q	Dynamic pressure, $q = 1/2\rho V^2$ [Pa]
$\bar{R}$	Resultant force that acts on the entire airframe or section thereof [N]
Re	Reynolds number [-]

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S_{ref}	Reference area [m^2]
V	Air velocity, true airspeed (TAS), along the positive X_w-axis [m/s]
X	Axial force, component of R acting along the negative X_b-axis [N]
α	Angle of attack, the angle between the X_b-axis and the relative wind, in the plane defined by the plane spanned up by the X_b and the Z_b axis [°]
β	Angle of side slip (the angle between the X_b-axis and the relative wind in the Y-plane) [°]
ρ	Air density [kg/m^3]
~	Proportionality (e.g. force ~ V^2)

To describe important stations in the airflow duct, Seddon[1] is used. This includes four stations, see fig 2.

0 (∞)	undisturbed free-stream flow, ahead of the intake duct
1 (c)	duct entry or capture
2 (f)	engine face
3 (e)	duct exit in the meaning jet engine exit, jet engine exhaust, or nozzle

Subscripts

cr, 1	Critical Mach number at station 1 - Mach number at which shock waves start occurring [-]
D	Drag
d	Drag rise (due to Mach)
f	friction
L	Lift
N	Normal force
p	Pressure
pre	pre entry
X	Axial force

Introduction

CRUISE missiles are rarely tested in a configuration that is useful for determining the relative contributions from drag, air intake performance and jet engine performance to overall thrust/drag modeling. It is thus of interest to be able to use the available wind tunnel data, jet engine data and air intake data to develop a valid simulation model for a generic missile similar to the Kongsberg Joint Strike Missile (JSM).

A description of the JSM missile can be found on the manufacturer's homepage[2].

This work aims at establishing a method for thrust and drag accounting; produce a valid thrust and axial force partial simulation model by combining wind tunnel data and analytical methods; and suggest ways of performing flight tests in order to validate the model.

In aircraft with fuselage-mounted jet engines, coupling exists between the internal aerodynamic flow through the intake and the engine, and the external flow along the outside of the fuselage[3]. This coupling may be described as a throttle-dependent drag force named spillage drag. Establishing a model for spillage axial force will be the core objective in this report.

This process has most probably been executed numerous times in the past by various airframe makers, but the results are generally not published. Instead, they are kept within the company as proprietary information. A number of good references exist, and these are referred to numerous times in the text. However, most such references focus on typical subsonic airliner pod-mounted engine installations, or, with fuselage-mounted engines, focus primarily on supersonic conditions. Since no published general method has been found, certain aspects of this report attempts to establish a method that is specific to the test case at hand.

Method

Two main methods are used. Firstly, wind tunnel tests have been performed outside the scope of this report, and are used as a data source. Three sets of data exist, all supplied by the airframe manufacturer:

- Data of the entire airframe, with air intakes closed and covered with an aerodynamic fairing, referred to as faired intakes. This includes drag data.
- Wind tunnel intake test data, but not drag data
- Engine data, installed and uninstalled

Secondly, a literature study is undertaken with the aim of establishing axial force components analytically based on available theory and, where applicable, certain wind tunnel data. This will include computing intake drag data from the intake wind tunnel data, intake dimension data, and engine mass flow data. Next, the faired intake wind tunnel data and intake drag analytical data is combined to yield a more complete drag model.

To perform the necessary computations, Matlab is used as a tool. A Matlab script, using wind tunnel data, flight condition data and airframe dimension data as inputs, performs numerical analytical computations, combines these results and provides axial force data as output.

Limitations

A speed range from Mach 0,6 to slightly below 1 is investigated. This may include intake lip shock. The altitude range is from sea-level to 20000 feet or approximately 6500 meters.

All flows are assumed to be one-dimensional homogeneous unless otherwise stated.

Model

Wind tunnel drag data with faired intakes is used as a reference condition. Throttle-dependent drag forces are computed in the model and added to the reference.

Drag accounting system, Bookkeeping

The forces necessary to incorporate into a valid model must be identified and denoted. Determining the magnitude of these forces will be done in later sections in this report, including any dependence on throttle setting.

All the forces allocated to THRUST and to DRAG must be accounted for once and only once. Generally, internal forces (inside intake duct, engine and nozzle) are accounted as thrust, while external forces (outside of intake duct, cowling, fuselage and nozzle) are accounted as drag. The system of Rooney[4] is used:

$$F_{ex} = [F_n + \Delta F_{inl} + \Delta F_{exh} + \Delta F_{trim}] - \left[D_{ref} + \Delta D_{inl} + \Delta D_{exh} + \Delta D_{trim} + \Delta D_{rn}\right]. \tag{1}$$

The first parenthesis is referred to as installed net thrust, F_{ipf} ; the second parenthesis as airframe system drag, D_{afs} . Incremental forces (denoted by a preceding Δ) are assumed to be zero at a certain reference flow ratio, normally assumed to be 1. These forces are referred to as throttle-dependent. According to Rooney[4], for buried (not pod-mounted) engine installations, the effects of the intake and exhaust nozzle can be measured separately and within ideal angles of attack combined linearly. This assumption is utilized in the following.

Thrust forces

F_n	installed engine net thrust. Given as an input variable.
ΔF_{inl}	throttle-dependent force increment due to change in intake condition. Includes pre-entry thrust, which is the propulsive force that the internal fluid exerts on the boundary of the pre-entry stream tube[5]. Also includes thrust variation due to pressure recovery variation.
ΔF_{exh}	throttle-dependent force increment due to change in exhaust condition. Not treated in this study.
ΔF_{trim}	throttle-dependent force increment due to change in trim condition. Not treated in this study.

Drag forces, axial forces

As the term drag is not used, the terminology is converted into equivalent components of axial force X.

$D_{ref} \rightarrow X_{ref}$	full scale reference axial force. Given as an input variable from wind tunnel tests. Includes intake axial force in the reference condition.
$\Delta D_{inl} \rightarrow \Delta X_{inl}$	force increment due to change in intake condition, normally and most significantly mass flow ratio. Includes spillage axial force which is derived from pre-entry drag (additive drag) + cowl suction (lip suction or cowl drag).
$\Delta D_{exh} \rightarrow \Delta X_{exh}$	force increment due to change in exhaust condition. Not treated in this study.
$\Delta D_{trim} \rightarrow \Delta X_{trim}$	force increment due to change in trim condition. Not treated in this study.
$\Delta D_{rn} \rightarrow \Delta X_{rn}$	force increment due to model-full scale Re effects.

The forces defined above have their origin in certain defined areas around the air intake. The influenced physical areas of some of these forces are shown in Fig. 3.

Reference force X_{ref}

The faired intake wind tunnel test provides a reference axial force to which the throttle-dependent forces will be added. An illustrative reference axial force is shown in Fig. 4.

Determining the throttle-dependent forces

The throttle-dependent forces will be developed by analyzing the experimental data and applying analytical methods to obtain a model. An important step is to express the intake axial force as a function of given or set parameters, as wind tunnel drag data does not exist. First, some basic concepts are explained.

Flow ratio m_R

The air intake allows a certain amount of the approaching air to enter. This relation between free stream condition and intake capture condition is called flow ratio, m_R , also known as C_A or ε. In incompressible flow, flow rate is defined as

$$m_R = \frac{V_1}{V_0}. \tag{2}$$

This definition is not valid in compressible flow, but may still aid in understanding the concept of m_R . In compressible flow, m_R is expressed by the ratio between upstream infinity stream tube area and capture area, defined as

$$m_R = \frac{A_0}{A_1} = \frac{\rho_0 V_0 A_0}{\rho_0 V_0 A_1} = \frac{\dot{m}}{\rho_0 V_0 A_1}. \tag{3}$$

The free stream area A_0 can be described as the area of the stream tube actually entering the intake. The value of A_0 is not fixed but is related to engine airflow requirements, hence flow ratio varies from 0 to above 1; Hoerner[6] suggests 0,6-1,6. Normal cruise condition is below 1. m_R above 1 usually occurs only at take off or other high throttle low speed conditions and is not treated in this report.

A typical scoop intake produces approximately zero drag at $m_R = 1$. In the prevailing situation of $m_R < 1$ there is drag produced due to spilling. This drag may become significant at m_R below 0,6[7].

Pressure recovery P_R

Pressure recovery is the ratio between average total pressure at engine face and the free stream total pressure. It is also described as recovery ratio, η_{in} or intake efficiency[8], or as the ratio of total energy available converted to compression in the intake. It is defined as[9]

$$P_R = \frac{Pt_2}{Pt_0}. \tag{4}$$

Pressure recovery is not a direct throttle-dependent force. It is, however, an indirect result of changing engine mass flow. Any change in pressure recovery will cause (and hence be accounted as) a change in installed engine thrust as a component of ΔF_{inl}.

ΔX_{inl} – axial force due to intake conditions

The incremental force ΔX_{inl} contains axial force corrections necessary to modify the force measured on a faired-intake wind tunnel model into full scale axial force, excluding effects of trim, Re and exhaust plume. A schematic air intake with some dimension parameters is shown in Fig. 5.

Reference drag and drag due to change from that reference condition may be separated and written as[10]

$$D = \left(D_f + D_p\right)_0 + \Delta D_0 + D_{pre}. \tag{5}$$

These terms can be translated into the terms used in the thrust-drag model. The effects of the plume are disregarded, setting $\Delta D_{exh} = \Delta X_{exh} = 0$. The remaining expression is divided in two parts, one part with reference drag D_{ref} independent of m_R and the second part ΔD_{inl} depending on m_R . This gives

$$\Delta D_0 + D_{pre} = \Delta D_{inl} \tag{6}$$

and

$$\left(D_f + D_p\right)_0 = D_{ref}. \tag{7}$$

The total drag D can then be written as

$$D = D_{ref} + \Delta D_{trim} + \Delta D_{rn} + \Delta D_{inl}. \tag{8}$$

Disregarding the effects of trim drag and Re gives

$$D = D_{ref} + \Delta D_{inl} \tag{9}$$

which can be translated into the body fix coordinate system, as

$$X = X_{ref} + \Delta X_{inl} \tag{10}$$

where

$$\Delta X_{inl} = X_{spill} \tag{11}$$

and X_{spill} is spillage axial force, defined below and used in the following.

Spillage axial force X_{spill}

Spillage axial force is the inlet force due to m_R different from the reference condition. Slightly simplified, at $m_R < 1$ the engine is using less air than the intake is designed for. Air is then spilled from the intake and into the external airflow, causing the spillage force. X_{spill} is defined as

$$X_{spill} = \Delta X_0 + X_{pre} \tag{12}$$

where ΔX_0 is cowl axial force (aka lip suction, cowl suction), normally negative. The magnitude of cowl axial force depends on installation geometry, and without test data or accurate CFD data it can only be estimated. X_{pre} is pre-entry axial force (aka additive force), normally positive. The physical limit between these two forces is the inlet stagnation points around the intake circumference. This stagnation point is not stationary, it will shift with m_R and α, for instance, and the line connecting the stagnation points may be curved. For simplicity, this is approximated by the capture plane which is used in the following.

Pre-entry axial force X_{pre}

Pre-entry axial force is the loss in momentum from free stream to the intake entrance for the particular amount of air included in A_1. To quote Osmon[11] : “Additive (pre-entry) drag is not a drag in the ordinary sense. It is a simple but often misunderstood accounting method that corrects the net thrust as a function of engine operation and actual or presumed inlet flow conditions”.

One has that

$$X_{pre} = C_{Xpre} q_0 A_1. \tag{13}$$

To get an overview of the mechanisms behind this force, a stream tube analysis is useful. In Fig. 6, the air intake is shown schematically (compare with Fig. 2) along with a stream tube control volume typical for $m_R < 1$. At station 0, free stream conditions prevail, described by p_0 T_0 V_0 and ρ_0 .

Inside the control volume, mass is conserved and mass flow rate is constant at steady conditions. The external force on the stream tube can be found by means of the momentum theorem[12]

$$\bar{F}_{ext} = \iint_S \rho \bar{V} (\bar{V} \hat{n}) dS. \tag{14}$$

Samuelsson[13] and Sibulkin[14] show that this expression can be developed and written as the net internal thrust or intrinsic thrust, F_{ni}

$$F_{ni} = \dot{m} V_3 - \dot{m} V_1 + (p_3 - p_0) A_3 - (p_1 - p_0) A_1. \tag{15}$$

Sibulkin suggests that

$$D_{pre} = F_n - F_{ni} \tag{16}$$

where F_n is the net standard thrust, defined as[15]

$$F_n = \dot{m}V_3 + (p_3 - p_0)A_3 - \dot{m}V_0. \tag{17}$$

This gives the component of the force in the free stream direction as

$$D_{pre} = (p_1 - p_0)A_1 + \dot{m}V_1 - \dot{m}V_0 = [(p_1 - p_0) + \rho_1 V_1^2]A_1 - \rho_0 V_0^2 A_0 \tag{18}$$

which is a useful result. Further, the drag coefficient C_{Dpre} is defined as

$$C_{Dpre} = \frac{D_{pre}}{q_0 A_1} \tag{19}$$

which gives

$$C_{Dpre} = \frac{(p_1 - p_0)A_1 + \dot{m}V_1 - \dot{m}V_0}{q_0 A_1}. \tag{20}$$

When assuming adiabatic flow between station 0 and 1, this can be written as

$$C_{Dpre} = \frac{2}{\gamma M_0^2}(\frac{p_1}{p_0} - 1) + 2\frac{p_1}{p_0}\frac{M_1^2}{M_0^2} - 2\frac{p_1}{p_0}\sqrt{\frac{1+\frac{\gamma-1}{2}M_1^2}{1+\frac{\gamma-1}{2}M_0^2}}\frac{M_1}{M_0}. \tag{21}$$

Equation (21) is equivalent with the expression of Leyland[16] for pre entry drag for a pitot-type intake with no frontal area, which is

$$C_{\varphi pre} = \frac{2}{\gamma M_0^2}\left[\frac{\eta_1\left({}^{P_1}/_{P_{T1}}\right)(1+\gamma M_1^2)}{{}^{P_0}/_{P_{T0}}} - 1\right] - 2m_R. \tag{22}$$

Equations (21) and (22) were examined in Matlab and were found to give identical results. Values for pre-entry drag were then extracted.

To compute C_{Dpre} , P_1 and P_{t1} are needed. These are computed assuming isentropic compressible processes from free stream through the intake to engine face. We have that[17]

$$p = Pt\left[1 + \frac{\gamma-1}{2}M^2\right]^{\frac{-\gamma}{\gamma-1}} \tag{23}$$

which, assuming isentropic flow where $P_{t0} = P_{t1}$, can be combined to

$$\frac{p_1}{p_0} = \left[\frac{1+\frac{\gamma-1}{2}M_0^2}{1+\frac{\gamma-1}{2}M_1^2}\right]^{\frac{\gamma}{\gamma-1}}. \tag{24}$$

Mach number at station 1, M_1 , is calculated in MatLab with an iterative function using m_R as an input variable, where

$$m_R = \frac{M_1}{M_0}\left[\frac{1+\frac{\gamma-1}{2}M_0^2}{1+\frac{\gamma-1}{2}M_1^2}\right]^{\frac{\gamma+1}{2(\gamma-1)}}. \tag{25}$$

With M_1 known, all other parameters at station 1 can be calculated. With these known, C_{Dpre} can now be computed.

Cowl axial force, ΔX_0

General

The cowl force ΔX_0 occurs when spilled air accelerates past the external cowl lip[18 19]. The acceleration causes a pressure drop and a suction effect; consequently ΔX_0 is negative in most cases and actually reduces spillage axial force. In some literature this phenomenon is described as cowl thrust. Geometrically ΔX_0 extends from the intake stagnation point to a point on the external surface along the intake duct equivalent to the point of maximum thickness, refer to Fig. 3.

The intake and lip geometry highly affects ΔX_0; therefore, it is not possible to establish a general method which covers all air intakes. Here, an approximate method is established based on published wind tunnel tests on similar intakes and other relevant data.

As ΔX_0 stems from the air that is spilled, it has a dependency on flow ratio. It also depends on M_o and α.

Mounts method

Mount[20] suggests a method for obtaining intake spillage drag $D_{\varphi pre}$ by modifying the value $C_{\varphi pre}$ by a factor K_{add} which contains information about the cowl drag component ΔD_0. K_{add} is a function of the intake geometry, m_R and M, the most notable geometry being the ratio of cowl projected frontal area to capture area. This gives the alternative D_{spill} definition

$$D_{spill} = C_{\varphi add} K_{add} q_0 A_1 \tag{26}$$

For the given cowl area ratio, Seddons general graphical solution gives a K_{add} between 0,3 and 0,5 depending on m_R and M. However, a more detailed model is desirable, which makes it possible to take into account M_{cr} and α effects. McMillan[21] states that ΔD_0 is depending on m_R and exact cowl or lip geometry to such an extent that even though the above method provides correct general order of magnitude, it may not be correct.

Generic empirical model

As a first step in developing a more detailed model, Mounts model is assumed to closely represent the ΔX_0 order of magnitude. At m_R around 1, the amount of spillage is very small and so ΔX_0 should be close to zero. As m_R decreases the spillage will increase, which should increase ΔX_0 due to higher mass flow and higher acceleration. At a certain lower m_R depending on geometry and M, lip separation will occur and ΔX_0 will no longer increase, and may even decrease.

Based on this, ΔX_0 may be regarded as a function depending on m_R^3. The magnitude of ΔX_0 at low m_R is difficult to assess, but is chosen so that the average magnitude coincides with Seddons value. This also happens to coincide quite well with McMillans measured results for pitot-type intakes, which are based on wind tunnel tests on a pitot-type intake.

Pressure coefficient model

An alternative method would be to use test or CFD lip pressure data to compute ΔX_0 . Ward[22] suggests that the cowl force may be described as

$$\Delta X_0 = \int_0^{A_{lip}} (P_{lip} - P_0) dA_{lip}. \tag{27}$$

In this case, the pressure distribution across the lip, P_{lip} is not known or measured. It is highly dependent on both geometry and m_R and any estimate will be uncertain. McMillan has published plots of both ΔX_0 and P_{lip} but these are not generic and of limited value in this case. Re[23] has published wind tunnel tests of three different NACA 1-series intakes in relevant M and m_R , showing C_p .

A particular problem would be to determine the size of the area over which to integrate. The integration shall be done from the intake stagnation point to the point equivalent to maximum thickness, and this point may be difficult to locate.

The method is not attempted here but could possibly give a better estimate for ΔX_0 given relevant input data.

Conclusion, ΔX_0

It is quite clear that an accurate result cannot be obtained without accurate CFD results or wind tunnel tests. However, the generic empirical model suggested here yields results in the same order of magnitude and average value as Mounts method and the curve shape coincides with known wind tunnel results. Hence, this model is used in the following. Effects of α and M_0 are incorporated into this model in ways described below.

ΔF_{inl} – Thrust due to change in intake condition

Jet intake and exhaust will influence the whole flow field of the aircraft. In supersonic flight, subsonic expansion inside the intake duct may be the largest contributor to total thrust (≈75%)[24]. In this context, it is not relevant to compute a theoretical value for thrust. Instead, drag is computed and thrust is set equal to the resulting axial force, assuming that engine performance makes this realistic within reasonable flight regimes. Of greater importance is to identify and include any changes in thrust due to intake conditions.

The thrust definition used is that for Net standard thrust F_n , Eq. (17). This takes into account gross thrust, momentum drag and pre-entry thrust force.

The most significant change in thrust due to intake condition is that due to changes in pressure recovery. This can be approximated by[25]

$$\frac{\Delta F}{F} = 0{,}35 K M_0 \frac{\Delta Pt}{q_0} = \frac{\gamma}{4} K M_0 \frac{1-P_R}{1-\frac{p_0}{Pt_0}} \tag{28}$$

Where F denotes thrust and K is a factor generally close to 1,5. Equation (28) is used to compute ΔF_{inl} .

Effects of wetted surface area, intake aspect ratio and boundary layer ingestion

Besides the effects discussed above, at least three additional factors[26] will affect performance and should be mentioned. These are intake AR; the relation between area of the wetted surface ahead of the intake and A_c ; and the relation between boundary layer thickness at station 1 and intake diverter gap δ.

Pre entry drag X_{pre} is not affected by these factors. The wetted area and diverter gap affect $P_R \sim m_R^3$ [27], and are accounted as a change in thrust. The intake AR affects ΔX_0 as this depends on projected lip front area compared to A_1.

Intake AR is the relation between intake height h (the dimension parallel to the adjacent fuselage surface) and width w (the distance perpendicular to the adjacent fuselage surface). Intake AR is taken into account by adjusting the average ΔX_0 .

At higher Mach numbers, there is also loss due to heating in compressible flow, but this is not significant at subsonic speeds.

Increasing α and β and effect on axial forces

Increasing α will affect intake conditions and performance. First, both projected capture area A_1 and projected frontal area will change due to the change in angle. This is a purely geometric phenomenon and will lead to an increase in X_{spill} approximately ~ cos(α).

Also, ΔX_0 will be affected due to areas of separation around the intake lip. This means that ΔX_0 will increase with α, increasing X_{spill}. There is data suggesting that this increase is ~ m_R^2 [28], but with a shallow slope and a large linear contribution. This information is incorporated into the model in an approximate way.

Increasing α will also lead to a decrease in pressure recovery. This phenomenon has been examined through wind tunnel tests of this particular air intake, these test results may be incorporated into the model at a later date and are not shown here.

The final known effect is that M_d is reduced by 0.003 per degree of α increase up to 6° [29]. This means that at a higher α, drag increase due to increased M_0 will occur at a lower M_0.

Transonic conditions and effect on axial forces

As M_0 increases, a similar effect as that of increasing α can be expected, both due to local separation and local shocks, referred to as disturbed flow. This will reduce ΔX_0 because the pressure level around the cowl is increased by the shock[30], which consequently increases X_{spill}.

Seddon has some information on the dependency on M_0. This can also be described as a shallow function depending on M_0^2 [31]. This function is said to be only negligibly dependent upon m_R.

However, Seddon also mentions a phenomenon referred to as supersonic reattachment[32]. This phenomenon may actually lead to a decrease in ΔX_0 in a certain M_0-region, delaying the drag rise Mach number. However, conditions necessary for this phenomenon to occur are not explained and it is therefore not included in the model.

Adding experimental and computed forces

As a final step, wind tunnel results and computed results are combined. This means summing X_{ref} and A_{spill} in a way that provides a realistic result.

$$X_{ref} = X_{ref,measured} - X_{fairings} \tag{29}$$

For this to happen, the exact m_R corresponding to X_{ref} must be determined. In reality, this cannot be done as no such specific data exists. A usual assumption is that $X_{tot} = X_{ref}$ at $m_R = 1$. This may introduce an error as it assumes that drag from the wind tunnel test intake fairings is exactly similar the actual intake drag at $m_R = 1$. This is correct only if $X_{spill} = 0$ at $m_R = 1$, and if total airframe drag with fairings = D_{ref} .

Results

For a user-selected value of altitude and Mach number, a solution containing X_{ref} and X_{spill} is computed in MatLab. The related figures are shown in Appendix 1.

Computed forces, X_{spill}

Spillage force X_{spill} is computed as described above. Some results are presented here, for the case of sea level and M=0,6. First evaluated is the value of the Mach number at intake capture, M_1 . This is important as it is used to calculate most other parameters, and small errors in M_1 will infuse larger errors into the forces. It is therefore of interest to see the full progress.

In Fig. 7 the lower line shows M_1 at the treated values of m_R in compressible flow. Most notably one can see that at $m_R = 1$, $M_1 = M_0$.

Pre-entry Drag coefficients are shown in Fig. 8. This is pre entry drag computed from Leyland, Seddon and Sibulkins models, as they all give identical results.

Fig. 9 shows Cowl Drag. The graph has a shape and magnitude that coincides with Seddon and McMillan. The exact values are uncertain, particularly at higher α, and it is difficult to assess any errors.

In Fig. 10, the change of cowl drag with increasing α is shown. Again, the magnitudes are uncertain.

In Fig. 11, the change of cowl drag with increasing M_0 is shown. Here, the magnitudes away from the reference $M_0 = 0,8$ are uncertain.

Measured force, X_{ref}

From the wind tunnel results, X_{ref} is measured and plotted. An example plot of this is shown in Fig. 5.

Combined forces, X_{ref} and X_{spill}

When adding X_{ref} and X_{spill} the result becomes as shown in Fig. 12. This is the total drag with combined wind tunnel results and computed results.

Similar results are obtained for other applicable mach numbers and altitudes. To see plots and data for all combinations, access to the Matlab file is necessary.

Flight test suggestions

A set of flight test maneuvers are required to verify and refine the modelled axial force results.

In the model, every flight condition given by altitude, Mach number and alpha is associated with a certain axial force, and, to maintain constant speed at that condition, a certain rotor velocity. This means that for any steady state condition computed, an engine control input giving the correct RPM in percent may be predicted. During missile flight test, the computed steady state engine control input should allow the missile to hold a constant speed. If the speed is not constant, the drag model contains an error.

The computed results depend on m_R, M_0 and α. In Table 1, a set of seven test conditions are suggested, verifying one parameter while the two other parameters are constant.

Discussion

The effects and magnitude of pre-entry axial force are relatively established and accepted equations are available. It is therefore possible to compute, provided the necessary input data is available and correct.

Pre-entry axial force cannot be measured in wind tunnel tests. It must be verified in flight tests, but this may still be difficult, as, while any deviation is easy to notice, the exact source of that deviation is difficult to identify. However, such verification is likely to have been performed several times in the past, and should not be necessary.

The effects and magnitude of cowl axial force are substantially less examined, and methods to compute or simulate it are less developed, a consequence of the close dependency on geometry. It was therefore necessary to develop a method which made it possible to estimate cowl axial force using published data. The accuracy of this method is unknown, but it corresponds with established methods and experiments in order of magnitude and dependency upon flow ratio.

This method shall be seen as an estimate, but also as a data structure ready to accept refined data from CFD analysis, flight tests or wind tunnel tests. Again, flight test will of course give correct data, but it may prove difficult to identify and isolate separate drag components. There are wind tunnel methods designed to measure this kind of partial drag which will provide the desired information.

Conclusion

A model for computing and summing reference drag and intake drag is established. Certain aspects of the model is dependent on exact geometry, while other aspects are depending on the relation between reference drag and flow ratio. These relationships can only be measured in a specific wind tunnel test or possibly computed in high resolution CFD-systems.

Short of such information, existing best-practice models and published information are employed and integrated, themselves stemming from numerous wind tunnel tests of air intakes and CFD-computations, though none of them for this particular geometry.

This should yield a model of at least some relevance.

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