Intake Aerodynamics

An account of the mechanics of flow in and around the air intakes of turbine-engined and ramjet aircraft and missiles

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Foreword

Since the advent of the jet engine rapid developments in airframe and engine performance have presented the air intake designer with many new challenges. For example, maintaining good quality intake flow for the Harrier in conventional flight, through transition and down to the hover; combining the requirements of transonic manoeuvrability and sustained Mach 2 flight for the Tornado; or reconciling the conflicting needs of Concorde for efficient supersonic cruise performance and carefree engine handling in other flight conditions. The future looks no less challenging with prospects of military designs involving ultra high incidence manoeuvring capability; supersonic VSTOL; contrarotating unducted fan installations; second generation supersonic transports and air breathing missiles and space launchers.

The subject of intake aerodynamics, therefore, has been and will remain of primary importance to the aerospace industry, in which progress depends on combining fundamental research and practical development in a way that the authors clearly understand.

John Seddon and Laurie Goldsmith are both international authorities in the field and, between them, combining some seventy-five years of experience of intake aerodynamics, could not be better qualified to write this book. In their research they have had to probe the fundamentals of the subject and to elucidate important considerations as they have arisen, for example, spillage drag, shock oscillation, dynamic distortion and swirl. At the same time they have between them headed up the Royal Aircraft Establishment's advice to industry throughout the entire history of jet propulsion and in varying degrees have been associated with every British jet aircraft development. In addition they have been consulted by overseas manufacturers.

Now the authors have assembled their extensive knowledge and experience in this book, which as a comprehensive and practical appraisal of intake aerodynamics, is the first of its kind. The subject matter is well digested and excellently presented, and the authors have combined an easily understood treatment of the basic ideas and concepts employed in intake aerodynamics with discussion of the more specialised aspects of the subject.

This book will prove invaluable both to the newcomer to the subject and to the specialist alike and can be recommended to young aerospace engineers and to the not so young as a refresher and reference text. I am sure it will prove to be of great service to academic centres and research organisations as well as to design and development departments in industry.

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Preface

The title of the book calls for a small apology to readers across the Atlantic. It is surprising perhaps but true, that in a field of technology which over the years has seen much valuable exchange and collaboration between countries, the English-speaking nations have persisted in using different names for the main topic. In Britain the object of our attention is an *intake:* in the United States it is an *inlet.* No doubt an interesting semantic argument could be mounted, as to whether the air is being taken in or let in, an argument in which the balance of logic might well come down on the American side. But after due consideration, home loyalty has prevailed and the traditional British terminology has been retained.

The subject of intake aerodynamics has developed since the Second World War, in parallel with the development of the jet engine itself, taking over, however, a good deal of background initially from earlier experience on the aerodynamics of cooling systems for piston-engined aircraft. The advent of supersonic flight in the late 1940s led to a burgeoning of research on intakes, around a central theme of the efficiency of shock-wave systems. Practical limits to what could be achieved were evaluated, based on necessary compromises between the requirements of internal and external flows. More recently the effects of aircraft attitude and local flow fields have been brought in and much attention has been given to the aspects of airflow compatibility between intake and engine. The subject has never been lacking in interest to research workers and major surprises have emerged at roughly decade frequency. Two such in the '40s and '50s were (1) the reality of spillage drag, a problem not restricted to supersonic speeds but virtually unknown before the subject moved into the supersonic field, and (2) the phenomenon of intake shock oscillation, for which the American colloquial term 'buzz' has been widely appropriated, including in the present text. In the late '60s the significance of dynamic distortion became apparent, while in the late '70s a problem to emerge unexpectedly was that of swirl, restricted to certain types of intake but occurring at both subsonic and supersonic speeds. None of these problems has 'gone away' and all are treated in this book.

Some explanation may be offered for the lack of previous textbooks on the subject. The air intake stands in a position of linking the aircraft and engine in a continuum of aerodynamics but intake aerodynamics as a subject differs from the corresponding subjects on either side in an important respect. Whereas both airframe aerodynamics and compressor aerodynamics are based heavily on the lift function and less on that of drag, with the intake the reverse is true. Loss of total pressure is the form taken by the drag function in the internal flow and in the external flow it is basically the drag which has to be evaluated and used to effect a final compromise in design. This almost entire emphasis on drag leads to a subject much influenced by the behaviour of the turbulent boundary layer and hence heavily weighted on the experimental side. Because, moreover, the boundary layer is usually operating in a significantly adverse pressure gradient, flow separation is rarely far away and, unlike the situation in classical wing aerodynamics, say, where the occurrence of separation is generally taken to mark a limit of operation, an intake is often required to operate satisfactorily in separated flow regimes. Thus from a practical aspect, exact theories are rarely available and the designer looks rather to empirical generalisations, the applicability of which may become questionable as more evidence is accumulated.

It is felt that the time has come to face this situation and to put together a comprehensive and practical treatment of the subject which will serve to initiate the student, reliably assist both research worker and design engineer, and display the undoubted fluid-dynamical interest of an important subject. The book is the first of its kind. Kuchemann and Weber (1953) treated aspects of the subject for subsonic intakes only. Hermann (1956) set out the theory of supersonic diffusers in non-viscous flow and Fabri (1958) edited an AGARD ograph containing a set of good, though necessarily condensed, accounts of intake problems at supersonic speeds up to that time, as presented at a meeting of the AGARD Combustion Panel. Other AGARD publications from conference proceedings have followed but these of necessity treat particular aspects of the subject from advanced starting points. The present book covers *ab initio* the aerodynamics of both subsonic and supersonic intakes in real flows and aims to demonstrate continuity through the transonic range, as applies particularly to the behaviour of the boundary layer. Both internal and external flows are treated and both civil and military types of application are embraced.

The treatment is based on a lecture course which has been given in recent years by the first author, at the University of Bristol, to students in their final BSc year together with visitors from the aircraft and engine branches of industry, attending by invitation. The lecture course aims to present the fluid dynamics of the subject from first principles. In the book, topics are gone into more deeply and additional research information, both well-established and recent, has been included, largely by contribution of the second author. In this way it is hoped that the book will be of interest to students at both undergraduate and postgraduate levels, to research workers in industry and research establishments and to design teams as a reference text.

The presentation is not highly mathematical; rather the emphasis is placed always on giving a physical picture of the flow. When this has been done, the reader may be referred for greater detail to original authors' papers: this is especially so in respect of the use of modern numerical methods. The chief stock-in-trade is the relatively simple working formula, usually empirical but useful for practical application and displaying within its derivation and content the essential fluid-mechanical aspects, thus conveying an understanding of the nature of the problem.

In the arrangement of the book, the first eight chapters are concerned with internal flow (the flow to the engine, considered from initial free stream conditions) and the general progression is from subsonic through transonic to supersonic. Next the topic of external drag is treated. This would logically divide similarly into a number of chapters dealing with various aspects. Owing however to a close interplay amongst most of the items, it was decided that continuity combined with cross-linking could best be achieved by keeping the subject within the bounds of a single chapter: a somewhat massive division results, in which however the succession of subsonic, transonic and supersonic is broadly preserved. After establishing in this way the principles of internal and external performance, which can henceforward be referred to whenever required, the book turns to consideration of other aspects which go into a practical compromise design: these are concerned with flow quality (distortion, swirl and buzz), with engine and intake matching and with incidence effects, which have grown in importance in recent times. Finally, Chapter 14 describes some unusual concepts of intake design that have cropped up over the years and Chapter 15 discusses the techniques of wind tunnel testing and analysis which apply specially to intakes.

An area excluded from our treatment is that of aerodynamic interference between engine pod and airframe in an installed situation. At subsonic speeds, particularly approaching Mach 1.0, interference forces exist between pod, strut and wing or fuselage, of such a form as usually to increase the drag and often to modify lift and moment characteristics also. At supersonic speeds the problem of impingement of intake shock waves on wing or body must be considered. In suitable conditions, favourable interference is a possibility, at least in principle. The subject of interference is difficult to quantify, however, except in terms of specific situations: moreover it calls generally for consideration of the total engine nacelle rather than simply the intake and this in turn involves the aerodynamics of afterbody and nozzle flows, a subject area quite outside the present one.

References are listed at the end of each chapter. Many of them are unpublished but are quoted nevertheless because readers may have, or be able to gain, access to them. Abbreviations used in the text and in the references – mostly the initials of research organisations and learned institutions – are defined in a list on page xxviii and the headquarters locations of the various bodies are noted.

The authors would be pleased to receive notification of any errors or omissions which readers think should be brought to their attention for future printings.

We wish to record, with our warm thanks, the contributions made by Molly Gibbs, who typed the whole text save for a late portion during a temporary incapacitation, by Joyce Shade and Eleanor Gibbins, who stepped in to close that particular gap, and by Noeline Rycroft, in whose capable hands rested the production of the diagrams, a mammoth task. We also acknowledge our gratitude to two wives for unfailing support and encouragement despite much provocation and neglect.

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Much use has been made of American data, published and unpublished. In this context we are greatly indebted to NASA for permission to reproduce Figs 5.7, 5.9, 5.10, 5.22, 6.15, 6.16, 6.18, 7.8, 7.12, 8.14, 8.16, 8.17, 9.34, 11.7, 11.9, 11.11, 13.6, 13.7, 13.8, 14.10, 14.11, 14.24, 14.25 and 14.26; to the AIAA for Figs 11.4, 11.5, 12.8, 12.9, 12.12, 13.1, 13.4, 13.9, 14.13 and 14.23; and to the Marquardt Corporation for Fig. 10.7.

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If other sources are involved, the failure to acknowledge them specifically is not intentional and our thanks are hereby conveyed.

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J.S.
E.L.G.

Notation List

A general list is given, followed by lists special to individual chapters. Some symbols are used in more than one context, where this can be done without confusion. In a small number of cases the same quantity is defined by different symbols in different chapters (for example, l and L are both used to define geometric lengths) as the context appears favourable. The use of numerical suffixes for stations in a flow and of shorthand suffixes such as 'max' and 'spill' is so ephemeral in the one case and so obvious in the other as not to require their inclusion in these lists.

General

p	static pressure
P	total pressure
ρ	density
T	temperature
R	gas constant
γ	ratio of specific heats, taken as 1.4 for numerical purposes
V	velocity of flow
a	velocity of sound
M	Mach number, V/a
q	dynamic pressure, $\frac{1}{2}\rho V^2$
A	area of cross section
A^*	sonic area
m	mass flow, $\rho A V$
C_p	static pressure coefficient, $(p-p_\infty)/q_\infty$
η_σ	total-pressure efficiency, compressible flow (little used)

$\eta_{\sigma i}$	incompressible-flow form of η_σ (much used)
η_p	total-pressure ratio (most-used definition of efficiency)
η_R	'ram' efficiency (used only for one illustration in Chapter 3)

[Any of these four definitions can be referred to loosely as 'intake pressure recovery']

S	aircraft surface area ahead of entry 'wetted' by internal flow
g	perimetric length of cross section, whole or partial
C_f, C_F	friction coefficient, local or mean
J	position ratio, S/A or kS/A
I	duct integral
μ	inverse flow ratio, A_c/A_∞
δ	boundary layer thickness (also flow turning angle, see below)
δ^*	boundary layer displacement thickness
θ	boundary layer momentum thickness (also lip position angle, see below)
H	form parameter, δ^*/θ
H_i	form parameter for incompressible flow
n	reciprocal of index for boundary-layer profile power law
δ	flow turning angle (wedge angle or cone semi-angle)
β	oblique-shock angle relative to incident flow direction
θ	lip-position angle
β_D	value of β or θ when oblique shock is on cowl lip
η_e, η_o	cowl-lip external ('outer') angle relative to duct axis
η_i	cowl-lip internal angle relative to duct axis
η_v	cowl-lip included angle
h	height dimension representing cross-section area A in two-dimensional flow
CR	contraction ratio, (highlight area) ÷ (throat area)
X	engine thrust
D	intake drag

t	shorthand for factor $(1 + (\gamma-1)M^2/2)$

Suffixes

o	stagnation values of flow quantities other than pressure
∞	free-stream conditions (station 'at infinity' in flow)
c	conditions at entry (gross entry area enclosed by cowl lip)
f	conditions at nominal engine face (end of intake duct)
e	conditions at duct exit
i	net flow area at entry
t	duct throat (normally just inside entry)
a	relates to approach length
d	relates to duct length
s	relates to shock system
i	relates to shock and boundary-layer interaction (Chapters 3, 8)
L	relates to local flow conditions (Chapters 13, 15)

Prefix

Δ	change in a quantity (usually ΔP, loss of total pressure)

Chapter 1

c_p	specific heat at constant pressure
c_v	specific heat at constant volume
k	constant in relation $P = kq_f$
K	constant in relation $(\Delta X/X) = K\ (\Delta P/P_\infty)$

Chapter 2

l	length of streamtube in direction of flow
F	friction force on elementary length of streamtube
k	empirical factor in approach loss
α	effective cone angle

R_{eff}	effective Reynolds number
d	station of duct immediately before sudden enlargement
N	number of propeller blades
t	representative thickness of blade section
r	representative radius of blade section
L	projecting length of spinner and hub
P,Q,R	points on flow characteristic of twin intake
P',S	points on static pressure characteristic of twin intake

Chapter 3

l	length of streamtube in direction of flow
C_{pm}, C_{ps}	minimum and actual rise in pressure-coefficient for flow separation
Q	flow factor in interaction-loss formula
G	geometric factor in interaction-loss formula
Φ,Ψ	Mach number functions in interaction-loss formula
A_θ	effective boundary layer ingestion area, based on momentum thickness
R_θ	Reynolds number based on momentum thickness
A_{h}	duct area at half length
p	suffix relating to length over which pressure rise acts
s	suffix relating to separated flow conditions
λ	perimeter factor g_c/g_a

Chapter 4

u	velocity in boundary layer
l	conditions at edge of boundary layer
r	recovery factor for turbulent layer
ρ	cowl lip radius
R	cowl inside radius

Chapter 5

$L_{\text{N}},l_{\text{n}}$	geometric dimensions ahead of entry (Fig. 5.6b)

n	number of shocks in a general system
r,ϕ	radial and angular coordinates in Prandtl-Meyer expansion
x, y	linear coordinates in Prandtl-Meyer expansion
μ	Mach angle, $\sin^{-1} 1/M$
ν	turning angle in expansion
K	constant in Prandtl-Meyer flow, function of γ
a, b, c	zones behind shock intersection point
L	distance of detached shock ahead of entry, measured to point where outer shock crosses stagnation streamline
r	distance out from axis of flow
β_s	slope of shock hyperbola at sonic point
A_σ	area of flow section between sonic point and cowl lip
λ_s	inclination of streamline at sonic point on shock
λ_{da}, λ_{dt}	angle of shock detachment from lip at free stream Mach number for axisymmetric and two-dimensional flow respectively
B, C	Mach number functions in expression for L
L_i	distance of shock intersection point ahead of entry
L_N	distance of tip of compression surface ahead of entry

Suffixes

w	conditions behind a normal shock
s	conditions behind a total compression system
i	quantities relating to total flow turning in oblique-shock compression

Chapter 6

χ	limiting contraction ratio for internal compression

Chapter 7

M_n	Mach number ahead of normal shock
A_n	net flow area ahead of normal shock

A_i	net flow area at entry
r	radial distance from axis of duct
ϕ	angle of lip overhang relative to shoulder of compression surface
A_s	pre-entry wetted surface area of compression system

Chapter 8

η	bleed efficiency
h	bleed or diverter height
ϕ	a momentum integral across the boundary layer
l	denotes outer edge of boundary layer
m	mass flow in boundary layer
en	suffix for bleed entry
ex	suffix for bleed exit

Chapter 9

C_D	drag coefficient
C_f	flat-plate friction coefficient
l	cowl length to maximum section
d	cowl diameter
ρ	lip radius
F	thrust force on cowl exterior
M_D	drag-rise Mach number
D_{DF}	maximum disturbed-flow drag
D_{NS}	maximum normal-shock drag
α, β	coefficients in definition of spillage drag
L_{max}	stand-off distance of bow shock ahead of bluff body
x, r	cylindrical coordinates
u, v	axial and radial velocities
ϕ	velocity potential
u_p, v_p	perturbation velocities
β	$\sqrt{M^2-1}$
r	body radius

η	cone semi-angle
U_1, T	functions of x in quasi-cylinder approximations
n	power index for Willis and Randall cowl profiles
K	empirical factor for blunt-lipped cowl drag

Suffixes

O, I, N	forms of drag definition
f	friction drag
p	pressure drag
o	pressure drag at full flow
m	maximum section of cowl
w	conditions behind normal shock

Chapter 10

f_1, f_2	functions of P_i/p_i

Chapter 11

$DC(\theta)$	distortion coefficient based on θ deg. sector
P_θ	mean total pressure in θ deg. sector
$K_{A2}, K_\theta, K_{rad}, K_{DA}, K_{DM}$	alternative distortion coefficients
b	weighting factor
n	number of rings of pitot tubes
m	number of pitots per ring
U	mainstream velocity round a duct bend
U'	reduced velocity, as in boundary layer
R	radius of bend
ΔC_{pbt2}	difference in pressure coefficient between bottom and top of duct after second bend

Chapter 12

N	engine rpm