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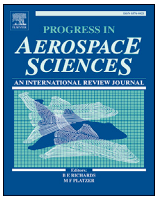

A review of recent developments in the understanding of transonic shock buffet

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ABSTRACT

Within a narrow band of flight conditions in the transonic regime, interactions between shock-waves and intermittently separated shear layers result in large amplitude, self-sustained shock oscillations. This phenomenon, known as transonic shock buffet, limits the flight envelope and is detrimental to both platform handling quality and structural integrity. The severity of this instability has incited a plethora of research to ascertain an underlying physical mechanism, and yet, with over six decades of investigation, aspects of this complex phenomenon remain inexplicable. To promote continual progress in the understanding of transonic shock buffet, this review presents a consolidation of recent investigations in the field. The paper begins with a conspectus of the seminal literature on shock-induced separation and modes of shock oscillation. The currently prevailing theories for the governing physics of transonic shock buffet are then detailed. This is followed by an overview of computational studies exploring the phenomenon, where the results of simulation are shown to be highly sensitive to the specific numerical methods employed. Wind tunnel investigations on two-dimensional aerofoils at shock buffet conditions are then outlined and the importance of these experiments for the development of physical models stressed. Research considering dynamic structural interactions in the presence of shock buffet is also highlighted, with a particular emphasis on the emergence of a frequency synchronisation phenomenon. An overview of three-dimensional buffet is provided next, where investigations suggest the governing mechanism may differ significantly from that of two-dimensional sections. Subsequently, a number of buffet suppression technologies are described and their efficacy in mitigating shock oscillations is assessed. To conclude, recommendations for the direction of future research efforts are given.

1. Introduction

Within a narrow region of the transonic flight regime, the interactions between shock-waves and thin, separated shear layers give rise to large amplitude, autonomous shock oscillations. This instability, commonly known as transonic shock buffet, acts as a limiting factor in aircraft performance. The reduced frequency of shock oscillation is typically on the order of the low-frequency structural modes, resulting in an aircraft that is susceptible to limit cycle oscillations (LCOs), and as a consequence, diminished handling quality and fatigue life.

Hilton & Fowler [1] first observed transonic shock-induced oscillations over six decades ago, yet the physics governing aspects of this complex phenomenon remains elusive. Various numerical and experimental investigations have identified two distinct types of shock buffet on aerofoils. Type I buffet typically occurs at zero incidence on biconvex sections and encompasses shock oscillations on both the pressure and suction surfaces of an aerofoil. Through the investigations of Mabey [2] and Gibb [3], a working model of Type I buffet was developed, whereby shock-wave/boundary layer interactions on both surfaces initiate phase-locked shock oscillations in opposing directions. As the shock on the upper surface moves upstream, it weakens. This permits reattachment of the separated zone and propels the shock downstream. The shock motion on the lower surfaces occurs in an identical manner, with a 180° phase shift, yielding self-sustained shock buffet cycle. As Type I buffet is critically dependent on the shock having sufficient strength to produce separation, several authors have proposed the prediction of buffet onset by the Mach number immediately ahead of the shock [2–4].

Type II shock buffet is characteristic of modern supercritical aerofoils and involves upper surface shock oscillations at non-zero angles of attack. A working model of this second type that is unequivocally accepted by the research community has yet to be determined. Early work by Pearcey [5,6], Pearcey & Holder [7] and Pearcey et al. [8] was instrumental in

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Nomenclature

M	freestream Mach number
α	freestream angle of attack/vortex generator pitch angle
Re	chord-based Reynolds number
x_s	mean shock location
a_p	downstream pressure perturbation convection velocity
a_u	upstream pressure perturbation convection velocity
c	chord
b	span
τ	buffet period/time delay
ϕ	phase
a	speed of sound
M_c	local Mach number
R	constant
M_s	upper surface Mach number
ρ	freestream density
q	two-dimensional flow state vector $\{\rho, u, v, T, \tilde{\nu}\}$
u	streamwise velocity
v	transverse velocity
T	temperature
t	time
ω	frequency
S	blending function
C_L	lift coefficient
f	frequency
y^+	nondimensional wall-normal distance
$\tilde{\nu}$	eddy viscosity
d	wall distance (length scale)
$\tilde{S}$	local deformation rate
Δ	grid size ($= \max(\Delta_x, \Delta_y, \Delta_z)$)
C_{DES}	constant
$\tilde{d}$	modified length scale
f_d	delaying function
x^+	nondimensional streamwise distance
z^+	nondimensional spanwise distance
τ_p	period downstream propagation
τ_u	period upstream propagation
$\tau_{u,u}$	period upstream propagation above upper surface
$\tau_{u,l}$	period upstream propagation below lower surface
f_{sb}	shock buffet frequency
f_α	pitch natural frequency
f_h	heave natural frequency
f_{α_0}	wind-off pitch natural frequency
f_{h_0}	wind-off heave natural frequency
ω^*	reduced frequency
ζ	structural damping
V^*	reduced velocity
Λ	sweep angle
δ	TED deflection
$\bar{\delta}$	mean TED deflection
A	TED amplitude
P	pressure
β	trailing edge flap deflection/vortex generator skew angle
C_{l0}	balanced lift coefficient
λ	dimensionless controller gain/spanwise vortex generator spacing
h	vortex generator height
l	vortex generator length
d	fluidic vortex generator orifice diameter
C_μ	momentum coefficient
θ_{ramp}	shock control bump ramp angle
l_{tail}	shock control bump tail length

characterising the various forms of upper surface separation, particularly shock-induced separation bubbles, experienced by conventional aerofoils at transonic conditions. Two distinct modes of separation were identified; Model A consisting only of a shock-induced separation bubble and Model B for which trailing edge separation is either additionally present or incipient. Three variants of Model B were also identified; rear separation provoked by the formation of a bubble, rear separation provoked by the shock and a third in which rear separation is present from the outset.

The investigations by Pearcey and his co-authors culminated in the first model for the prediction of buffet onset in Type II shock oscillations; a relationship between trailing edge pressure divergence and large-scale unsteadiness. For aerofoils in which separation bubbles are present, Pearcey [6] and Pearcey & Holder [7] related the onset of buffet to the Mach number or angle of attack for which the separation bubble extends to the trailing edge and bursts. This *bubble bursting* mechanism governing buffet onset is easily identified through the divergence of trailing edge pressure. Although bubble bursting as the cause of onset was initially supported by experimental and computational findings, recent investigations have produced conflicting evidence [9,10] and bubble bursting is now widely discounted as a potential mechanism governing shock buffet.

In the seminal work of Tijdeman [11], three distinct modes of shock motion were characterised experimentally by observing the effects of sinusoidal flap deflections on the NACA 64A006 aerofoil. Type A shock motion is represented by near sinusoidal shock oscillations across the upper surface of the aerofoil, for which the shock is present throughout the entire buffet cycle but varies in strength, with maximum shock strength achieved during the upstream excursion. Type B motion resembles Type A; however, the magnitude of shock strength variation is considerably larger, resulting in a disappearance of the shock during the downstream excursion. Type C motion is qualitatively distinct from the preceding modes. The shock travels upstream, initially strengthening and then weakening, but continuing to move forward, eventually propagating forward into the oncoming flow as a free shock-wave. Although these shock motions were originally identified with oscillating aerofoils, each has subsequently been observed in rigid wing sections at certain flight conditions [12].

Considering Tijdeman Type A [11] shock motions, Lee [13] proposed an acoustic wave-propagation feedback model as the underlying mechanism governing the autonomous shock oscillations. In this model, the motion of the shock-wave generates downstream propagating pressure waves, with the instability growing as it travels from the separation point through the shear layer. The separated flow induces a de-cambering effect, and interactions with the flow at the trailing edge produce pressure waves that travel upstream in the subsonic flow above the boundary layer. Interaction between these upstream propagating disturbances and the shock completes a feedback loop, yielding sustained shock motion. Analogous to the bubble bursting mechanism of Pearcey [6], conflicting evidence has been presented in literature regarding the validity of Lee's [13] model.

A mechanism underlying Tijdeman Type B [11] shock oscillations on the NACA 0012 aerofoil based on an unstable shock-wave/separation bubble interaction has also been proposed by Raghunathan et al. [14]. The authors highlight that the shock strength must be sufficient to induce a separation bubble. The appearance of this separation bubble initiates periodic motion of the shock, which is sustained through the alternating expansion and collapse of the bubble on the upper aerofoil surface. Throughout the cycle, the varying extent of the separated region acts to change the effective camber of the aerofoil, with the trailing edge playing an integral role in communicating flow states between the suction and