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Transition Issues for Atmospheric Entry

Eli Reshotko*
Case Western Reserve University, Cleveland, Ohio 44106

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Much has been learned about the physics underlying the transition process at supersonic and hypersonic speeds through years of analysis, experiment, and computation. The application has been principally to simple shapes like plates, cones, and spherical nose tips. But the shapes of the new entry vehicles are not simple. They will invariably be at angle of attack, and so three-dimensional effects will be very important, as will roughness effects due to ablation. This paper will review the physics basis of our present understanding of the transition process. Further, because of the complex geometries, it will address the need for careful experimental work as per the guidelines enunciated years ago by the U.S. Transition Study Group. Following these guidelines is essential to obtaining reliable, usable data for use in refining transition estimation techniques.

I. Introduction

ENTRY vehicles descend rapidly through the atmosphere and decelerate as the drag forces increase with the increasing atmospheric density. The vehicle starts out fully laminar. Because Reynolds numbers increase rapidly through the descent, transition tends to move very rapidly over the whole vehicle over a narrow range of altitudes. One tries to minimize the aerodynamic heating loads in entry so as to minimize the thermal protection needs of the vehicle. This means delaying transition to as low an altitude as possible.

The history of high-performance entry vehicles begins with the development of the Intercontinental Ballistic Missile (ICBM) in the 1950s. These vehicles were essentially cone cylinders with large nose bluntness to minimize stagnation point heating. The nose materials were often subliming ablators to take advantage of the further reduction in stagnation region heating due to the surface blowing from the subliming surface. Transition would move forward from the cylinder to the cone as the vehicle descended through the atmosphere. If transition occurred asymmetrically on the cylinder or cone (leading to drag asymmetry), it was essential that the asymmetric effects be small enough to be corrected by the control system of the missile so as to minimize the circle of error about the target. In some cases, the transition unexpectedly moved forward onto the spherical nose, a phenomenon named the "blunt-body-paradox." A study in that time period by Allen and Eggers [1] showed that for orbital and suborbital entry (<8 km/s), the convective aerodynamic heating rate was directly related to the vehicle's ballistic coefficient (W/C_DA). The lower the ballistic coefficient, the lower the heating rates in entry, hence the tendency to design for low-weight and high-drag coefficient. The highly blunted capsule shapes of the Mercury, Gemini, Apollo, and Soyuz vehicles with ablating heat shields are a consequence of this argument.

At entry speeds above about 10 km/s, the shock layers ahead of the entering blunt shapes become luminous and radiate. These radiative heat transfer rates are highly density dependent. Thus, the blunt body may not be the best entry shape for supercircular entry speeds. Studies by Allen et al. [2,3] show that to minimize total heat transfer or total ablated mass, the optimum shape gets progressively more slender as the entry speed is increased. Not enough was done with these vehicles to identify the major transition issues.

The next class of entry vehicles, chronologically, are the lifting entry vehicles exemplified by the space shuttle. Because of the tile-based thermal protection system (TPS) used, the transition on the shuttle is roughness dominated. Because many tiles have to be reapplied or replaced before each flight, and because of possible protrusion of the gap filler material between the tiles, the effective roughness can vary from flight to flight. Thus, there is no great consistency in the transition behavior between different flights, even of the same vehicle.

Presently, there are two types of entry vehicle being considered. One is exemplified by the HTV-1 shape of the DARPA/AF FALCON (Defense Advanced Research Projects Agency/Air Force) program. Generically, the vehicle has a blunted elliptical forebody. The flowfield is inherently three-dimensional and becomes more so with angle of attack. The second category comprises the capsules being considered by NASA for the Crew Exploration Vehicle (CEV) and the Mars Lander. The seemingly preferred NASA shape for the CEV is a modernized Apollo capsule.

Many review articles on the state of supersonic and hypersonic transition research have appeared over the years [4–11]. In addition, Schneider [12–14] has provided very useful summaries and discussions of wind tunnel and flight data for both slender shapes and entry capsules.

In this paper, emphasis will be given to using research information in understanding and influencing vehicle design and performance. This first requires a discussion of our present physical understanding of the paths to transition. This will be followed by discussions of transition estimation, transition control, and transition testing.

II. Paths to Transition in Wall Layers

Until about a dozen years ago, the predominant view of laminar-turbulent transition was centered around the slow linear amplification of exponentially growing ("modal") disturbances (the familiar T-S, crossflow, and Görtler disturbances), preceded by a receptivity process to the disturbance environment and followed by secondary instabilities, further nonlinearity, and finally a breakdown to a recognizable turbulent flow.

However, there are transition phenomena in flows that are linearly stable and so could not be attributed to the aforementioned "T-S path." These were labeled by Morkovin [15] as bypass transition. The general feeling then expressed by both Morkovin and the present author was that bypass transition was inherently nonlinear, having bypassed the linear modal processes We often joked that bypass transition either bypassed the T-S processes or bypassed our knowledge, or both. This picture had to be urgently reconsidered in the early 1990s with the emergence of a literature on transient growth.

Transient growth arises through the nonorthogonal nature of the Orr-Sommerfeld and Squire eigenfunctions. The largest effects come

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*Kent H. Smith Professor Emeritus of Engineering. Fellow AIAA.

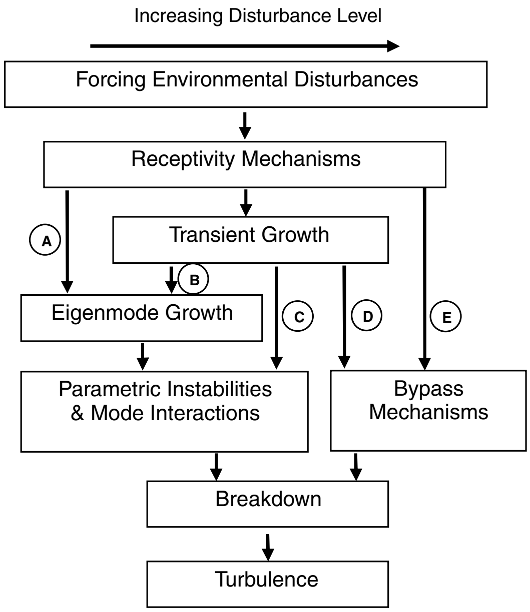

Fig. 1 Paths to turbulence in wall layers.

from the nonorthogonal superposition of slightly damped, highly oblique (near streamwise) T-S and Squire modes. These modes are subcritical with respect to the T-S neutral curve. The transient growth signature is essentially algebraic growth followed by exponential decay. A weak transient growth can also occur for two-dimensional or axisymmetric modes. Transient growth is therefore a candidate mechanism for many examples of bypass transition.

The early developments in transient growth are described and summarized in the book by Schmid and Henningson [16]. Butler and Farrell [17] determined optimal disturbance parameters for maximum transient growth in plane Couette, plane Poiseuille, and Blasius flows. These optimal disturbances have a decided three-dimensionality. It is important to emphasize that the transient growth theory is linear.

The aforementioned transient growth references use a temporal formulation of the disturbance equations, that is, that the disturbances grow in time rather than in space. The spatial formulation emerged later and is described by Reshotko and Tumin [18]. In the spatial theory, the optimal disturbances are stationary streamwise vortices. They are for zero frequency and a particular spanwise wave number. The consequence of these arguments is that transient growth can be a significant factor in the transition to turbulent flow for flows that are T-S stable. A summary of the early application of transient growth theory to cases of bypass transition is by Reshotko [19].

Consideration of transient growth has led to an enlargement and clarification of the paths to transition by Morkovin et al. [20] and is shown in Fig. 1. Five paths to transition, A–E, are shown in this figure. For the low disturbance environments of flight, only paths A–C are relevant. A discussion of each of these paths follows.

Path A: Path A corresponds to the situation in which transient growth is insignificant and transition is due to traditional T-S, crossflow, or Görtler mechanisms. This is the traditional path to transition for low disturbance environments where modal growth is dominant. Summaries of all aspects of this path (disturbance environment, receptivity, linear and nonlinear instability, transition prediction, and transition control) are available in Reshotko [8,11], Reed et al. [21], and Saric et al. [22]. For this path, transition estimation is best done by e^N methods. Although these methods ignore the details of the disturbance environment and receptivity, the success of the methods for both wind-tunnel and flight data suggests that an "e^N environment" could be considered a "standard environment" just as we have a "standard atmosphere" for design purposes.

The control of transition for path A is best done by making the boundary layers more stable through shaping (longer regions of favorable pressure gradient and reducing or eliminating crossflow and concavities), suction, and cooling. The Hyper-X/X-43 configuration is a good example of this means of transition control. In the design of such vehicles, it is usually assumed that the vehicle surface is smooth. However, the addition of TPS, often in the form of tiles, introduces subcritical roughness effects (path C) which can negate the premises of the original design.

Path B: As described by Morkovin et al. [20], the path B scenario indicates some transient growth, providing a higher initial amplitude to the eigenmode growth upon crossing into an exponentially unstable region. There are no obvious examples in the literature of this scenario. It is somewhat troublesome because of the following: Transient growth (nonmodal) is largest for stationary *streamwise* disturbances. Modal growth is largest for traveling *transverse* disturbances at low speeds, or traveling oblique disturbances at supersonic speeds. How a streamwise disturbance would couple to a transverse disturbance is not clear. On the other hand, the boundary layer might be stabilized by streamwise streaks of sufficiently large amplitude to cause a nonlinear distortion of the basic flow. This has been suggested by Saric [23] for Görtler vortices, and by Saric et al. [24] and Haynes and Reed [25] for the crossflow boundary layer. In the latter case, the stabilization has been shown computationally [25,26], and the transition delay has been shown experimentally both at low speed [24] and supersonically [27,28].

Path C: Path C is the case in which eigenmode growth is absent. This is the transient growth path that has received the most attention because it covers the most salient cases of bypass transition. The blunt-body-paradox is an example of path C. Extensive transient growth calculations have been carried out by Reshotko and Tumin [29] for axisymmetric stagnation point flows. These are relevant to the spherical nose tip of hypersonic sphere-cone configurations for which there is an extensive experimental database and significant transition correlations (Batt and Legner [30,31], Reda [32,33]). A transition model [29] based on that of Andersson et al. [34] is developed that can incorporate the transient growth results. This model assumes that disturbance velocities are proportional to the roughness height and results in the following relation:

$$Re_{\theta,\mathrm{tr}} = 180(k/\theta)^{-1}(2T_w/T_e)^{1.27}$$

which well correlates the PANT (passive nose tip technology) [30,31] and Reda [32,33] data. The only obvious control is to reduce the surface roughness.

Using transient growth results, Reshotko [35] shows that for roughness-induced transition on a flat plate in supersonic flow, the transition Reynolds numbers can be represented by

$$Re_{\theta,\mathrm{tr}}(k/\theta) = f(M_e, T_w/T_{\mathrm{aw}})$$

where the specific function is shown in Fig. 2 of [35]. This is of the same form as $(Re_{\theta,\mathrm{tr}}/M_e)(k/\delta) = \mathrm{const}$, the empirically obtained boundary-layer transition tool for the space shuttle gap filler induced transition (see Fig. 7 of [36]). For the space shuttle, transition occurs in very narrow local Mach number and surface temperature ranges ($M_e \approx 2$, $T_w/T_{\mathrm{aw}} \approx 0.3$) [37].

Path D: In path D, the result of the transient growth is that the spectrum of disturbances in the boundary layer is full: it looks like a turbulent spectrum (even while the basic flow profiles are still laminar). The spectra decrease monotonically with increase in frequency, whereas the intensity level increases with distance downstream. Examples of path D are primarily for internal flows at elevated turbulence level as in the experimental results of Suder et al. [38] and of Sohn and Reshotko [39] for $Tu > 1\%$. Based on transient growth theory, Andersson et al. [34] have developed a very plausible correlation for incompressible flat plate transition at elevated freestream turbulence levels.

Path E: Path E represents the case of very large amplitude forcing in which there is no linear regime. Such large amplitude forcing might come from chopping the freestream to obtain very large disturbance levels. The resulting freestream spectra do not resemble wind-tunnel or grid turbulence spectra.

III. Current Examples of Entry Shapes

As mentioned in the Introduction, the entry vehicles currently being considered are either slender bodies or blunt capsules. An example of the slender shape is that of the FALCON HTV-1 forebody (Fig. 2), which is essentially a blunted elliptic cone. Despite its seemingly simple shape, transition estimation is not trivial. The flowfield is inherently three-dimensional and is even more so at angle of attack. It is subject to crossflow instability over the swept leading edges, perhaps some T-S instability over the central regions, and swallowing effects downstream of the blunted nose. If at any point in its trajectory, the surface becomes rough, or if it is rough because of the TPS, then it may also be subject to transient growth. In addition, one must consider real gas effects, air chemistry, and surface catalycity.

The configuration shown in Fig. 3 is representative of modern capsule-shaped entry vehicles. It is a very large half-angle cone, rounded at the apex and at the edges. The payload module is mounted on the back of the heat shield. The figure itself lists the many processes at play on the heat shield that have to be accounted for in flowfield determination and in transition estimation. Of major importance is the possibility of very large heat transfer rates to the payload module if the shear layer impinges and reattaches on the payload module. Even if the shear layer remains laminar, the reattaching flow would likely become turbulent. Even if the body itself is axisymmetric, the flowfield at angle of attack is quite asymmetric and makes transition estimation more difficult.

Computational codes for flowfield and stability calculations for these complex flowfields are slowly being constructed. Note particularly the parabolized stability equations (PSE) code of Malik [40] and the PSE-Chem code development by Johnson and Candler [41,42], as well as the LASTRAC.3d code of Chang [43] for three-dimensional boundary layers.

Fig. 2 FALCON HTV-1 configuration.

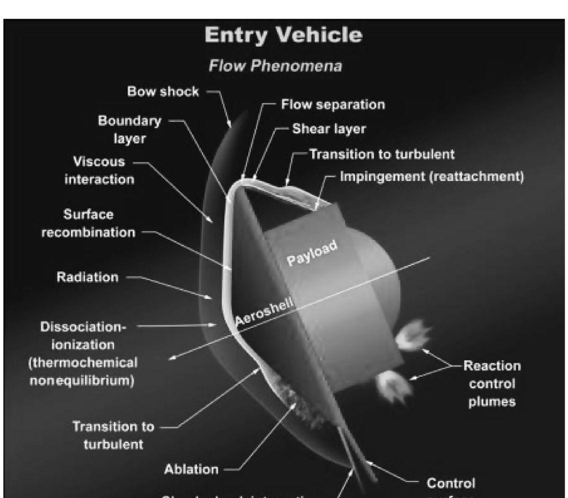

Fig. 3 Hypersonic blunt body flow (from [45]).

Meanwhile, such configurations are being studied experimentally in a number of facilities. It is important that the experimental studies be done according to the guidelines given in the next section, so that the results be meaningful for comparison with computation and for extrapolation to flight conditions.

IV. Guidelines for Conducting Experiments

It is well known that transition behavior in conventional supersonic wind tunnels above $M = 2$ is dominantly due to the noise radiated onto the model from the turbulent boundary layers on the tunnel walls. This accentuates the need for research and testing in "quiet" wind tunnels (those that have extensive laminar flow on the tunnel walls) and in flight. Unfortunately, the roster of quiet tunnels is sparse. There is the $M = 3.5$ Pilot Quiet Tunnel at NASA Langley, the Purdue University Ludwieg tube facilities at $M = 4$ and $M = 6$, and the former NASA Langley $M = 6$ quiet tunnel due to be installed at Texas A&M University. This sparsity has prompted many to consider flight experiments.

The standards for research quality experiments on stability and transition are the "guidelines" formulated by the U.S. Boundary Layer Transition Study Group [5]:

1) Any effects specifically and only associated with the test facility characteristics must be identified and if possible avoided.

2) Attention must be given to disturbances introduced by the model surface, model material, and internal structure. Experimental studies should include documentation of these various factors.

3) Details of coupling of disturbances of various kinds to the boundary layer must be understood theoretically and experimentally, so that the sensitivity to the flight environment might be determined.

4) Whenever possible, tests should involve more than one facility. Tests should have ranges of overlapping parameters and, whenever possible, experiments should have redundancy in transition measurements.

The preceding guidelines apply to flight experiments as well. Their implementation in flight experiments, however, requires special attention to a number of additional factors [44]:

1) The measurement of disturbance environment must be incorporated into the model design and, in fact, must be part of the model.

2) Attention has to be given to the maintenance and monitoring of test conditions such as Mach number, Reynolds number, angle of attack, yaw angle, and surface temperature for the duration of the measurement period.

3) Attention has to be given to the maintenance and monitoring of model surface conditions for each flight. This includes protection of the model surface before launch, and recovery of the vehicle for inspection and reconditioning of the surface before the succeeding flight.

4) Because stability phenomena at supersonic and hypersonic speeds occur at frequencies of hundreds of kilohertz and even to megahertz levels, there is a need for very high data sampling rates, especially when monitoring multiple channels. This poses special problems in data acquisition and data reduction.

Reliable digital telemetering of data from the vehicle may also be necessary to minimize weight and volume of the data acquisition equipment.

V. Conclusions

Our present understanding of transition scenarios has been reviewed and discussed. The roles of both modal (T-S, crossflow, and Görtler) and nonmodal (transient growth) mechanisms have been described. The transient growth of streamwise vortices is shown to be an important factor in explaining phenomena that have eluded us in the past.

The major message of this paper is that an appreciation and understanding of the physics of transition can lead to more sophistication in vehicle design and in transition control. In the hypersonic regime, transition control can be a major factor in the thermal management and sustainability of flight vehicles, and so it is important that transition phenomena be properly assessed. The use of correlations of questionable basis and reliability should be replaced by methods based on stability theory such as e^N methods and transient growth considerations.

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R. Kimmel
Associate Editor