Technical Notes

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Upstream-Influence Scaling of Sharp Fin Interactions

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Introduction

UPSTREAM influence is a salient feature of all shock-wave/boundary-layer interactions. For sharp-fin-generated swept interactions a scaling law has been developed[1,2] to describe the upstream influence as a function of Reynolds number and normal Mach number. Most of the data validating this fin-interaction scaling law,

$$\tilde{\zeta}_U/M_n = f(\tilde{\xi}_U) \quad (1)$$

where $\tilde{\xi}_U = (\xi_U/\delta)Re_\delta^b$, $\tilde{\zeta}_U = (\zeta_U/\delta)Re_\delta^a$, $a = b = 1/3$ are empirical constants, and (ξ, ζ) is a shock-based coordinate system (Fig. 1), were obtained at Mach 3 (Ref. 1). This Note presents data extending Eq. (1) to Mach numbers of 2.5–4. Furthermore, arguments are presented to suggest that this scaling law may be valid over a wider Mach number range by making a connection between Eq. (1) and classical hypersonic similarity.

Fin interactions were studied at $M_\infty = 2.47$, 2.95, 3.44, and 3.95 with corresponding $Re = 54$, 59, 64, and $76 \times 10^6\ \mathrm{m}^{-1}$. The undisturbed boundary layer developing over the flat-plate test surface transitioned naturally and was two dimensional, turbulent, adiabatic, and in equilibrium at the test region. The incoming boundary-layer thickness δ was 3.3 ± 0.1 mm for the four Mach numbers.[2]

The upstream-influence data from surface-flow visualization (ξ_U, ζ_U) were normalized by δ (indicated by overbars on the symbols). At each of the four individual Mach numbers, the upstream influence scales according to

$$\bar{\zeta}_U/M_n = f(\bar{\xi}_U) \quad (2)$$

(plots not shown for brevity).[3] To further determine if there is a residual M_∞ effect in the scaling, the scaled data at each Mach number were replaced by third-order least-squares curve fits to simplify the task of examining the 36 test cases. The standard deviation of the data scatter about the fitted curve at each Mach number was ±5–10% and is indicated by a cross in Figs. 2a and 2b. The curve fits in Fig. 2a show that Eq. (2) is applicable to $2.5 \le M_\infty \le 4.0$, with no noticeable M_∞ effect within the data scatter. Thus, the effect of shock strength on the interaction scaling can be accounted for by a shock-based coordinate system and a scaling by M_n, as expected in a quasiconical interaction.[1]

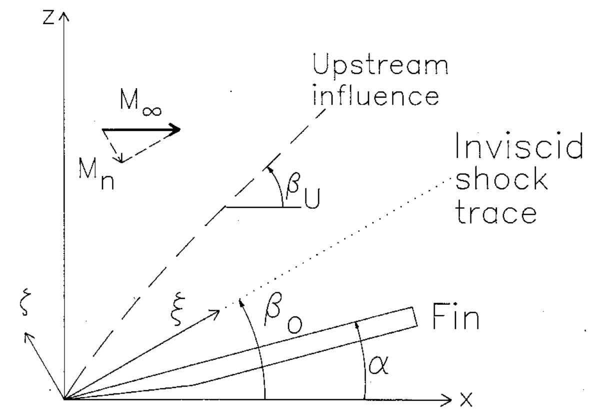
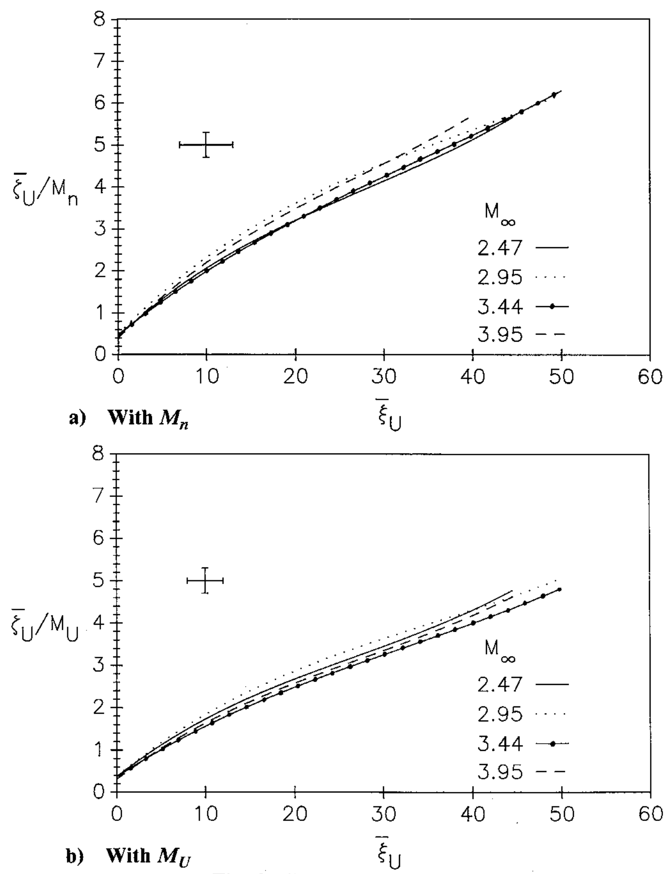


Fig. 1 Fin.



a) With M_n

b) With M_U

Fig. 2 Interaction scaling.

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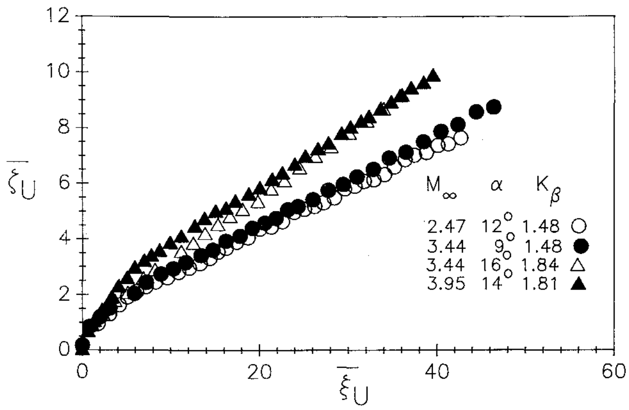

Fig. 3 Hypersonic similarity of the upstream-influence line.

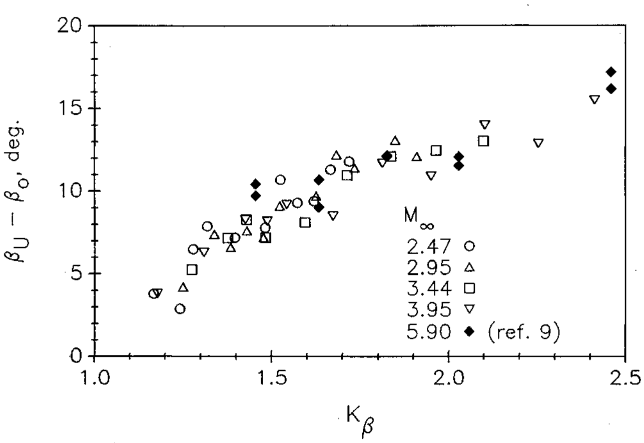

Fig. 4 Hypersonic similarity of ($\beta_U - \beta_o$).

Furthermore, from the present data we infer that there is a negligible M_∞ effect on the Reynolds number scaling constants a and b. With the Reynolds number kept fairly constant for the four test Mach numbers, the data correlated well according to Eq. (1) with $a = b = 1/3$. Inger's analysis[4] showed that a and b also depend on the wake strength parameter of the incoming boundary layer. However, in the present experiments Π was essentially constant (0.54–0.58).

A quasiconical free-interaction principle also holds for fin interactions.[5,6] In particular, for separated interactions the upstream-influence line also marks the most upstream excursion of the unsteady separation shock. The upstream-influence line lies at an angle β_U (Fig. 1), and its inclination angle scales with $M_U = M_\infty \sin\beta_U$ (Ref. 6). Therefore, the interaction may be expected to scale according to

$$\bar{\xi}_U/M_U = f(\bar{\xi}_U) \tag{3}$$

Third-order least-squares curve fits to the data sets at each value of M_∞ are plotted in Fig. 2b, illustrating this behavior. This scaling, previously reported by Zheltovodov et al.,[7] reinforces the local similarity concept embodied in the quasiconical free-interaction principle.

Inviscid hypersonic flows past slender bodies of thickness-to-chord ratio τ scale according to a hypersonic similarity parameter, $K = M_\infty \tau$.[8] Analogously, swept (hypersonic) interaction scaling by M_n or M_U is similar to scaling by $K = M_\infty \alpha$ since $M_n = M_\infty \sin\beta_o \approx M_\infty \beta_o = K_\beta$ and $\lim_{M_\infty \to \infty} K_\beta \to K$. In the supersonic regime, however, K_β appears to be a better similarity parameter. Two examples from the present experiments with approximately equal values of K_β correlate well (Fig. 3), demonstrating this hypersonic similarity scaling by K_β. Furthermore, the far-field slope of $\bar{\xi}_U$, $\tan^{-1}(\beta_U - \beta_o)$, *can be obtained. Figure 4 shows that* $(\beta_U - \beta_o)$ also scales with K_β. The figure includes data extracted from surface pressure measurements by Law,[9] who provide some additional evidence to the validity of the proposed hypersonic scaling. (Further work at high Mach numbers with larger values of K_β is necessary to properly demonstrate the validity of the proposed hypersonic scaling.)

The preceding evidence demonstrates that hypersonic similarity, although rooted in inviscid theory, is applicable to strong viscous-inviscid interactions as well. This reinforces a previously stated view[1] that inviscid parameters are dominant in the overall scaling of such interactions. Viscous effects are accounted for by $Re_\delta^{1/3}$ in Eq. (1). Hence, the complete interaction scaling parameter $Re_\delta^{1/3}/M_n$ is, in the hypersonic limit, simply $Re_\delta^{1/3}/K$.

As an afterthought, Korkegi's and Zheltovodov's incipient separation criteria,[1]

$$M_\infty \alpha_{\text{incip}} = K_{\text{incip}} = 0.3 \quad \text{and} \quad M_\infty \alpha_{2\text{incip}} = K_{2\text{incip}} = 0.6 \tag{4}$$

respectively (where α is in radians), can be viewed as results of hypersonic similarity. Incipient separation appears remarkably insensitive to Reynolds number in studies conducted to date. However, the dependence of the interaction on the incoming boundary-layer state (e.g., the wake parameter[4]) or on wall temperature conditions have not been thoroughly investigated.

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