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Computational and experimental investigation into aerodynamic interference between slender bodies in supersonic flow

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ABSTRACT

Aerodynamic interference can occur between high-speed bodies when in close proximity. A complex flowfield develops where shock and expansion waves from a generator body impinge upon the adjacent receiver body and modify its aerodynamic characteristics. The aims of this paper are to validate a computational prediction method, to use the predicted solutions to interpret the measured results and to provide a deeper understanding of the associated flow physics.

The interference aerodynamics for two slender bodies were investigated through a parametric wind tunnel study where the effect of axial stagger was investigated for different receiver body incidence angles. Measurements included forces and moments, surface pressures and shadowgraph visualisations. Supporting computational predictions provided a deeper understanding of the underlying aerodynamics and flow mechanisms. Good agreement was found between the measured and predicted interference loads and surface pressures for all configurations.

The interference loads are strongly dependent upon the axial impingement location of the primary shockwave. These induced interference loads change polarity as the impingement location moves aft over the receiver. Distinct interference characteristics are observed when the receiver is placed at high positive incidence, where the impinging shock has a strong effect on the crossflow separation location. Overall, the observed interference effects are expected to modify the subsequent body trajectories and may increase the likelihood of a collision.

1. Introduction

Aerodynamic interference occurs when two bodies are placed in close proximity in a supersonic flow. This can affect the force and moment characteristics and change the subsequent trajectory of the bodies [1–6]. The interference flowfield is primarily dominated by shock and expansion waves, which originate from an adjacent generator body and impinge upon the primary body of interest (the receiver). The induced changes in static pressure and flow angularity across the impinging disturbances modify both the local and overall aerodynamics of the receiver in comparison to the isolated body case.

There is currently, very little information in the open literature on the effects of mutual interference between slender bodies at high-speed. Previous work reported on this complex research topic can be categorised into three main areas. Many of the papers report the integrated force and moment characteristics of a slender body in close proximity to a second body or flat plate. In most cases there is a very limited explanation about the underlying aerodynamics and about why the integrated effects change with the primary geometric parameters such as body incidence and separation distances. These investigations were usually experimental and focussed on receiver bodies which remained at low incidence. The second category of previous work studied the more detailed aspects of shock-body interactions. These were primarily wind tunnel investigations which used simplified experimental arrangements such as planar shockwaves impinging onto axisymmetric bodies. Finally, there are a small number of computational studies which attempt to understand the problem of high-speed mutual interference. The important contributions from these three areas are now briefly summarised and used to place the current work in context.

An early experimental investigation by Gapcynski and Carlson [3] examined two axially aligned bodies of revolution at a free-stream Mach number of $M_\infty = 2.01$. These researchers reported changes in normal force coefficient of up to $\Delta C_Z = 0.1$ as a result of the interference flowfield between the bodies. Another study showed that a planar shock impinging on a cone–cylinder body at zero incidence induced changes in normal force and pitching

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Nomenclature

a	sonic velocity ($\mathrm{m\,s^{-1}}$)
C_p	pressure coefficient $C_p = \frac{p - p_\infty}{q_\infty}$
ΔC_p	pressure coefficient difference at given body location $\Delta C_p = C_p - C_{p,iso}$
$C_{X,t}$	measured axial force coefficient $C_{X,t} = \frac{F_X}{q_\infty S}$
C_X	axial force coefficient, corrected to zero base drag $C_X = C_{X,t} + \frac{S_b(p_b - p_\infty)}{q_\infty S}$
C_Z	normal force coefficient $C_Z = \frac{F_Z}{q_\infty S}$
C_m	pitching moment coefficient (about $x = 0$, $y = 0$, $z = 0$) $C_m = \frac{M_Y}{q_\infty S D}$
ΔC_Z	normal force interference load at a given σ_R $\Delta C_Z = C_Z - C_{Z,iso}$
ΔC_m	pitching moment interference at a given σ_R $\Delta C_m = C_m - C_{m,iso}$
dC_Z/dx	local normal force coefficient ($\mathrm{m^{-1}}$)
D	maximum body diameter at base (m)
F_X	receiver body axial force (N)
F_Z	receiver body normal force (N)
L	maximum body length (m)
M_Y	receiver body pitching moment (Nm)
M	Mach number $M = \frac{U}{a}$
N_{fine}	total number of cells in fine grid
N_{med}	total number of cells in medium grid
p	static pressure ($\mathrm{N\,m^{-2}}$)
p_b	model base pressure ($\mathrm{N\,m^{-2}}$)
q	dynamic pressure ($\mathrm{N\,m^{-2}}$)
Δr	distance from generator leading edge to receiver nearside impingement location (m)
r_{eff}	effective grid refinement ratio for an unstructured grid $r_{eff} = \left(\frac{N_{fine}}{N_{med}}\right)^{1/3}$
Re_D	freestream Reynolds number based upon base diameter $Re_D = \frac{\rho_\infty U_\infty D}{\mu_\infty}$
S	receiver body reference area ($\mathrm{m^2}$)
S_b	receiver body base area ($\mathrm{m^2}$)
T	static temperature (K)
U	velocity ($\mathrm{m\,s^{-1}}$)
X, Y, Z	body fixed axes attached to receiver leading edge
X_w, Y_w, Z_w	wind axes (X_w is aligned in the freestream flow direction)
Δx	axial stagger between bodies (m)
x'	axial impingement location of the primary disturbance measured from receiver leading edge (m)
x_{res}	spatial resolution of PSP (m)
Δy	spanwise offset between bodies (m)
Δz	lateral separation between bodies (m)

Greek symbols

β	body sideslip angle (°)
δ	uncertainty for a given parameter
μ	dynamic viscosity ($\mathrm{m^2\,s^{-1}}$)
$\theta_{s,G}$	generator bow shock angle, measured from freestream flow axis (X_w–Y_w plane) (°)
θ_{obl}	shock obliqueness angle ($\theta_{s,G}$–σ_R) (°)
ρ	density ($\mathrm{kg\,m^{-3}}$)
σ	total incidence angle (°)
σ_{eff}	effective total incidence based on interference load (°)
Δ	difference of a given parameter from isolated configuration
φ	receiver azimuth angle (°)

Subscripts

near	receiver nearside conditions
iso	isolated conditions
0	stagnation conditions
∞	(inf) freestream conditions
R	receiver body
G	generator body

moment coefficient in the range of $-0.22 < \Delta C_Z < 0.048$ and $-0.39 < \Delta C_m < -0.20$ [1]. The pitching moment values reported by Wilcox [1] have been transformed to be consistent with the definition used throughout this paper. These induced changes were found to increase when the receiver body was placed at an incidence of $\sigma = 15°$. Interference effects of this order are likely to modify the trajectory of the slender body [6]. This would become significant if the slender body pitches, or translates, towards the generator since this may subsequently lead to a collision. A more recent study, which investigated two axially aligned slender bodies at zero incidence, found that the polarity of the resulting pitching moment load was strongly dependent upon the lateral separation between the bodies [7]. It has been noted by several authors that the mutual interference flowfield and resulting induced pitching moment could have a notable effect on the trajectory of both bodies [3,4,8–10].

In addition to studies which report the overall interference loads, it is important to understand the detailed underlying flow physics. Of particular interest are the shock-body interactions which have been studied previously for a number of configurations [7,8,11–15]. Brosh et al. [14] and Hung [2] investigated a wedge-generated shock impinging on a cylinder at $M_\infty = 3$ which showed that the shock footprint, in terms of local pressure rise, decreased as the shock diffracted around the body. The difference between the strength of the nearside and farside regions of augmented pressure significantly affect the local normal force distribution over the body. Finally, the nearside pressure rise also resulted in a local boundary-layer separation and a double-reflected shock structure around the primary induced separation bubble. Both studies found that due to the induced circumferential pressure gradient a strong crossflow occurred which resulted in a local separation on the farside of the receiver body.

Finally, in addition to the mainly experimental research discussed above, there have been some computational studies of mutual interference for slender bodies at high speeds [14,16,17]. Brosh et al. [14] and Hung [16] conducted one of the few CFD validation exercises using a thin-layer approximation of the 3D RANS equations to simulate the experimental set-up tested by Brosh et al. [14]. This configuration featured a planar shock impinging onto a cylinder which was at zero incidence. Hung focussed on assessing the ability of the CFD solver to predict the complex shockwave boundary-layer interactions around the cylinder. It was reported that the prediction of surface axial pressure distributions on the cylinder were in good agreement with the measurements. However, some of the viscous flow structures were not predicted well by the CFD. In particular, the flow topology on both the nearside and farside of the cylinder which included induced flow separations were not predicted accurately. More recently, Volkov and Derunov [7] investigated the effect of lateral separation between two axially aligned slender bodies and found reasonably good agreement between the measured and predicted loads. Finally, both Malmuth and Shalaev [8] and Fedarov et al. [13] have reported theoretical approaches to the prediction of overall loads on two slender bodies in close proximity.

It is clear from the discussion above that there are a number of knowledge gaps related to the understanding and prediction of