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TRANSITION AT HYPERSONIC SPEEDS

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Robert G. Voigt
Director

TRANSITION AT HYPERSONIC SPEEDS*

Mark V. Morkovin

(A) PREFATORY CONJECTURES ON THE PHYSICS OF HIGH-M INSTABILITIES

(1) Upstreaming and cross-flow signal communication (influence) is essential for instabilities at supersonic and hypersonic speeds: MACK'S RULES of allowable parameter zones, Mack (1984). Figure 1 illustrates their application to insulated flat plates. Figure 2 demonstrates radical changes in wakes as upstream influence is almost cut off by the local supersonic regions indicated by the Mach waves.

(2) Therefore, there will be preference for "more subsonic" skew waves (contrary to the Squire theorem) probably even in case of nonlinear instabilities. Exceptions are Mack's primary instability higher modes, Figures 1 and 3, which correspond to acoustic trapping of energy near the wall. Trapped, they do not radiate outward. The reflections of the pressure (Mach) waves at the wall and the sonic layer in Fig. 3 are more efficient for non-skew waves. Secondary instabilities and "bursting" (if any) are likely to have (highly) skewed geometries.

(3) The amplified inviscid modes start and end at loci of families of neutral modes, Figure 1. One important family is associated with the generalization of Rayleigh's "sliding and roll-up laminar" of "inflectional"

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*At the request of the editors, Morkovin's 4-slide position paper has been expanded to be more comprehensible to nonspecialists and non-old timers.

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instability. But this kinematic motion now centers on the local maxima of mean $-\bar{\rho}(\frac{\partial U}{\partial y})$, the angular momentum, not the vorticity $-\frac{\partial U}{\partial y}$. This generalized inflection point moves to the outer regions of the boundary layer by M of 4 and the associated evolved TS waves cease to be viscously enhanced. Mack's higher modes then become primary suspects for the first instability on the road to transition on smooth walls.

(4) At relative supersonic speeds Reynolds stresses are generated by potential u, v motion, radiating energy away to the first order. This will probably increase the importance of pressure fields (hyperbolic fields) at hypersonic speeds and possibly modify the structure of unstable and turbulent hypersonic wall layers for $M > 5$. This feature will also probably sap energy from potential pairing of spanwise (ω_z) vortices--which involves violent v(x,t). Amalgamation of equal and unequal (nearly) streamwise vortices, ω_x, should be much less limited and could possibley dominate secondary instabilities.

(5) Centrifugal instability and Görtler vortices, ω_x, should be similarly unimpeded. In fact, G vortices evidently lead to transition on the top and bottom of supersonic tunnel walls, where there is concave curvature. There is a serious problem of computing growth rates, see Hall (1982, 1983).

(6) Generation of streamwise vorticity, ω_x, by isolated and distributed 3-dimensional roughness may be as important as at low speeds. 3-D roughness definitely causes transition at supersonic speeds, bypassing the known models of instability. Wall cooling makes roughness more powerful and dangerous.

(7) However, 2-D single roughness (e.g., trip wires) are increasingly less effective, because the separated mixing layer becomes more stable with M. Basically, this is associated with Mack's Rules on cross-stream influence,

see item (1) above. The importance of the effect is illustrated in Figure 4 by the rapid decrease of the spatial amplification rate, $-\alpha_i$ or $-k_i$, with M as computed for mixing layers (shown in the inset) by H. S. Gropengiesser (1968). Figure 5 shows the corresponding effect on experimentally observed Reynolds number of transition, Re_t. Note that for these experiments the acoustic sidewall radiation from tunnel walls increases more than linearly with M (which should decrease Re_t substantially, contrary to the trend in Fig. 5). The stabilization is therefore stronger than the experimental rise in Fig. 5.

(8) The nonlinear Vorticity-Stretching and Tilt Mechanism, so important in secondary instabilities, acts full force at high speeds, modulated by density stratification $\bar{\rho}(y)$. The mechanism probably insures the existence of turbulence at hypersonic speeds.

(9) The Biot-Savart induction law survives only in a linearized form. We must also include the fact that its effect is propagated at the speed of sound: it operates within Mach cones. Such constraints on "interactions" are probably meaningful in the nonlinear, density-modulated reality, even in presence of real-gas effects.

(10) As at low speeds, transition will be generally forced by the disturbances in the free stream. Because of the body shock wave, the parabolic free-stream disturbances (vorticity, τ_1 and entropy-temperature spottiness, σ_1) can influence the boundary layer directly only when their carrier-streamline enters the shock near its apex (near D in Figure 6a). Together with the hyperbolic isentropic pressure disturbances, π_1, they generally influence the layer at E^1, indirectly through the pressure fluctuations π_2, resulting from their interaction with the shocks at E in

Fig. 6a and 6b. Small perturbations τ_1, σ_1, or π_1 generate first-order post-shock disturbances τ_2, σ_2, and especially π_2, computable by linearizing shock equations and Fourier superposition, e.g., Morkovin (1960). In wind tunnels for $M_1 > 3$, the disturbances are dominated by sound wave-packets, π_1, emanating from turbulent eddies and roughness on the side-walls. In atmospheric flight, some vorticity τ, may be present but density-temperature spottiness σ_1 (as in tunnels with stream mixing up-stream of the test section) and aerosols, dust, and moisture are probably the primary forcing agents. Recently, C. Donaldson suggested that particulates may be largely responsible for the transition in ballistic-range tests. This calls for controlled tests.

(11) Figure 6c illustrates how a roughness or temporary increase in pressure at the wall may feed back additional π_2 type disturbances at E'. Under the extreme heat generated in hypersonic flight local buckling or erosion of surface is likely as in ICBM flights. When three-dimensional, such roughness also creates dangerous streamwise vorticity: item (6) above.

(12) As Khan and Reshotko (1979) demonstrated at hypersonic speeds, attention has to be paid increasingly to the instability of the combined entity of the entropy layer and the boundary layer. Possibly the "reflections" from the shock wave, illustrated in Fig. 6c will have to be taken into account as well, at higher hypersonic speeds. Stetson and DT (1984) found experimental evidence of instability at M_1 of 8 in the entropy layer of a blunt body, which contaminated the boundary layer. It coincided approximately with a one-sided maximum of the angular momentum of Section (3).

(B) ON THE STATE OF KNOWLEDGE OF HYPERSONIC TRANSITION

The Quality of our Knowledge

What do we really know well enough to be able to plan rationally a program of research? or a design costing billions? First, we must restudy critical reviews of the past: Reshotko (1976), Whitfield and Dougherty (1977, with its concluding section entitled "Current State of Confusion"), Morkovin (1969, 1977, 1978). Shortly after 1977, most funding for hypersonic research and testing was terminated, adding an experiential and memory gap to our predicament.

We should reemphasize generalized Guideline No. 4, Reshotko (1976), recommending cross-checking and duplicating in different facilities and through distinct computer codes of results on instabilities and transition. Most of the information covered by the above reviews is not buttressed by such cross-checks and forms therefore a dubious data base for correlations and predictions. Two historical examples should illustrate the severity of our uncertainty predicament.

Thirty years ago, also in March, twenty experts, similary assembled, concluded from flight data on the blunt nose of X-17 that early transition takes place at Re_θ (θ = momentum thickness) of 150 to 300, despite the highly stabilizing favorable pressure gradient. This shocking BYPASS of expected instabilities vitiated two ICBM nose-cone designs. This Blunt-Body Paradox has not yet been rationally explained (!) and remains a warning to explore possible bypasses in designs involving transitions, see Morkovin (1978).

In the sixties, three European countries cooperated on the Jaribu MK.2 Project where the same instrumented parabolic-nose model was tested in flight and in a ground facility. Despite "almost perfect aerodynamic simulation" at

M = 7.17, Lemcke, et al. (1970) and Naysmith (1970) reported agreement only on the purely laminar and purely turbulent rate of heat transfer along the vehicle skin. Local Re_t of transition in the presumably acoustically contaminated tunnel was higher, above 10^6 even at angles of attack of 5^o. In the presumably little disturbed flight, Re_t remained below (!) 0.5×10^6, for undetermined reasons, another set of discordant results. How can such discordances be removed? The reports should well be read by all predictors of high-speed transition.

Lists of Open Questions

In 1971, the author compiled a two-page list of "Major Open Questions Relevant to (high-speed) Applications," (also in Mack and Morkovin, 1971). Only one conceptual question seems to have been clarified since then (by Lysenko and Maslov, 1981, 1984) namely the nature of the dependence of Re_t reversal and rereversal with increasing wall cooling in supersonic wind tunnels. In their clever experiments, the reversal was shown to correspond to frost formation on the wall, the frozen droplets at first forming effective discrete roughness. (The roughness bypass again rears its ugly non-quantified head!) With further cooling, there is a tendency to form a wavy considerably smoother frozen film, thus moving transition downstream again. We can only hope that this qualitative explanation is valid for the other observations of the phenomena. This will have little relevance for flight, but it is essential to explain the experimental trends vis-â-vis theory.

In 1987, we have to add the problems associated with real-gas effects and heat-induced surface changes to the list! How many parametric degrees of freedom does that add?

It would be presumptuous for anyone to compose a list of suggested physical or numerical experiments for different high-speed and computer facilities. One may educate oneself to become a constructive critic with respect to such facilities but only the local practitioners know their tools well enough to propose a program optimally suited to their facilities. See further comments on Desirable Research and Development in Section V in Morkovin (1969) which also states: "Without organized cooperation, the practical open questions of Section IV are unlikely to find even partial answers in a reasonable time span. The U. S. Transition Study Group was formed, under E. Reshotko, to provide some of the national cooperation initially on hypersonic transition.

Eighteen years later, national pressures apparently cannot wait for the resumption of a more fundamental research program. Under the circumstances, a crash program such as outlined by D. Bushnell earlier today seems reasonable, provided special attention is conscientiously paid to the possible bypasses (in particular to roughness-induced transition which also governed the Shuttle and to the risks involved in the earliest bypasses.

Minimum Re for Self-sustained Turbulence at a Wall, $Re_{turbmin}$

At very low Reynolds numbers, triggered turbulence damps out though relatively slowly, i.e., does not sustain itself. For each flow geometry, Mach number, and wall cooling, there is a minimum $Re_{turbmin}$ at which wall turbulence can sustain itself and develop downstream through transverse contamination (a bypass mechanism). With exception of the case of low-speed flat plates, it seems that $Re_{turbmin}$ is always lower than the critical Re_{cr} for amplification of infinitesimally small disturbances (e.g., TS waves), the lowest Re on the neutral curve. The conditions for $Re_{turbmin}$ have remained almost uninvestigated. The more or less known cases, all at low speeds, are sketched in Figure 7. Note that favorable pressure gradients shift $Re_{turbmin}$ forward of Re_{cr} on blunt bodies though the numbers are not known. It is possible that the 1957 $Re_{\theta} = 150$ criterion established on the X-17 corresponds to $Re_{turbmin}$ for hot accelerated flows over cooled axisymmetric stagnation flow regions. The 1956-1960 NACA flight tests added a dimensional consideration: a stylus-indicated roughness below 5 microinches r.m.s. for laminarity, see discussion, pp. 46-47 of Morkovin (1969).

When a design in presence of transition involves lives, it would seem appropriate to use the conservative $Re_{turbmin}$ for the lowest estimate. This is one area where numerical experimentation may be helpful: because of the low Re, the relevant turbulent scales should be resolvable on our advanced computers. Intentionally highly disturbed boundary layers may exhibit ultimately (i.e. far enough from inital conditions) decaying turbulence--evidence of Re below the self-sustaining condition. The cases of Fig. 7 can be used for calibration at low M.

The increment of $Re_{t\text{-}design}$ over $Re_{turbmin}$ is a measure of the risk we are willing to undertake. Any $Re_{tdesign}$ clearly needs unequivocal support from a sufficiently dense data base. If degradation of Re_t should occur on a prototype, it does matter whether it results in a mere percentage decrease in performance of the vehicle or in more catastrophic consequences. It is our professional responsibility to convey to the designers (who cannot be expected to appreciate the intricacies of multiple instabilities) the non-deterministic, poor-statistical-sample quality of our transition prediction. Perhaps this could be done by carefully defined bracketed estimates, with explicit caution about bypasses.

Major Difficulties and Opportunities

One objective of unstinting cooperation is to collectively overcome the severe shortcomings of each of our tools, experimental, analytical or numerical in the face of the very large number of parameters. The low-speed techniques that brought us the degree of understanding (except for roughness effects) of the sequence of instabilities leading to turbulence are essentially unavailable at high speeds. The inclement hypersonic environment (surface heating, large aerodynamic loading on instruments, poor disturbance or particulate control) for practical purposes precludes the needed higher-Re microscopic measurements and intentional perturbations which identified at low speeds the competing classes of primary and secondary instabilities, and the spreading and intermittent character of the transition phenomenon. Identification of potentially dominant primary instabilities and bypasses is crucial, as recognized in Bushnell's program. Analysis and numerics may have to do much of that for us, along the lines outlined by L. M. Mack at this meeting.

However, it may be a provident signal that Mack (1986) reports a significant discrepancy between calculated instability modes and those inferred from hot-wire measurements of Stetson and TDS (1983) for as simple a body as a cone at zero angle of attack at M_1 of 8! In absence of measurement of response to controlled monochromatic disturbances, the interpretation of evolution in x of broad environmentally induced spectra in terms of passive two-dimensional theory, where receptivity for each frequency f is assumed to be a delta function at the neutral curve, $\delta[x - x_{cr}(f)]$, may bias the inferred results, but is unlikely to resolve the discrepancy of preferred f development. Nonhomogeneity in f of the reservoir fluctuations, their wave-packet and three-dimensional character, and some feature of the boundary layer not completely reflected in the theory may also contribute to the explanation.

Credibility of the theory is essential. We need a resolution of the above cone discrepancies! How otherwise can any N-factor approach be considered rational, even with N = 0?

Parameter Profusion and the Unit-Re Dilemma

Most of our insights came from mean flows with similarity properties and we are used to think in terms of a single local Re, most rationally based on local boundary layer thickness. But in instability and transition the history and cummulative growth of disturbances matter greatly, not just local Re_θ. Typically, an unsteady disturbance due to small roughness in a favorable pressure gradient at Re_{xA} may evolve into a turbulent burst at $Re \sim 6Re_{xA}$, but may also be damped out, depending on the strength of the disturbance, the strength and the x-distribution of the pressure drop. A single roughness by itself corresponds to two Reynolds number, one based on its x location and one on its height.

In compressible flows, pressure gradients change not only the free-stream velocity U_e at the edge of the layer but also the edge Mach number, in a nonsimilar fashion. At incompressible speeds, the Falkner-Skan family of pressure gradients yield a continuous family of amplification characteristics for each (!) Re_{δ^*}, Wazzan, et al. (1969). Now, at each Re_{δ^*} the growth rates depend additionally on M. The only (cursory) treatment of this problem is in Chapter 5 of Gapanov and Maslov (1980) using the inadequate Dunn-Lin approximations. Streamwise dependent wall cooling and wall suction both add new families of growth-rate dependence at each nominal Re_{δ^*}. Realistic spanwise z-dependence of all these fields adds further unexplored families of growth factors and turbulence onsets.

Furthermore, receptivity to unsteady pressure gradients depends strongly on the variation in x of their amplitudes, Nishioka and Morkovin (1986). The free stram disturances themselves cannot be characterized by any simple nondimensional parameters, since wave-numer k and frequency f spectra definitely matter in the response. Even at low speeds, our instruments have not yielded the f and k characteristics of the vorticity, entropy, and acoustic fluctuation components of the free-stream disturbances: the true input is unknown in practically all our experiment.

Presentation of a litany of needed unknown (and partly unknowable) information to engineers with design responsibilities is usually resented as non-constructive and unhelpful*. Researchers can pick out the problems they can solve. For each description of an unknown or ununderstood effect, one can ask: "Is it important to know?", "What features suggest which approach?", and thus compose for oneself a private list of possible research targets. At this stage of hypersonic research, exploration of conceptual effects and trends, rather than numerical Re_t predictions, are especially functional.

Usually, the design engineer will fall back on various correlations of limited data, often quite ambiguous. Time and again the data will be plotted against the dimensional Reynolds number per unit length, Re_L, the preceding discussion of the unknown factors should help him understand that in such correlations the physics of all the contributing factors is lumped into the UNIT-Re. As such, the correlation must be a swath, over a limited range of Re_L,

*Having had the responsibility for final transition estimates in several high-speed designs, the author empathizes with the frustrations of the design engineer.

the wider, the more data and Re_L range are included, Morkovin (1974). There is no mystical UNIT-Re EFFECT (nor Re/M dependence), valid across the span of wind tunnels, ballistic ranges, variants of shock tunnels, an atmospheric flight trajectories. Rather the dependence on Re_L reflects the varied environmental disturbance factors, combined with the effects of geometries with variable wall temparatures $T_w(x,z,y)$, Mach number $M(x,z,t)$, history of gradp(M,x,z,t), entropy layer development, roughness (distributed and isolated, including heat-induced swellings and gaps) and distinct receptivities, not to speak of real-gas effects. These influences cover a tremendous richness of linear and nonlinear phenomena. Figure 8, Notes on Leading Edges, illustrates the difficulities for the relatively simple case of flate plates, which of course must have finite thickness $2R_N$. Far downstream the asymptotic layer is approached, but the nose strongly affects the growth rates and transition and causes dependence on the unit Re.

No reliable methods of connecting data from test facilities to atmospheric flight has been advanced. No wonder there remains seeming contradictions in Re_t measurements by different workers, e.g., the old cooling controversy, see pp. 50-52 of Morkovin (1969). Unless induced by probe interference, the observed effects probably did occur. They simply may be located in different regions of the more complete multidimensional parameter-phase space, without contradictions. As such, they register as different branches of the swaths in the projection onto the Re_L (or other parameter) subspace.

Reprise

It is not a coincidence that all the discussion of theory in Section B referred to linear theory. There is simply no information on secondary and higher instabilities. It is unlikely that improvements in instrumentation and hypersonic facilities will be able to resolve the secondary fields in the author's life time. However, we may not need to know much beyond the more "cultural" conceptual likelihood of occurrence! As noted, Bushnell's emphasis on best linear theory is correct provided equally serious search for bypass possibilities is undertaken.

In an honest, unpressured research program, we must validate the linear theories to the best of our abilities. The linear Physics of Section A is probably correct but may need additional attention to body and streamwise curvature. (The mean U(x,y,z) profiles must be accurate for any responsible usage of N-factor philosophy). Mack and Kendall showed us how to approach the problem. For non-bypass problems, we must aim at

CONTROLLED MICROSCOPIC EXPERIMENTS DESIGNED IN CONJUNCTION with THEORY and NUMERICAL EXPERIMENTS.

Only such cooperation can clarify the mechanisms rather than add to the large number of discrepancies between stability and transition information.

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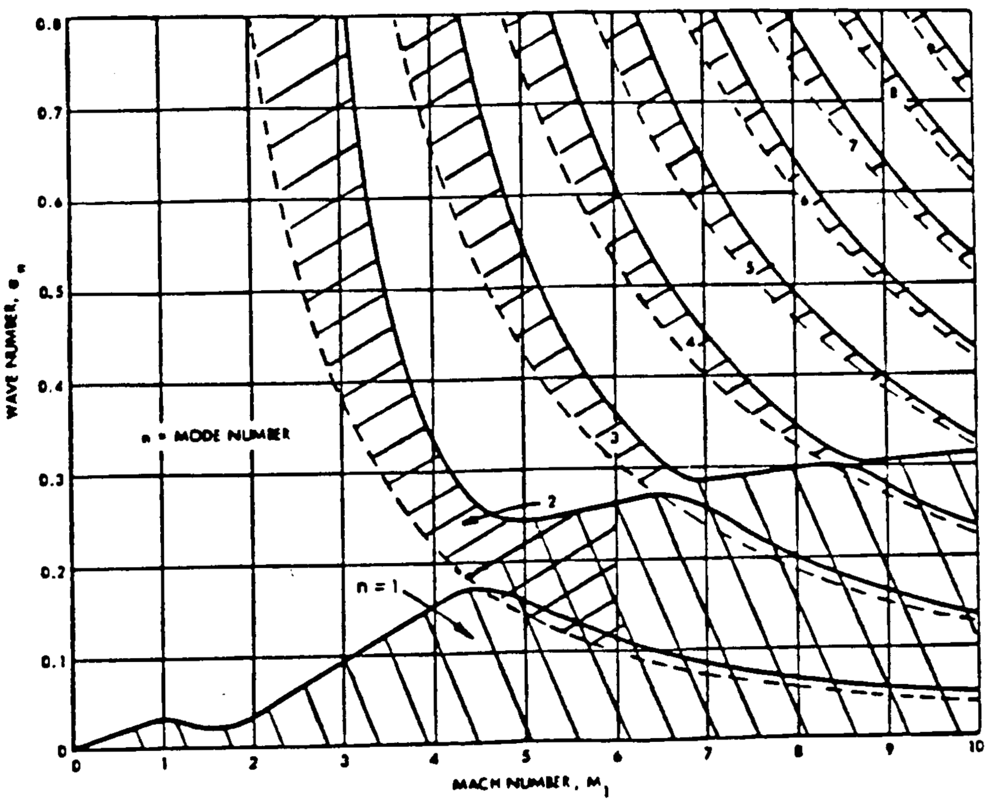


Fig. 1: Wave numbers $2\pi L^*/\lambda^*$ corresponding to inviscid compressible instabilities in insulated flat-plate boundary layers.

Starred symbols are dimensional velocities and lengths referred to free stream U_1^* and $L^* = (\nu^* x^*/U_1^*)^{1/2}$ (which is proportional to boundary layer thickness given in Table 11.1 of Mack, 1984).

——— α_{sn}: the <u>inflectional neutral</u> modes, all travel with the same phase speed $c_s^* = U^*(y_s)$ and have adjacent regions of amplification if c_s^* is subsonic with respect to U_1^*.

- - - α_{1n}, those <u>noninflectional neutral</u> modes which travel with the free-stream, $c_1^* = U_1^*$; they have neighboring amplifying modes with $c^* < U_1^*$ whenever a y region in the layer has relative supersonic speed, $U^*(y) - c^* > a^*(y)$.

The mode along the <u>horizontal axis</u> $\alpha = 0$, with phase speed c^* sonic relative to U_1^* is also <u>neutral</u>.

Unstable modes are located between neutral curves; for $M_1 > 4.5$ the first mode extends to the rising "anomalous fault line" and overlaps increasingly with Mack's instability modes.

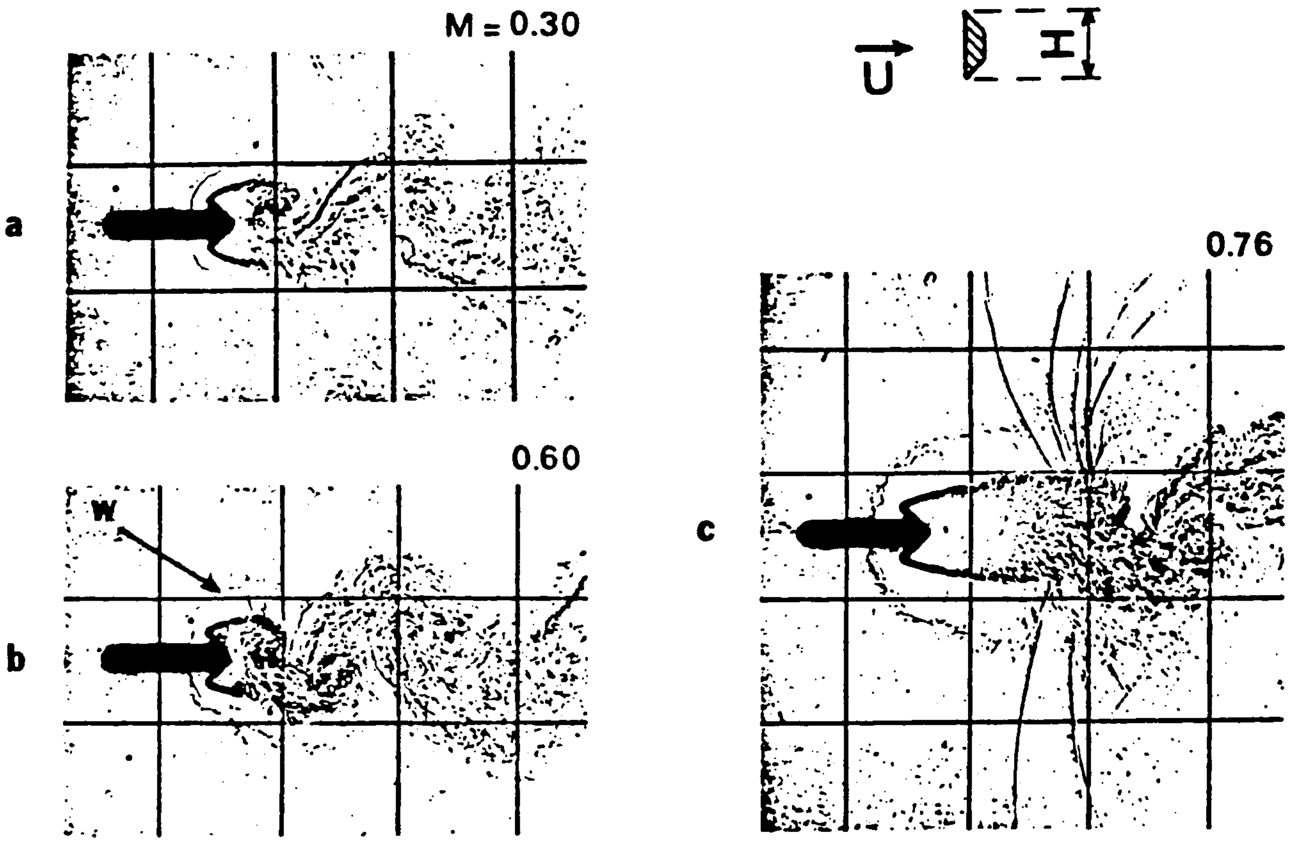


Fig. 2: Mach number inhibition of upstream influence in a self-excited wake generated by a flat plate normal to the stream. Dyment and Gryson (1978)

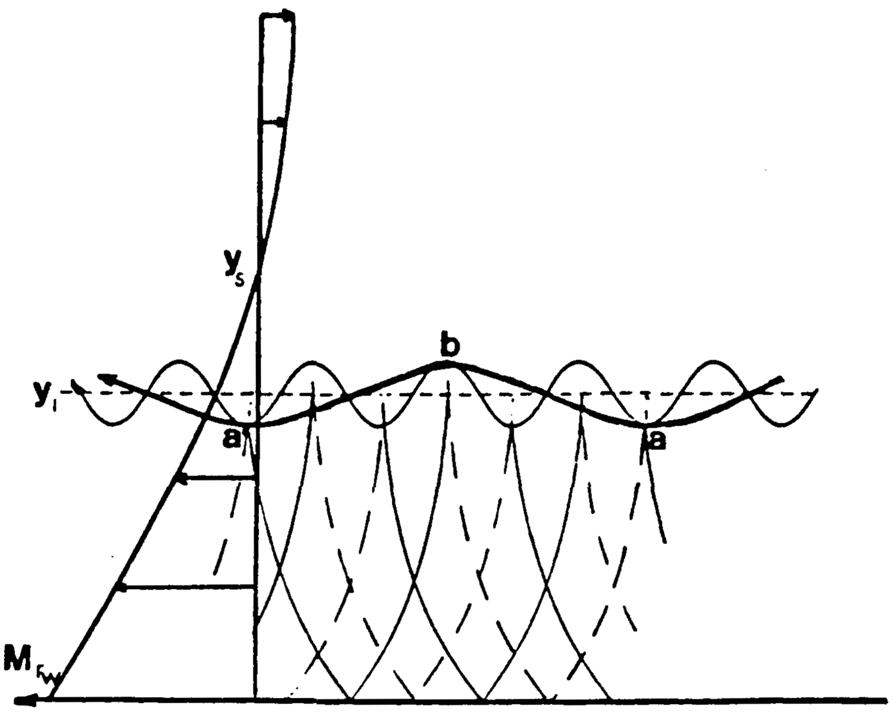


Fig. 3: Mack's neutral trapped acoustic mode as viewed from the reference frame traveling with mean speed at the generalized inflection point y_s. Harmonic vorticity and entropy perturbations, traveling along y_1 (the height of the sonic speed relative to y_s), are shown phase-tuned to coupled trapped acoustic perturbations traveling to the wall and back along Mach lines, steady in this frame of reference.

The reflection at the sonic streamline changes compression to expansion and vice versa (the essence of the trapping). As a geometrical consequence, perfect phase coincidences at any Mach number occur only for wave number α_{1n} in the exact ratios to α_{11} of 1, 3, 5...2n-1. This is the property of Mack's noninflectional neutral mode families shown as dotted lines in Fig. 1.

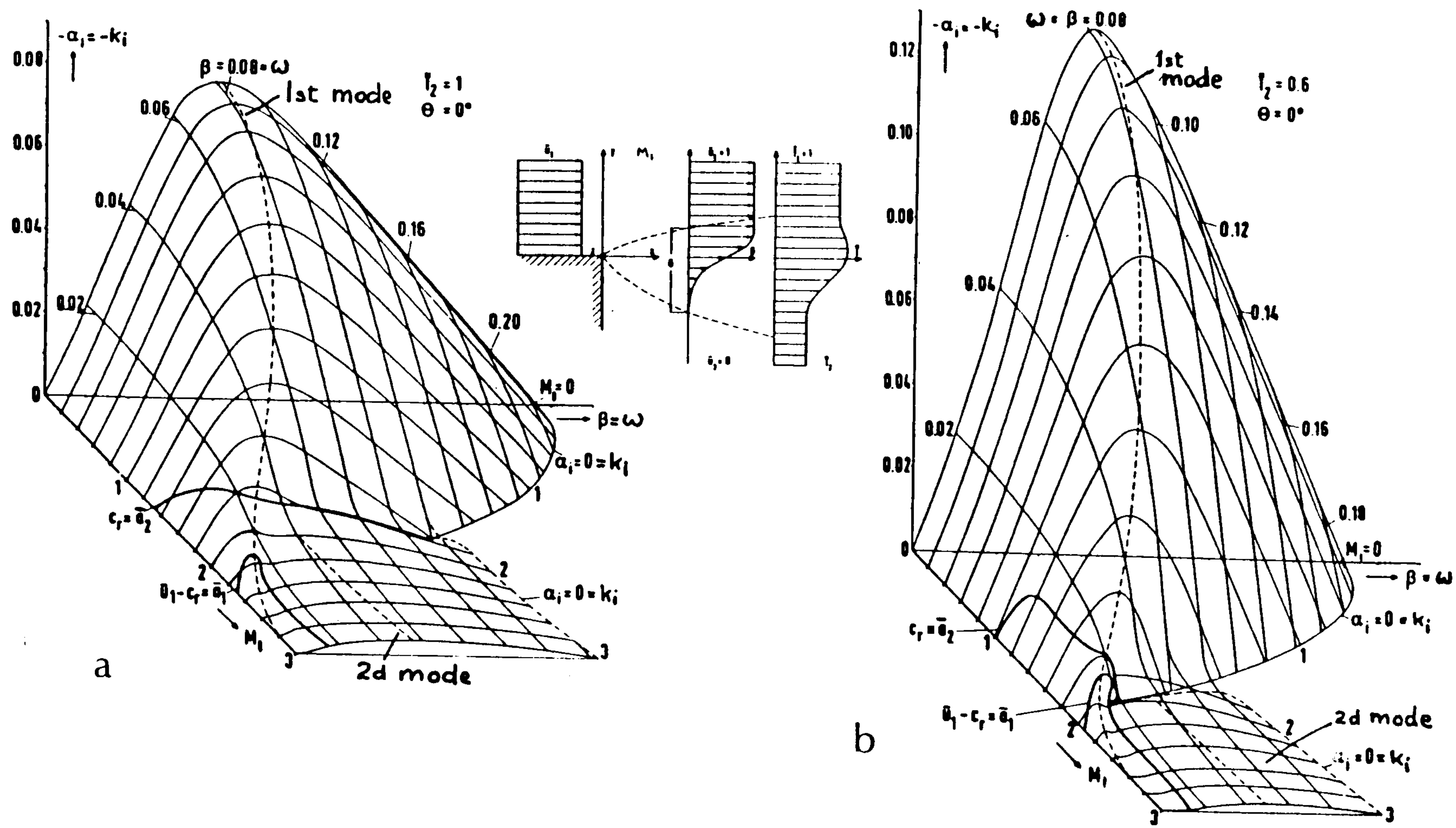


Fig. 4: Gropengiesser's spatial amplification of inviscid instabilities for laminar mixing layers: (a) without cooling, $T_2/T_1 = 1$; (b) with cooling, $T_2/T_1 = 0.6$.

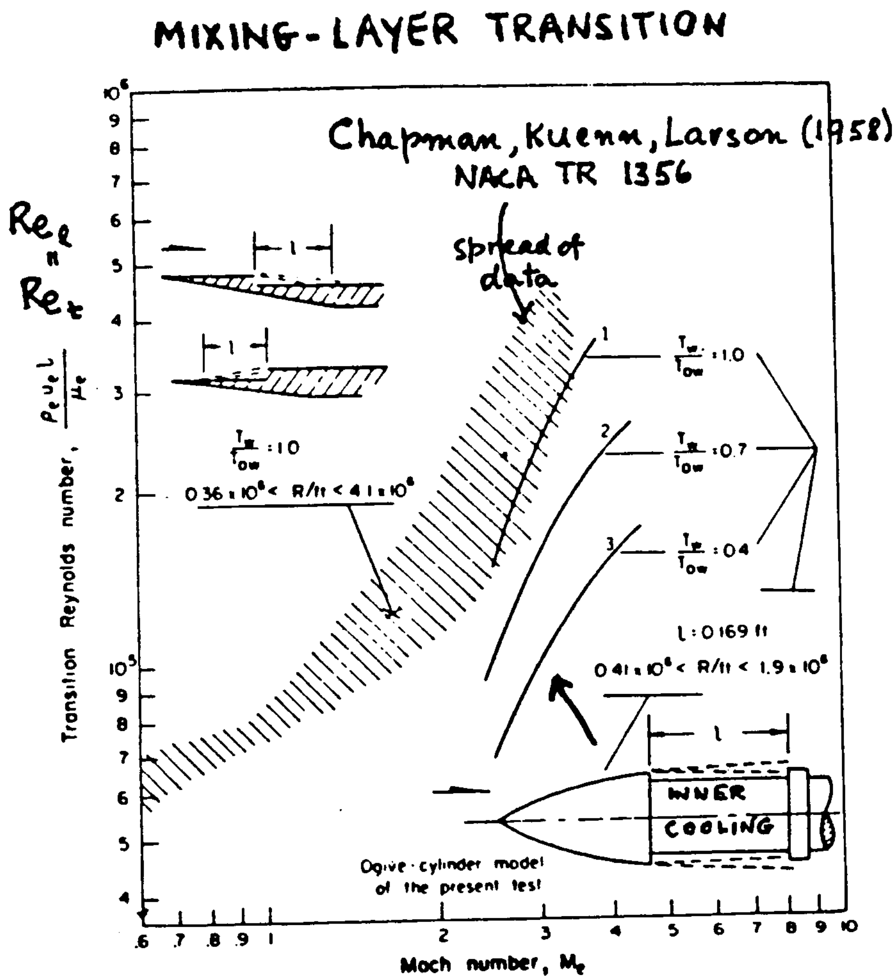


Fig. 5: Variation of Re_{tr} with M and cooling in compressible mixing layers with reattachment; B. Larson and S. Keating, Jr. (1960), NASA TN D-349.

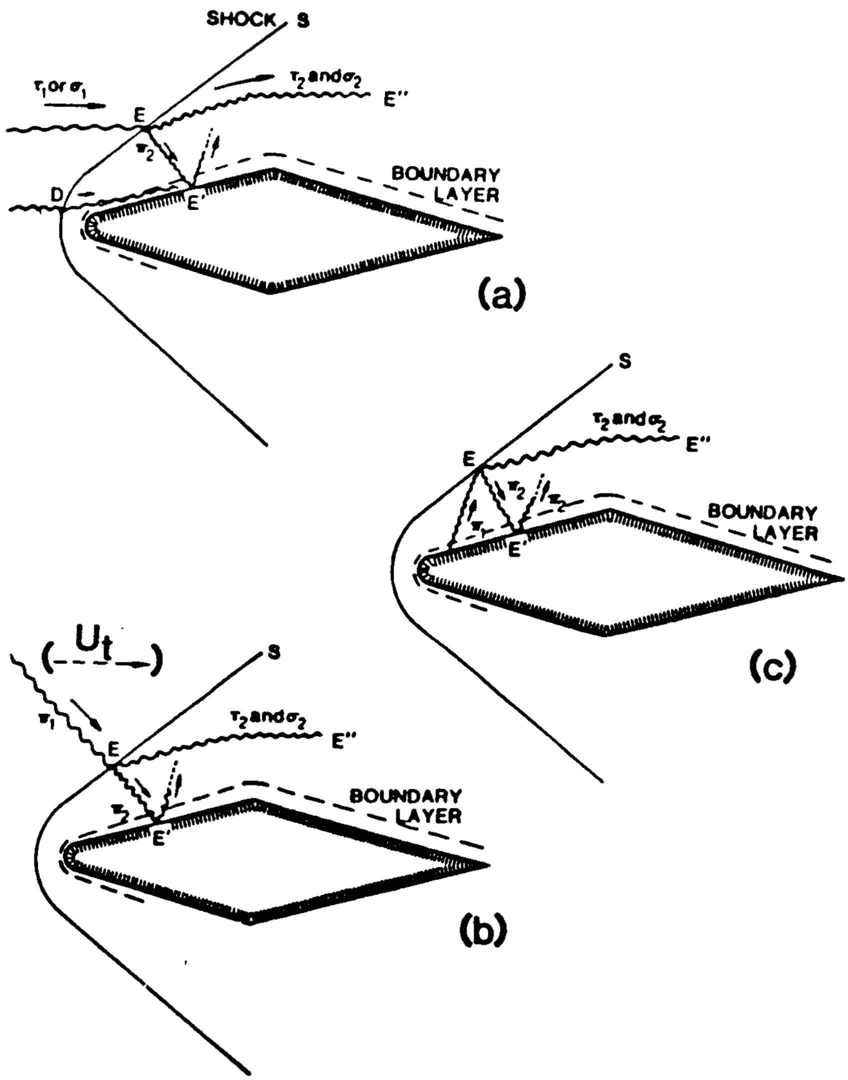


Fig. 6: Forcing of fluctuations in the boundary layer at E′ by free-stream disturbance modes, vorticity τ, entropy spottiness σ, and sound π, is indirect. Interaction of each mode with the bow shock wave generates all three modes downstream of the shock (subscripts 2). In (c), pressure disturbances in the layer are shown to feed back to the layer after interaction with the shock. At hypersonic speeds, this effect could lead to new resonance instabilities of the fused entropy layer and boundary layer up to the shock.

This schematic illustrates wind-tunnel conditions where sources of oscillatory disturbances are fixed, e.g. pressure waves due to side-wall roughness. When the sources are moving, their motion generally causes E and E′ to move and further complicates analysis.

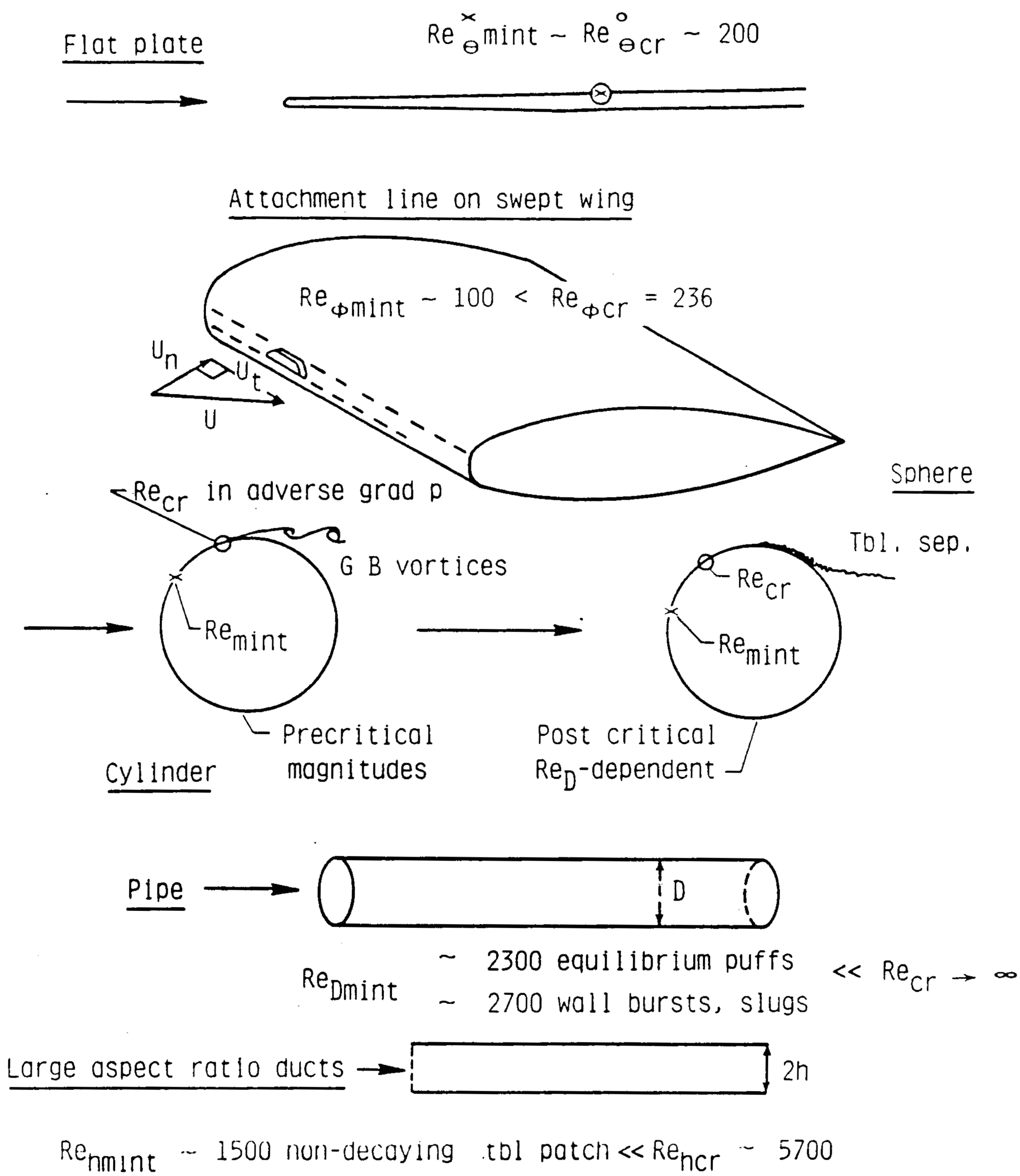
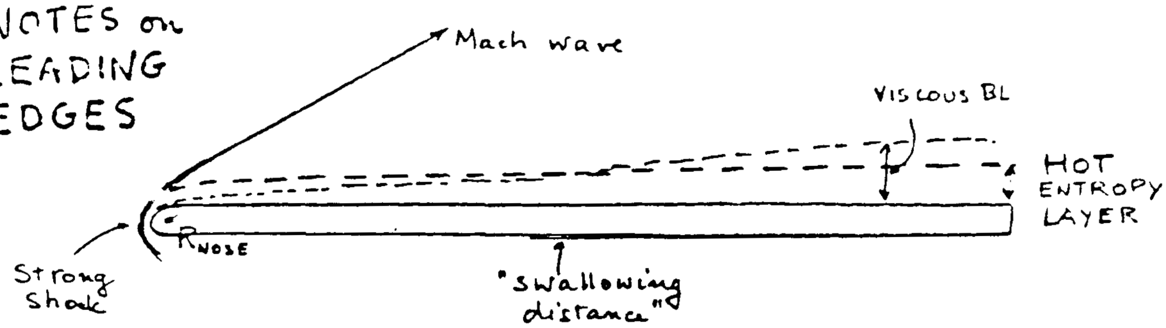


Fig. 7: Minimum Re for self-sustained turbulence compared to linear critical Re for T-S like instabilities.

NOTES on LEADING EDGES



Extra characteristic Length

At supersonic speeds finite R_N causes strong shock and entropy-temperature rise in layer on the order of R_N which changes heat transfer and $Re_L = Ve/\nu e$ over that of an "infinitely" sharp plate.

Double dependence of flow on Re_N and Re_x causes another $\boxed{\text{unit Re}}$ effect on stability characteristics.

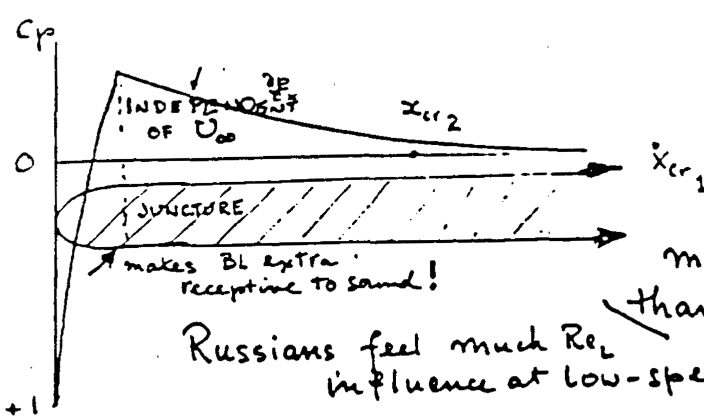
The flow is non-similar--would need very expensive computing for any given realization.

Experimental procedure: Find Re_{tr} for several bluntnesses: Extrapolate to $R_N = 0$.

At low speeds; problems (a)⟶induction of adverse $\partial p/\partial x$
(b)⟶shaping to prevent separation bubble!

Too many experiments (including Russian studies of neutral curve) assume δ" of BLASIUS BL with thes. origin at nose. There is a virtual origin x_0 for far downstream BL profiles!

Adverse: INFLECTED PROFILES!⟶Faster growth of δ^*; + more unstable profiles.



CLEARLY a UNIT Re EFFECT

All grad p's in practice present R_L problems

FOR $U_{\infty_2} > U_{\infty_1}$, x_{cr} moves forward much faster than $(U_\infty)^{-1}$ power.

Russians feel much Re_L influence at low-speeds comes from Leading edges.

Fig. 8

Standard Bibliographic Page

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Final Report

16. Abstract

This position paper discusses certain conjectures on the physics of instabilities in high-speed flows and summarizes our state of knowledge of hypersonic transition. The case is made for unpressured systematic research program in this area consisting of controlled microscopic experiments, theory, and numerical simulations.

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