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Performance data for the critical operation of nominally two-dimensional double-ramp supersonic intakes

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PERFORMANCE DATA FOR THE CRITICAL OPERATION OF NOMINALLY TWO-DIMENSIONAL DOUBLE-RAMP SUPERSONIC INTAKES

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PERFORMANCE DATA FOR THE CRITICAL OPERATION OF NOMINALLY TWO-DIMENSIONAL DOUBLE-RAMP SUPERSONIC INTAKES

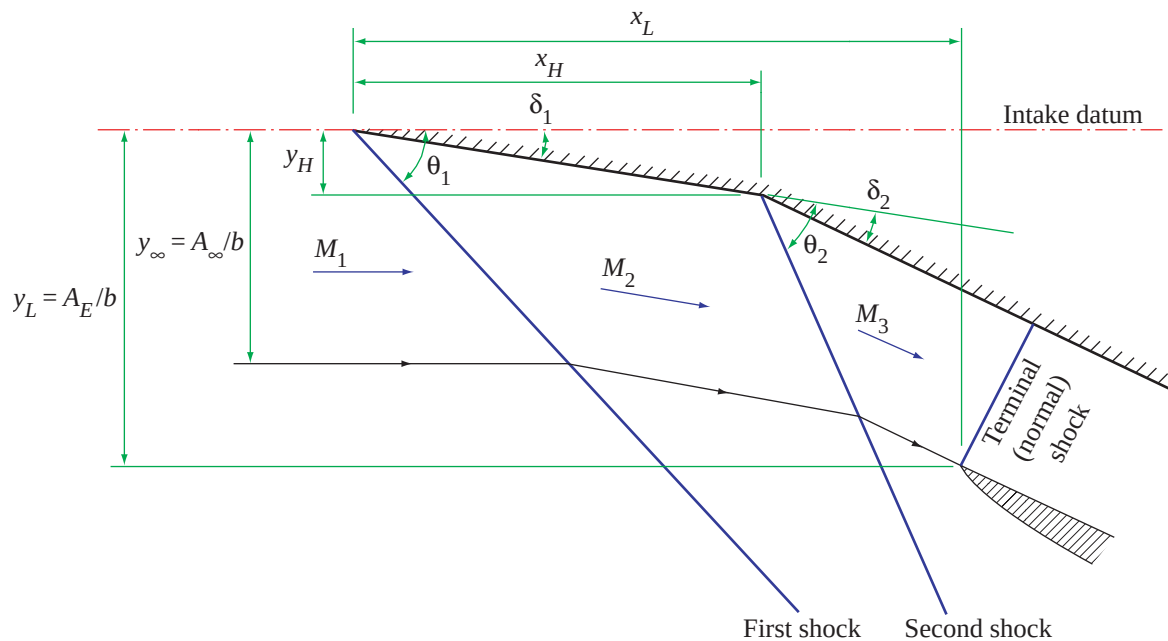
1. NOTATION AND UNITS

		SI	British
A	area used in sidespillage parameter G (see Sketch 4.1)	m^2	ft^2
A_E	intake entry area (see Sketch 1.1)	m^2	ft^2
A_∞	area of capture streamtube (see Sketch 1.1)	m^2	ft^2
$\Delta(A_\infty/A_E)$	loss in mass flow ratio due to sidespillage		
b	intake width	m	ft
C_D	pre-entry drag coefficient at critical mass flow, = $\text{drag}/\frac{1}{2}\gamma p_1 M_1^2 A_E$		
$(C_{D0})_{REF}$	pre-entry drag coefficient at $\delta_1 = 10^\circ$ and $\delta_2 = 0$		
$\Delta(C_{D0})_{\delta_1}$	increment in C_{D0} due to change in δ_1 from 10°		
$\Delta(C_D)_{\delta_2}$	increment in C_{D0} due to change in δ_2 from zero		
G	sidespillage correlation parameter (see Equation (4.1))		
K	$\Delta(C_D)_{\delta_2} / \left[\left(\frac{A_\infty}{A_E} \right)_0 - \frac{A_\infty}{A_E} \right]$		
M	Mach number		
p	static pressure	N/m^2	lbf/ft^2
p_t	total pressure	N/m^2	lbf/ft^2
x	distance measured from leading edge of first ramp parallel to intake datum (see Sketch 1.1)	m	ft
y	distance measured from leading edge of first ramp perpendicular to intake datum (see Sketch 1.1)	m	ft
α	angle of incidence of intake measured relative to intake datum	degree	degree
γ	ratio of specific heat capacities for air (taken as 1.4)		

δ_1	inclination of first ramp to intake datum	degree	degree
δ_2	angle of second ramp relative to first ramp	degree	degree
δ_{2L}	value of δ_2 for which second shock is on cowl lip; corresponds to δ_{2D} at design free-stream Mach number	degree	degree
δ_{2max}	maximum value of δ_2 for which second oblique shock remains attached at hinge	degree	degree
θ_1	angle of first oblique shock relative to free-stream direction	degree	degree
θ_2	angle of second oblique shock relative to first ramp	degree	degree

Suffixes

0	denotes value corresponding to $\delta_2 = 0$
1	denotes free-stream conditions
2	denotes conditions pertaining to first ramp
3	denotes conditions pertaining to second ramp
4	denotes conditions downstream of terminal shock
D	denotes design conditions, <i>i.e.</i> both oblique shocks simultaneously on cowl lip
H	denotes hinge between first and second ramps
i	denotes intersection of second oblique shock with dividing streamline
L	denotes cowl lip
α	denotes values at incidence



Sketch 1.1 Intake geometry

2. INTRODUCTION

For initial performance calculations the aircraft thrust requirements have to be matched by an engine thrust capability. These matching calculations provide an engine demand schedule for air mass flow with an assumed intake pressure recovery. This schedule of mass flow has to be provided by the air intake by matching airflow capacity and pressure recovery. This process is of necessity iterative as more information concerning pressure recovery becomes available. As a preliminary input to these iterative matching calculations this Item presents the theoretical performance characteristics of two-dimensional, external compression, double-ramp intakes at supersonic speeds in inviscid airflow. Only the critical operation of the intake, *i.e.* with the terminal shock attached to the lip, has been considered.

The design Mach numbers covered by the data range between 2.0 and 2.8, at free-stream Mach numbers of between 1.6 and design. Design Mach number in this Item is taken to be that free-stream Mach number at which both oblique shocks lie simultaneously on the lip. The design charts cater for values of δ_1 between 6° and 12° , and those of δ_{2D} between 6° and 16° . The Item applies basically to an intake operating at zero incidence; however it is equally valid for an intake operating at incidence provided that the transformations given in Section 3.6 are used.

Most of the data used in compiling the Figures were derived from a computer program, described in Derivation 2, which involves a solution to the oblique shock-wave relationships for air ($\gamma = 1.4$), described in Reference 7.

An example of the application of the Item is given in Section 7 and a step-by-step procedure is given at the end of the Item.

3. PRESENTATION

3.1 Intake Geometry

Figure 1 gives the second ramp hinge position as a function of M_{1D} and the chosen value of δ_{2D} , for particular values of δ_1 and Figure 2 gives the lip position in terms of the scaling length x_L for chosen values of M_{1D} and δ_1 .

If interpolations for δ_1 in Figure 1 are required, cross-plots of the values at $\delta_1 = 6, 8, 10$ and 12° may be produced and the required value read off. This also applies to subsequent Figures valid only for a particular value of δ_1 .

The maximum value of δ_2 for which the second oblique shock remains attached at the hinge is presented in Figure 3 as a function of M_2 . Values of M_2 are obtained from Figure 4, entering with M_1 and δ_1 .

3.2 Pressure Recovery

Figure 5 presents the shock pressure recovery, p_{t4}/p_{t1} , as a function of δ_2 and free-stream Mach number, each sub Figure being applicable to a particular value of δ_1 . These Figures are applicable to any design conditions provided that both oblique shocks lie outside the intake lip. If the second shock entered the intake, pressure recovery would be reduced, and flow distortion problems would arise due to shock wave and/or boundary layer interaction within the intake. Figure 6 gives the value of $\delta_2 (= \delta_{2L})$ below which the second oblique shock enters the intake.

The maximum possible pressure recovery for a three shock intake is shown in Figure 7 together with the corresponding values of δ_1 and δ_2 . The basis of these curves is explained in Derivation 1.

3.3 Mach Number on Second Ramp, M_3

Values of M_3 are obtained from Figure 4. Firstly Figure 4 is entered with M_1 and δ_1 to obtain M_2 , and then re-entered with M_2 and δ_2 to obtain M_3 . This Figure is valid for any design case since M_3 is a function of M_1 , δ_1 and δ_2 only.

Normally, in any practical intake design, an attempt is made to limit M_3 to values below about 1.4, but see Section 4.2.

3.4 Mass Flow Ratio, A_∞/A_E

The critical mass flow ratio for a double-ramp intake, at $\alpha = 0$, is given by:-

$$\frac{A_\infty}{A_E} = \frac{\sin\theta_1 \sin(\theta_{1D} - \delta_1)}{\sin\theta_{1D} \sin(\theta_1 - \delta_1)} \times \frac{\sin\theta_2 \sin(\theta_{2D} - \delta_2)}{\sin\theta_{2D} \sin(\theta_2 - \delta_2)} \quad (3.1)$$

The first part of this expression gives the mass flow ratio for the case $\delta_2 = 0$. Expressing the values of $\sin\theta_{1D}$ and $\sin(\theta_{1D} - \delta_1)$ in terms of the intake geometry this first part becomes

$$\left(\frac{A_\infty}{A_E}\right)_0 = \frac{\sin\theta_1}{\sin(\theta_1 - \delta_1)} \left(1 - \frac{x_L}{y_L} \tan\delta_1\right) \cos\delta_1 \quad (3.2)$$

From this it can be deduced that $(A_\infty/A_E)_0 / [1 - (x_L/y_L)\tan\delta_1]$ is a function of M_1 and δ_1 only, and this forms the basis of the presentation in Figure 8. As $(A_\infty/A_E)_D = 1$ the value of $1/[1 - (x_L/y_L)\tan\delta_1]$ can be read off the ordinate scale at the chosen design conditions, M_{1D} and δ_1 . Hence $(A_\infty/A_E)_0$ can be determined.

For the general case Equation (3.1) is rearranged as:-

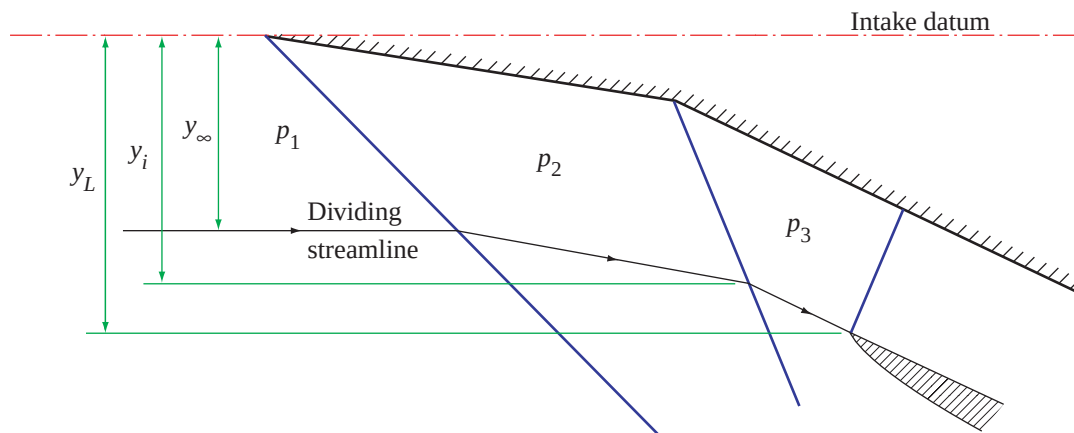
$$\frac{A_\infty}{A_E} = \left(\frac{A_\infty}{A_E}\right)_0 \frac{\sin\theta_2/\sin(\theta_2-\delta_2)}{\sin\theta_{2D}/\sin(\theta_{2D}-\delta_2)} \quad (3.3)$$

which can be evaluated with the aid of Figures 4, 8, 9 and 10. First $(A_\infty/A_E)_0$ is obtained from Figure 8, as described above. Then both M_2 as a function of M_1 and δ_1 and M_{2D} as a function of M_{1D} and δ_1 are determined from Figure 4. Next Figure 9 is used to determine θ_2 as a function of M_2 and δ_2 and also θ_{2D} as a function of M_{2D} and δ_{2D} . Finally the ratios $\sin\theta_2/\sin(\theta_2-\delta_2)$ and $\sin\theta_{2D}/\sin(\theta_{2D}-\delta_2)$ are obtained from Figure 10 entered, respectively, with θ_2 and θ_{2D} .

3.5 Pre-entry Drag at Critical Mass Flow

Pre-entry drag is defined as the component, in the free-stream direction, of the force acting on the streamtube bounded by the dividing streamline and the streamline impinging on the apex of the first ramp, between a station at infinity upstream and the inlet station. The pre-entry drag coefficient for an intake, at $\alpha = 0$, may be expressed by the following equation, the terms in which are defined by Sketch 3.1.

$$C_D = \frac{1}{0.7M_1^2 y_L} \left[\left(\frac{p_2}{p_1} - 1 \right) (y_i - y_\infty) + \left(\frac{p_3}{p_1} - 1 \right) (y_L - y_i) \right]. \quad (3.4)$$



Sketch 3.1 Pre-entry drag parameters

Values of the pre-entry drag coefficient for $\delta_2 = 0$ are presented in Figures 11a and 11b. Figure 11a presents pre-entry drag for $\delta_1 = 10^\circ$ and Figure 11b gives a correction for values of δ_1 other than 10° , so that C_{D0} can be evaluated from

$$C_{D0} = (C_{D0})_{REF} + \Delta(C_{D0})_{\delta_1} \quad (3.5)$$

The correlation of theoretical data in Figure 11b, which ignores a small scatter due to M_{1D} effects, does mean that values read from Figure 11b are in error to an increasing extent as δ_1 is increased.

For example at $\delta_1 = 12^\circ$ the error in $\Delta(C_{D0})_{\delta_1}$ is about 0.003 at the higher values of $\Delta(C_{D0})_{REF}$. However, to put this in perspective, for an aircraft with a wing area to intake area ratio of 20 to 1 this would result in an error in aircraft drag coefficient of 0.00015.

For values of δ_2 other than zero, at a given M_1 and δ_1 , plots of $\Delta(C_{D0})_{\delta_2}$ against $[(A_\infty/A_E)_0 - (A_\infty/A_E)]$ appear as a series of straight lines passing through the origin, M_3 being constant for each line.

If K is the slope of the line the increment in pre-entry drag coefficient due to δ_2 is given by

$$\Delta(C_{D0})_{\delta_2} = K \left[\left(\frac{A_\infty}{A_E} \right)_0 - \frac{A_\infty}{A_E} \right] \quad (3.6)$$

where K is a function of M_1 , M_3 and δ_1 .

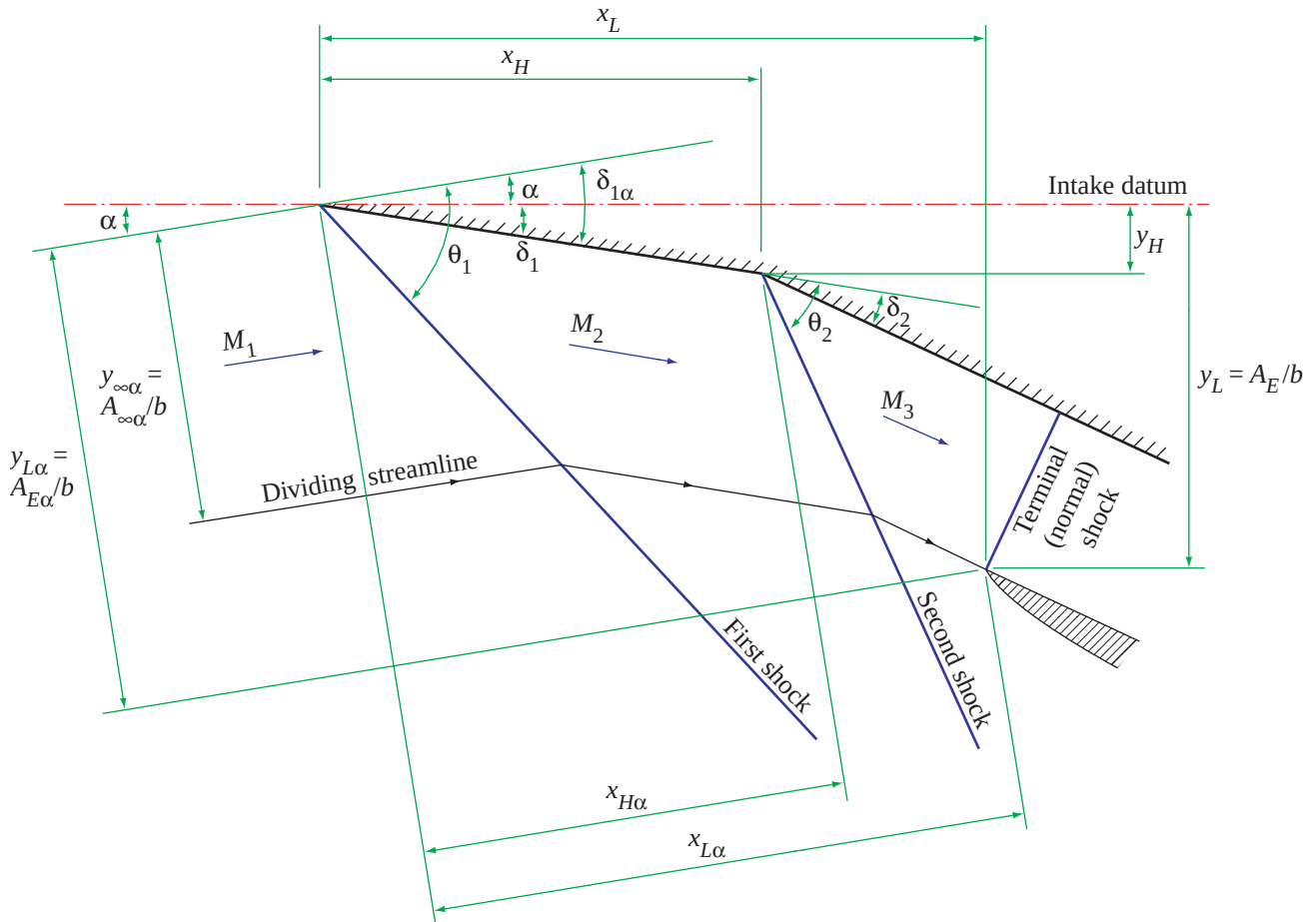
Values of K are presented in Figure 12 as a function of M_1 and M_3 , each carpet being applicable to a particular value of δ_1 . The value of K can thus be determined and knowing $[(A_\infty/A_E)_0 - (A_\infty/A_E)]$, $\Delta(C_{D0})_{\delta_2}$ can be found using Equation (3.6).

The total pre-entry drag coefficient is then given by

$$C_D = C_{D0} + \Delta(C_{D0})_{\delta_2} \quad (3.7)$$

3.6 Effect of Incidence

For an intake mounted with the leading edge horizontal and above the cowl, altering its incidence effectively alters its geometry relative to the undisturbed airstream as shown in Sketch 3.2.



Sketch 3.2 Effective geometry at incidence

The performance of an intake at incidence can be calculated by treating it as an intake at zero incidence, provided that the intake geometry is referred to the free-stream direction as given by the following transformations. The suffix α refers to the effective geometry at incidence, α .

$$\delta_{1\alpha} = \delta_1 + \alpha \quad (3.8)$$

$$\frac{x_{L\alpha}}{y_{L\alpha}} = \cot \left[\tan^{-1} \left(\frac{y_L}{x_L} \right) + \alpha \right] \quad (3.9)$$

$$\frac{x_{H\alpha}}{x_{L\alpha}} = \left(\frac{x_H}{x_L} \right) \frac{\sec \delta_1 \cos(\delta_1 + \alpha)}{[1 + (y_L/x_L)^2]^{1/2} \cos[\tan^{-1}(y_L/x_L) + \alpha]} \quad (3.10)$$

The value of $M_{1D\alpha}$ can be obtained from Figure 2 entered with $x_{L\alpha}/y_{L\alpha}$ and $\delta_{1\alpha}$ calculated via Equations (3.9) and (3.8). Similarly, using $x_{H\alpha}/x_{L\alpha}$ calculated via Equation (3.10) and $M_{1D\alpha}$ the value of $\delta_{2D\alpha}$ can be obtained from Figure 1. The performance parameters can then be determined, as described in Sections 3.2 to 3.5, using $M_{1D\alpha}$, $\delta_{1\alpha}$ and $\delta_{2D\alpha}$. This does however mean that both the mass flow ratio and pre-entry drag coefficient obtained will be based on an intake entry area ($A_{E\alpha} = y_{L\alpha} b$) measured perpendicular to the freestream direction. In order that the mass flow ratio and pre-entry drag coefficient be based on the standard entry area ($A_E = Y_L b$) it will be necessary to multiply the results obtained, for pre-entry drag coefficient and mass flow ratio, by the factor

$$\frac{y_{L\alpha}}{y_L} = \cos\alpha + \left(\frac{x_L}{y_L}\right) \sin\alpha. \quad (3.11)$$

4. PRACTICAL CONSIDERATIONS

4.1 Effective First Ramp Angle

Due to boundary layer growth on the first ramp there exists an “effective” first ramp angle which is greater than the geometric angle. This phenomenon is discussed in Derivation 2 and References 5 and 6. At full scale Reynolds number the “effective” δ_1 is approximately 0.75° to 1° greater than the geometric value.

Since δ_2 is measured relative to δ_1 , and the rate of growth of the boundary layer on the first and second ramps will be essentially similar, the value of δ_2 will be equivalent to the geometric value.

Any effects due to boundary layer growth on the intake sidewalls have been neglected in this Item.

4.2 Limit to Second Ramp Mach Number, M_3

In order to prevent the boundary layer separating at the terminal shock and creating flow distortion problems and excessive extra-to-shock losses, the value of M_3 should ideally be kept below about 1.3 to 1.4 (Nussdorfer criterion⁴). It may not be possible to achieve this condition, but suitable boundary layer bleeds may be employed to minimise the effects of boundary layer separation if M_3 has to be greater than that value.

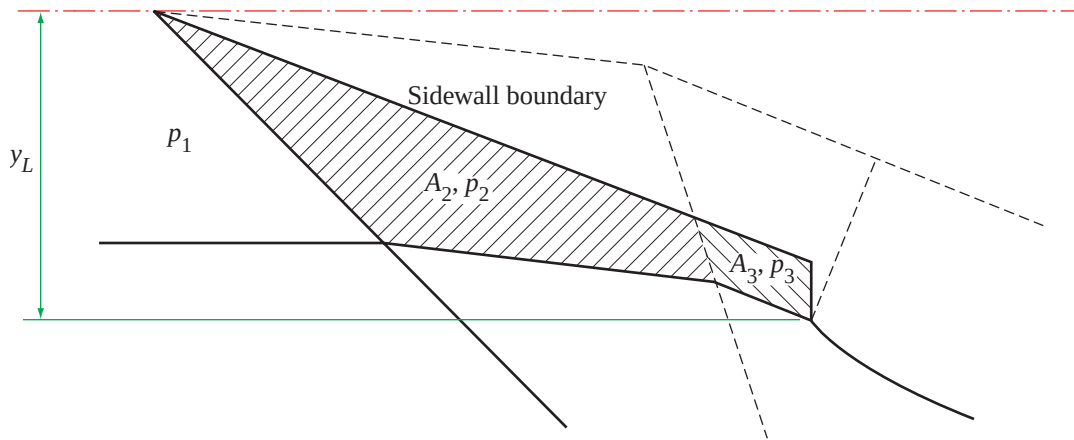
4.3 Correction for Sidespill

This Item assumes the intake flow to be two-dimensional; this is reasonable if the flow field is contained between parallel sidewalls. For triangular sidewalls extending from the leading edge of the first ramp to the cowl lip, the two-dimensional assumption is valid only at or near the design Mach number. For low Mach numbers, or if the sidewalls are cut away, spillage will take place sideways over the walls with a consequent loss in mass flow ratio. For cut-away sidewalls this loss can be up to 10 per cent of the two-dimensional prediction⁹.

Derivation 2 proposes a method whereby the loss in mass flow ratio due to sidespillage may be estimated. This method assumes that sidespillage is a function of the difference between the pressures inside and outside the shock system and of the area over which sidespillage can occur. With those assumptions a sidespillage correlation parameter, G , dependent on intake aspect ratio (b/y_L), is proposed and for an intake of width b is given by

$$G = \frac{A_2}{y_L b} \left[\frac{p_2}{p_1} - 1 \right] + \frac{A_3}{y_L b} \left[\frac{p_3}{p_1} - 1 \right]. \quad (4.1)$$

The shaded regions in Sketch 4.1 illustrate the areas A_2 and A_3 over which sidespillage can occur.



Sketch 4.1 Sidespillage parameters

The correlation, shown in Derivation 2, of the drop from estimated to measured mass flow ratios against the parameter G is good provided that the estimates are made with an “effective” first wedge angle 0.75° greater than δ_1 . This correlation of $\Delta(A_\infty/A_E)$ against G is reproduced in Figure 13. The measured results included in this correlation were for an intake with different sidewall shapes but a constant aspect ratio, b/y_L , of 1.546. It should be noted that this correlation is for an intake in which it is possible for spillage to take place over both sidewalls. Where one sidewall is shielded by, for example, the fuselage, the correction for sidespillage would obviously be reduced.

To determine the correction for sidespillage, A_2 and A_3 have to be determined. Also the pressure ratios p_2/p_1 and p_3/p_2 can be found from Item No. Aero S.00.03.10 and hence p_3/p_1 can be determined. The value of the sidespillage correlation parameter, G , is then calculated from Equation (4.1) and the value of $\Delta(A_\infty/A_E)$ is read from Figure 13 at the appropriate value of G .

4.4 Stable Flow Range

The data in this Item are for critical intake operation only, but it is important that an intake should operate in a stable manner over a range of mass flows. There are a number of possible reasons for flow instability discussed in References 3 and 8. Derivation 2 proposes a method of estimating the stable flow range using the “Ferri” criterion which appears to give reasonable agreement with experiment. The “Ferri” criterion states that, as the intake operation is made more and more subcritical, the terminal shock moves upstream under the influence of the back pressure, intersecting the second oblique shock. A vortex sheet arises from this intersection and eventually a mass flow will be reached at which the vortex sheet enters the intake and causes boundary layer separation just inside the cowl lip. This leads to intermittent intake choking and consequent unstable operation.

Unstable operation can also arise from boundary-layer/shock interaction on the second ramp causing separation and intermittent choking. This latter cause can however be alleviated by suitable boundary-layer bleeds, but at a performance penalty.

4.5 De-focussing of the Oblique Shocks

At the intake design Mach number both oblique shocks are, by definition, simultaneously on the cowl lip. There will then be no stable flow range because as soon as the engine is throttled and the terminal shock moves forward under the influence of the back pressure, the vortex sheet from the intersection of the terminal and second oblique shocks will enter the intake. In order to obtain a range of stable operation it is normal to arrange the lip position such that the two oblique shocks are focussed outside the cowl lip at the aircraft maximum operating Mach number. This can be achieved by making the intake design Mach number 0.1 to 0.2 greater than the aircraft maximum operating Mach number.

5. USE OF A STRONG OBLIQUE TERMINAL SHOCK

In some intake configurations, where internal pressure recovery and low cowl drag at a particular cruise condition are of prime importance, use has been made of some degree of internal supersonic compression from the lip. For such configurations the flow off the second ramp is compressed by the internal surface of the cowl, which is slightly inclined to the ramp flow to give an oblique internal cowl shock. For low second ramp Mach numbers the internal shock can be either of two types, weak or strong, and design methods have been evolved to produce the strong shock at the design operation point. It will be seen from oblique shock data (see for example Item No. Aero S.00.03.09) that two values of shock angle may be obtained for a given compression angle, the weaker one giving a supersonic Mach number behind the shock and the stronger a subsonic Mach number. The loss of total pressure is greater for the strong shock than for the weak shock plus the ensuing normal shock, but the transition from supercritical to subcritical operation of the intake is smooth and more adaptable for a control system.

Design requirements dictate that the turning compression at the inside of the cowl should be about 2° less than that for lip shock detachment, the change from the weak shock to the strong shock being controlled by the diffuser back pressure. As the intake moves from a supercritical condition recovery is enhanced by reduction of diffuser losses but decreased slightly by the greater losses of the strong oblique shock. Other features affecting the satisfactory operation of this type of intake are the performance of the throat bleed systems and the rate of the internal cowl compression.

6. DERIVATION AND REFERENCES

Derivation

The Derivation lists selected sources that have assisted in the preparation of this Item.

1. HERMANN, R. *Supersonic inlet diffusers and an introduction to internal aerodynamics.* Minneapolis-Honeywell Regulator Co., Minneapolis, 1956.
2. MCGREGOR, I. Some theoretical parameters relevant to the performance of rectangular air intakes with double-ramp compression surfaces at supersonic speeds. RAE tech. Rep. 71232, November 1971.

References

The References are sources of information supplementary to that in this Item.

3. FERRI, A.
NUCCI, L.M. The origin of aerodynamic instability of supersonic inlets at subcritical conditions. NACA RM L50K30 (TIL 2616), 1951.