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.

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

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To describe important stations in the airflow duct, Seddon \(^1\) is used. This includes four stations, see fig 2.

<table>
<thead>
<tr>
<th>Station</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (∞)</td>
<td>Undisturbed free-stream flow, ahead of the intake duct</td>
</tr>
<tr>
<td>1 (c)</td>
<td>Duct entry or capture</td>
</tr>
<tr>
<td>2 (f)</td>
<td>Engine face</td>
</tr>
<tr>
<td>3 (e)</td>
<td>Duct exit in the meaning jet engine exit, jet engine exhaust, or nozzle</td>
</tr>
</tbody>
</table>

### Subscripts
- **cr**, 1: Critical Mach number at station 1 - Mach number at which shock waves start occurring [-]
- **D, d**: Drag rise (due to Mach)
- **f**: Friction
- **L**: Lift
- **N**: Normal force
- **P**: Pressure
- **pre**: Pre entry
- **X**: Axial force

### Introduction
RUISE 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 \(^1\). 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 fairied 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 is used:

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

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 $\Delta$) 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, 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.
- $\Delta F_{inl}$: 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. Also includes thrust variation due to pressure recovery variation.
- $\Delta F_{exh}$: throttle-dependent force increment due to change in exhaust condition. Not treated in this study.
- $\Delta F_{trim}$: 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 $\varepsilon$. In incompressible flow, flow rate is defined as

$$ m_R = \frac{V_1}{V_0}. \quad (2) $$

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

$$ m_R = \frac{A_0}{A_1} = \frac{\rho_0 V_0 A_0}{\rho_0 V_0 A_1} = \frac{\dot{m}}{\rho_0 V_0 A_1}. \quad (3) $$

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 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.

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, $\eta_{in}$ or intake efficiency $^8$, or as the ratio of total energy available converted to compression in the intake. It is defined as

$$ P_R = \frac{P_{r1}}{P_{r0}}. \quad (4) $$

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 $\Delta F_{int}$.

$\Delta X_{inl}$ – axial force due to intake conditions

The incremental force $\Delta X_{inl}$ 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$^10$

$$ D = (D_f + D_p)_{0} + \Delta D_{0} + D_{pre}. \quad (5) $$
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 $\Delta D_{int}$ depending on $m_R$. This gives

$$\Delta D_0 + D_{pre} = \Delta D_{int}$$

(6)

and

$$(D_f + D_p)_0 = D_{ref}.$$  

(7)

The total drag $D$ can then be written as

$$D = D_{ref} + \Delta D_{trim} + \Delta D_{rn} + \Delta D_{int}.$$  

(8)

Disregarding the effects of trim drag and Re gives

$$D = D_{ref} + \Delta D_{int}$$  

(9)

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

$$X = X_{ref} + \Delta X_{int}$$  

(10)

where

$$\Delta X_{int} = X_{spill}$$  

(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

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

(12)

where $\Delta X_0$ 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 $\alpha$, 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\textsuperscript{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

$$X_{pre} = C_{xpre} q_0 A_1.$$  

(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 $\rho_0$.

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\textsuperscript{12}

$$F_{ext} = \int_{S_{ext}} \rho \vec{V} \cdot (\vec{V} \, d\vec{S}).$$  

(14)

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

$$F_{ni} = m V_3 - m V_1 + (p_2 - p_0) A_3 - (p_1 - p_0) A_1.$$  

(15)

Sibulkin suggests that
\[ D_{\text{pre}} = F_n - F_{ni} \]  

where \( F_n \) is the net standard thrust, defined as \(^{15}\)

\[ F_n = \dot{m}V_3 + (p_3 - p_0)A_3 - \dot{m}V_0. \]  

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

\[ D_{\text{pre}} = (p_1 - p_0)A_1 + \dot{m}V_1 - \dot{m}V_0 = [(p_1 - p_0) + \rho_1V_1^2]A_1 - \rho_0V_0^2A_0 \]  

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

\[ C_{\text{Dpre}} = \frac{D_{\text{pre}}}{\rho_0A_1} \]  

which gives

\[ C_{\text{Dpre}} = \frac{(p_1 - p_0)A_1 + \dot{m}V_1 - \dot{m}V_0}{\rho_0A_1}. \]  

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

\[ C_{\text{Dpre}} = \frac{2}{\gamma M_0^2} \left( \frac{p_1}{p_0} - 1 \right) + 2 \frac{p_1 M_1^2}{p_0 M_0^2} - 2 \frac{p_1}{p_0} \left( \frac{1 + \frac{\gamma - 1}{2} M_1^2}{1 + \frac{\gamma - 1}{2} M_0^2} \right). \]  

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

\[ C_{\text{Dpre}} = \frac{2}{\gamma M_0^2} \left[ \eta \left( \frac{P_i}{P_0} \right) \left( 1 + \frac{\gamma M_1^2}{2(\gamma - 1)} \right) \right] - 2m_R. \]  

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 \( C_{\text{Dpre}} \), \( P_1 \) and \( P_{i1} \) are needed. These are computed assuming isentropic compressible processes from free stream through the intake to engine face. We have that \(^ {17}\)

\[ p = P_0 \left[ 1 + \frac{\gamma - 1}{2} M_1^2 \right]^{\frac{\gamma}{\gamma - 1}} \]  

which, assuming isentropic flow where \( P_0 = P_{i1} \), can be combined to

\[ \frac{p_1}{P_0} = \left( \frac{1 + \gamma - 1}{2} \frac{M_1^2}{\gamma - 1} \right)^{\frac{\gamma}{\gamma - 1}}. \]  

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

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

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

**Cowl axial force, \( \Delta X_0 \)**

**General**

The cowl force \( \Delta X_0 \) occurs when spilled air accelerates past the external cowl lip\(^ {18} 19\). The acceleration causes a pressure drop and a suction effect; consequently \( \Delta X_0 \) is negative in most cases and actually reduces spillage axial force. In some literature this phenomenon is described as cowl thrust. Geometrically \( \Delta X_0 \) 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 \( \Delta X_0 \); 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 \( \Delta X_0 \) stems from the air that is spilled, it has a dependency on flow ratio. It also depends on \( M_0 \) and \( \alpha \).
Mounts method

Mount\textsuperscript{20} suggests a method for obtaining intake spillage drag $D_{\text{spill}}$ by modifying the value $C_{\text{pre}}$ by a factor $K_{\text{add}}$ which contains information about the cowl drag component $\Delta D_0$. $K_{\text{add}}$ is a function of the intake geometry, $m_{\text{c}}$ and $M$, the most notable geometry being the ratio of cowl projected frontal area to capture area. This gives the alternative $D_{\text{spill}}$ definition

$$D_{\text{spill}} = C_{\text{quad}}K_{\text{add}}\rho\alpha A_1 \quad (26)$$

For the given cowl area ratio, Seddons general graphical solution gives a $K_{\text{add}}$ between 0.3 and 0.5 depending on $m_{\text{c}}$ and $M$. However, a more detailed model is desirable, which makes it possible to take into account $M_\alpha$ and $\alpha$ effects. McMillan\textsuperscript{21} states that $\Delta D_0$ is depending on $m_{\text{c}}$ 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 $\Delta X_0$ order of magnitude. At $m_{\text{c}}$ around 1, the amount of spillage is very small and so $\Delta X_0$ should be close to zero. As $m_{\text{c}}$ decreases the spillage will increase, which should increase $\Delta X_0$ due to higher mass flow and higher acceleration. At a certain lower $m_{\text{c}}$ depending on geometry and $M$, lip separation will occur and $\Delta X_0$ will no longer increase, and may even decrease.

Based on this, $\Delta X_0$ may be regarded as a function depending on $m_{\text{c}}^3$. The magnitude of $\Delta X_0$ at low $m_{\text{c}}$ 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 $\Delta X_0$. Ward\textsuperscript{22} suggests that the cowl force may be described as

$$\Delta X_0 = \int_0^{A_{\text{tip}}}(P_{\text{tip}} - P_0)dA_{\text{tip}} \quad (27)$$

In this case, the pressure distribution across the lip, $P_{\text{tip}}$ is not known or measured. It is highly dependent on both geometry and $m_{\text{c}}$ and any estimate will be uncertain. McMillan has published plots of both $\Delta X_0$ and $P_{\text{tip}}$ but these are not generic and of limited value in this case. Re\textsuperscript{23} has published wind tunnel tests of three different NACA 1-series intakes in relevant $M$ and $m_{\text{c}}$, 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 $\Delta X_0$ given relevant input data.

Conclusion, $\Delta X_0$

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 $\alpha$ and $M_0$ are incorporated into this model in ways described below.

$\Delta F_{\text{int}}$ – 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 ($\approx 75\%$)\textsuperscript{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\textsuperscript{25}
\[
\frac{\Delta F}{P} = 0.35 K M_0 \frac{\Delta P_t}{q_0} = \frac{y}{4} K M_0 \frac{1-P_R}{1-P_R}
\]

(28)

Where \(F\) denotes thrust and \(K\) is a factor generally close to 1.5. Equation (28) is used to compute \(\Delta F_{\text{inl}}\).

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

Besides the effects discussed above, at least three additional factors 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 \(\delta\).

Pre entry drag \(X_{\text{pre}}\) is not affected by these factors. The wetted area and diverter gap affect \(P_R \sim m_R^3\), and are accounted as a change in thrust. The intake AR affects \(\Delta X_0\) as this depends on projected lip front area compared to \(A_c\). 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 \(\Delta X_0\).

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

**Increasing \(\alpha\) and \(\beta\) and effect on axial forces**

Increasing \(\alpha\) 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 \(X_{\text{spill}}\) approximately \(\sim \cos(\alpha)\).

Also, \(\Delta X_0\) will be affected due to areas of separation around the intake lip. This means that \(\Delta X_0\) will increase with \(\alpha\), increasing \(X_{\text{spill}}\). There is data suggesting that this increase is \(\sim m_R^2\) but with a shallow slope and a large linear contribution. This information is incorporated into the model in an approximate way.

Increasing \(\alpha\) 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 \(M_0\) is reduced by 0.003 per degree of \(\alpha\) increase up to 6°. This means that at a higher \(\alpha\), 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 \(\alpha\) can be expected, both due to local separation and local shocks, referred to as disturbed flow. This will reduce \(\Delta X_0\) because the pressure level around the cowl is increased by the shock, which consequently increases \(X_{\text{spill}}\).

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

However, Seddon also mentions a phenomenon referred to as supersonic reattachment. This phenomenon may actually lead to a decrease in \(\Delta X_0\) 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 \(X_{\text{ref}}\) and \(X_{\text{spill}}\) in a way that provides a realistic result.

\[X_{\text{ref}} = X_{\text{ref,measured}} - X_{\text{fairings}}\]

(29)

For this to happen, the exact \(m_R\) corresponding to \(X_{\text{ref}}\) must be determined. In reality, this cannot be done as no such specific data exists. A usual assumption is that \(X_{\text{ref}} = X_{\text{ref}} \text{ at } m_R = 1\). 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 \(X_{\text{spill}} = 0\) at \(m_R = 1\), and if total airframe drag with fairings = \(D_{\text{ref}}\).
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 \( \alpha \), and it is difficult to assess any errors.

In Fig. 10, the change of cowl drag with increasing \( \alpha \) 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 \( \alpha \). 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 depend 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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