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# Pseudo-shock waves and their interactions in high-speed intakes

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ABSTRACT

In an air-breathing engine the flow deceleration from supersonic to subsonic conditions takes places inside the isolator through a gradual compression consisting of a series of shock waves. The wave system, referred to as a pseudo-shock wave or shock train, establishes the combustion chamber entrance conditions, and therefore influences the performance of the entire propulsion system. The characteristics of the pseudo-shock depend on a number of variables which make this flow phenomenon particularly challenging to be analysed. Difficulties in experimentally obtaining accurate flow quantities at high speeds and discrepancies of numerical approaches with measured data have been readily reported. Understanding the flow physics in the presence of the interaction of numerous shock waves with the boundary layer in internal flows is essential to developing methods and control strategies. To counteract the negative effects of shock wave/boundary layer interactions, which are responsible for the engine unstart process, multiple flow control methodologies have been proposed. Improved analytical models, advanced experimental methodologies and numerical simulations have allowed a more in-depth analysis of the flow physics. The present paper aims to bring together the main results, on the shock train structure and its associated phenomena inside isolators, studied using the aforementioned tools. Several promising flow control techniques that have more recently been applied to manipulate the shock wave/boundary layer interaction are also examined in this review.



**Contents**



## 1. Introduction

Human kind has been fascinated by flight and speed for centuries. The combination of these two concepts has inspired multiple generations of aerodynamicists and engineers to put great effort in developing high-speed aircraft since the first successes in flight history. The purpose of this paper is to carry out a review covering approximately one century of technological research on air-breathing propulsion, focusing on the engine intake and, in particular, on the role of the isolator and the associated flow structures which develop inside.

For high-speed vehicles travelling at high altitudes significant compression and heating of the air entering the combustion chamber are required. The principle, which characterises the so-called air-breathing engine such as ramjet and scramjets

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**Nomenclature**

*Roman Symbols*

| | |
|---|---|
| $A$ | cross-sectional area ($m^2$) |
| $A/A_*$ | isentropic area ratio dependent on the Mach number only |
| $C_{f0}$ | initial friction coefficient |
| $C_P$ | specific heat of air at constant pressure (J/kg K) |
| $c$ | coefficient of the velocity deceleration in high-speed pseudo-shock regions |
| $D$ | duct diameter (m) |
| $D_\theta$ | degree of flow asymmetry |
| $H$ | duct height (m) |
| $K_W$ | airflow parameter |
| $M$ | mach number |
| $P$ | pressure (Pa) |
| $P_0$ | total pressure (Pa) |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $u$ | freestream velocity (m/s) |
| $w$ | Crocco number or dimensional velocity (m/s) |
| $x$ | generic position (m) |

*Greek Symbols*

| | |
|---|---|
| $\beta$ | experimental factor |
| $\gamma$ | ratio of specific heat capacity |
| $\delta$ | boundary layer thickness (mm) |
| $\delta*$ | boundary layer displacement thickness (mm) |
| $\zeta$ | correction factors for the mass flux |
| $\eta$ | correction factors for energy |
| $\theta$ | boundary layer momentum thickness |
| $\mu$ | mass flow ratio |
| $\rho$ | density ($kg/m^3$) |

*Subscript*

| | |
|---|---|
| 0 | total condition |
| 1 | initial condition |
| 2 | exit condition |
| $\theta$ | boundary layer momentum thickness |

*Superscripts*

| | |
|---|---|
| $\alpha$ | Reynolds number exponent |
| $*$ | sonic conditions |
| $'$ | high-speed region |
| $''$ | low-speed region |
| $-$ | mass averaging quantity |

(supersonic combustion ramjets), takes advantage of the high-speed airflow physics and compresses the air by means of internal geometry changes. This approach allows the engine to operate beyond the flight speeds at which the gas-turbine engine becomes inefficient and has become particularly attractive due to its simplicity for the absence of moving components.

The mechanism of flow compression, which takes place in a ramjet or scramjet inlet, finds other relevant applications characterised by the interaction of shock waves with the boundary layer such as supersonic compressors, ejectors, and wind-tunnel diffusers [1]. Therefore, the ability to accurately predict and control shock wave structures would provide a means to enhance the performance of flow devices operating at high speeds, the engine efficiency, or the mixing of fuel injected from the combustor walls [2].

The origins of ramjet technology were laid down around a century ago, in 1913, when a French engineer, René Lorin, published an article in the aviation magazine *L'Aérophile* expressing the idea to create jet propulsion by directing the exhaust gases from internal combustion engines into nozzles [3]. However, due to the lack of materials and technological limitations of the time, he could not have advanced this concept beyond the design stage [4].

Ramjet technology gained maturity after World War II. In 1947 the world's first aircraft powered exclusively by a ramjet, *Leduc 0.10*, illustrated in Fig. 1, successfully performed the first powered flight [6]. Since it could not take off unassisted, the aircraft needed to be carried and then released by a mothership at the appropriate altitude. In a subsequent flight, in 1949, the *Leduc 0.10* was released by a *Languedoc S.O.161* at 36,000 ft achieving the necessary pressure conditions for the ramjet to sustain power [7]. Nine years later, in 1958, the *Nord 1500 Griffon*, shown in Fig. 2, reached Mach 2.19, marking the first significant success in ramjet technology. A step further was made by Ferri and Nucci [8], who revolutionised the design of high-speed vehicles proposing a new type of supersonic inlet, as illustrated in Fig. 3, in which all the parts intended for the deceleration of the supersonic flow were placed outside of the diffuser. It was then recognised that an air-breathing propulsion vehicle could fulfil the possibility of hypersonic cruise and recoverable space launchers, a feature not achievable with rocket engines [9].

**Fig. 1.** The experimental ramjet aircraft Leduc 0.10 [5].


**Fig. 2.** The Nord 1500 Griffon in 1955 [5].