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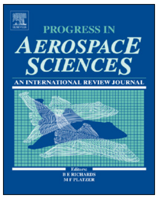

Transonic and supersonic ground effect aerodynamics

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ABSTRACT

A review of recent and historical work in the field of transonic and supersonic ground effect aerodynamics has been conducted, focussing on applied research on wings and aircraft, present and future ground transportation, projectiles, rocket sleds and other related bodies which travel in close ground proximity in the compressible regime. Methods for ground testing are described and evaluated, noting that wind tunnel testing is best performed with a symmetry model in the absence of a moving ground; sled or rail testing is ultimately preferable, though considerably more expensive. Findings are reported on shock-related ground influence on aerodynamic forces and moments in and accelerating through the transonic regime – where force reversals and the early onset of local supersonic flow is prevalent – as well as more predictable behaviours in fully supersonic to hypersonic ground effect flows.

Contents

1. Introduction

As an object passes through a compressible fluid such as air, the aerodynamics of the body are affected by density changes in the fluid around it. These aerodynamic effects are influenced – usually exaggerated – by proximity to a ground plane, in particular when shock waves reflect from the ground to interact with the body again one or more times. Traditionally, most aeronautical ground effect research (excluding study of vertical take-off and landing (VTOL)) has concentrated on the properties of wings in nominally incompressible flows, i.e. at relatively low subsonic Mach numbers. Applications have included aircraft in landing or takeoff modes, aircraft designed specifically to fly in ground effect, or in the case of inverted wings, high-performance racing vehicles. In these cases, proximity to the ground serves to enhance the lift (or downforce) performance of the wing, and often the overall aerodynamic efficiency as well.

Recent developments in the understanding of the aerodynamic influence of compressible ground effects and of shock/ground interaction for ground effect problems are timely, particularly given new or recurring interest in high-speed subsonic (free-stream Mach number, $M_\infty \geq 0.4$) wing-in-ground effect (WIG)

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Nomenclature

c	chord (m)
C_A	coefficient of axial force
C_D	coefficient of drag
C_L	coefficient of lift
C_M	coefficient of pitching moment
C_N	coefficient of force normal to the ground plane
C_P	coefficient of pressure
C_Y	coefficient of side force
C_Z	coefficient of side force (projectiles)
d	diameter (m)
D	drag force (N)
f	frequency (Hz)
h	height (m)
k	turbulent kinetic energy
l	length (m)
L	lift force (N)
M_∞	freestream Mach number
P_o	total pressure (Pa)
t	time (s)
u_∞	freestream velocity
α	angle of incidence
δ	boundary layer thickness
ε	turbulent dissipation rate
ω	specific dissipation rate

aircraft [1], magnetic-levitation space vehicle launch systems [2], and high speed rail [3] or tube transport systems. For more esoteric applications, it has also been speculated that the shock waves from an extremely low-flying supersonic aircraft could potentially be used as a means to suppress large-scale uncontrolled fires such as forest fires [4,5], or that the use of a sonic boom from a low-flying supersonic jet could be used as a non-explosive weapon to injure or disorient humans as part of a military operation [6].

To take aircraft as an example: in an comprehensive review of WIG aircraft aerodynamics and technology, Rozhdestvensky [1] affirms “it can be stated that little is still known with regard to GE (ground effect) at high subsonic Mach numbers”. By that time, in 2006, brief test studies indicated that increased aerodynamic efficiency may be possible for a high aspect ratio wing in ground effect at high subsonic Mach numbers [7], but other analytical treatments suggested the opposite [1]. However, the effects of the formation of shock waves either on a wing upper surface, or between the wing and the ground, were rarely considered in an applied or fundamental context until the most recent decade.

It should be noted that this paper is not concerned with phenomena such as sonic boom interactions with ground objects or water, or shock focussing effects from altitude, as these do not affect the aerodynamics of the body from which the waves originate. Similarly, while the case of a high speed subsonic or supersonic jet impinging on a surface from perpendicular or angled flow is certainly of considerable practical and fundamental interest [8], it lies outside the definition of a body travelling over a surface in close proximity that will suffice for the present work.

Ground effect is commonly categorised in terms of the clearance being within a few characteristic lengths of the ground plane in order for the aerodynamic performance of the body (i.e. an aircraft or vehicle) to be affected. Consider a wing of chord c at a height of h, for an h/c ratio of less than 5 (for other bodies a more meaningful characteristic length may be the total length, or diameter). Above this level, the ground has negligible influence, but at lower clearances the lifting performance of the wing is gradually enhanced with closer ground proximity. Extreme ground effect may be taken to mean a clearance that is less than 10% of the characteristic length of the body. This holds nicely into the transonic and supersonic domain, however, the ability for a body to be non-trivially influenced by a shock reflection from a ground plane at relatively high h/c ratios will later be described for Mach numbers close to 1.

Basic examples of the kinds of flowfields of interest for this review are shown in Fig. 1 using the example of an aircraft with relevant parameters annotated. The schematics are by no means a full survey of the possible flowfields for high speed ground effect scenarios. Fig. 1(i) shows a typical coalescence of waves from a supersonic aircraft to form a sonic boom felt at the ground, which would produce a characteristic N-shape pressure wave – with significant altitude, the waves cannot reflect back onto the aircraft again or into its wake, and with such distance the waves are also relatively weak. Thus, this flowfield is not considered to be a ground effect scenario.

Fig. 1(ii) presents a case where the ground clearance ratio, h/l, may be close to 1, with the Mach number close to 1 as well. In this situation, local areas of supersonic flow will form and the ground proximity will lead to a ground reflection that may impinge on the aircraft body again, and a ground-related asymmetry in the supersonic region would occur. A photograph highlighting this kind of reflection/interaction is presented in Fig. 2. In such a case, it is likely that a small effect on aircraft aerodynamic characteristics would occur. Fig. 1(iii) shows a supersonic case close to Mach 1 where oblique, near-inviscid reflection from the ground plane may occur depending on the Mach number and shock angle but it is also possible for the bow shock to bend to the wall and an entirely altered flowfield below the vehicle would establish.

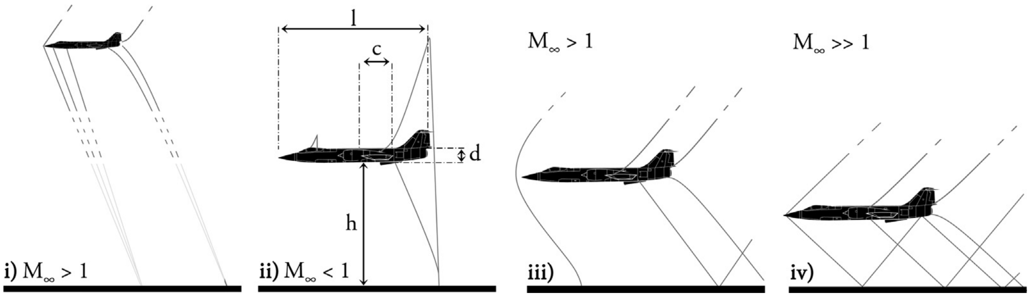

Fig. 1. (i) A high-altitude supersonic vehicle causes a sonic boom at the ground but is not operating in ground effect; (ii) within several height-to-lengths (h/l) at near-sonic speeds, shocks reflect from the ground (other relevant parameters are shown); (iii) at low-supersonic speeds both normal and oblique reflections may occur; (iv) at fully supersonic Mach numbers, one or more oblique shocks may interact with the ground and reflect back onto the vehicle when it is in close ground proximity.