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Fifty Years of Shock-Wave/Boundary-Layer Interaction Research: What Next?

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Because of their ubiquitous presence in high-speed flight and their impact on vehicle and component performance, shock-wave/boundary-layer interactions have been studied for about 50 years. Despite truly remarkable progress in computational and measurement capabilities, there are still important quantities that cannot be predicted very accurately, that is, peak heating in strong interactions, or cannot be predicted at all, that is, unsteady pressure loads. There remain observations that cannot be satisfactorily explained and physical processes that are not well understood. Much work remains to be done. Based on the author's own views and those of colleagues, some suggestions are made as to where future efforts might be focused. Just as the first workers in the field could not have foreseen the capabilities generated by the computer/instrumentation revolution of the past 20 years, it is probably fair to assume that the extent of our vision and imagination in the year 2000 is equally limited. New simulation and measurement techniques will doubtlessly become available in the next 10 or 20 years, the results from which will render many of the current concerns moot. However, as vehicle missions and cost constraints become ever more demanding, flow regimes harsher, and flow control/manipulation becomes an absolute necessity, the need for an ever deeper physical understanding and a more accurate, more robust simulation capability will only grow. Now is the time to lay the groundwork for the next 50 years.

Nomenclature

C_μ	=	constant in relation $\nu_t = C_\mu k^2/\varepsilon$
f	=	frequency
k	=	turbulent kinetic energy (TKE)
l_i	=	streamwise extent of free interaction
M	=	Mach number
P	=	pressure
Q	=	heat transfer rate
q	=	dynamic pressure
R	=	reattachment position
S	=	separation position
u, V	=	velocity
x, X	=	streamwise distance
y	=	distance perpendicular to wall
γ	=	shock foot intermittnecy
δ	=	boundary-layer thickness
δ^*	=	boundary-layer displacement thickness
ε	=	dissipation of TKE
ν_t	=	kinematic turbulent viscosity
σ_p	=	wall pressure standard deviation
τ	=	shear stress

Subscripts

E/A	=	ensemble-averaged value
w	=	value at wall
0	=	value at interaction start
∞	=	freestream value

Superscripts

$-$	=	mean value
$'$	=	fluctuating value

Introduction

Early Days

IT is tempting to try and identify the first published paper in the field, but to avoid challenging the reader to test my historical research competence, let it be said that Ferri[1] in 1939 probably made the first observations of a shock-wave/boundary-layer interaction (SWBLI) during testing of an airfoil in a high-speed tunnel. Shortly thereafter, in the mid-1940s, studies by Fage and Sargent,[2] Ackeret et al.,[3] Liepmann,[4] and Donaldson[5] showed the importance of the phenomenon at transonic speeds and how the nature of the interaction depended critically on the state of the incoming boundary layer. However, in such experiments, generally on curved surfaces, with only a small supersonic pocket embedded in a subsonic flow, and in a streamwise pressure gradient, it was difficult to investigate interaction properties systematically. To avoid such complicating influences, a series of experiments was carried out in the late 1940s and early 1950s in a purely supersonic boundary layer in which the only pressure gradients were those induced by the shock wave. These experiments used many of the basic geometries still in use today: flat plates and external shock generator,[6–11] flat plate/flat ramp configurations or flat plates with steps,[12,13] and axisymmetric bodies with flares/collars.[14,15] These studies yielded much useful data on the effects of Mach number, Reynolds number, and shock strength and reinforced the earlier observations of the importance of the state of the boundary layer. Much of the work up until 1955 has been summarized by Holder et al. in Ref. 16.

Should there be any doubt that SWBLI will continue to be a subject for study for another 50 years, it is worth considering where they occur, why they are important, what we currently understand about them and can predict, and what we do not understand and cannot predict. Examples of where they occur and why they are important are readily evident from the briefest of scans of the recent archival literature, conference proceedings, and proposal solicitations. The breadth of flows in which such interactions play an important, if not dominant, role spans the transonic to the hypersonic and from sea level to high altitude. The few examples cited hereafter simply skim the surface and are included to bring out the practical significance, the complexity, and the challenges that SWBLI pose both to experiment and computation. It is clear, at least to this author, that our fundamental knowledge of the underlying physics, and our ability to predict and control them (or at least mitigate their detrimental influences), is far from what is needed.

Applications

SWBLI are ubiquitous in high-speed flight, occurring in an almost limitless number of external and internal flow problems relevant to aircraft, missiles, rockets, and projectiles. Maximum mean and fluctuating pressure levels and thermal loads that a structure is

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*Professor and Chairman, Department of Aerospace Engineering and Engineering Mechanics. Fellow AIAA exposed to are generally found in regions of shock/boundary-layer and shock/shear-layer interaction and can effect vehicle and component geometry, structural integrity, material selection, fatigue life, the design of thermal protection systems, weight, and cost. Flow control is viewed by many as being a key issue for future vehicles and is a particularly vexing problem. The need to be aware of, and keep quantitative account of, the inevitable tradeoffs that occur calls for a deep physical understanding of parametric effects and for computer codes that are both robust and accurate. The task is extremely difficult, as illustrated by the recent work of Bur et al.[17] They investigated whether the detrimental effects of shock/boundary-layer interaction on transonic transport aircraft at off-design conditions (i.e., increased drag, buffet at high angle of attack) might be alleviated by passive control using perforated plates. Although the latter was successful in modifying the inviscid flowfield (replacing the single shock by a lambda system) and resulted in "a clear reduction of the wave drag,"[17] the viscous drag was significantly increased. The net drag reduction was too small to draw any definitive conclusions about the effectiveness of the technique or to propose an optimal passive device. In a recently published follow-up study[18] they explore both active control (boundary-layer suction) and a hybrid method (passive control cavity and downstream suction slot). Active control increased wave drag and decreased friction drag with hybrid control doing the opposite. No recommendations were made regarding the best approach.

A 1996 NASA research announcement stated that "improved air-breathing engines will require a clearer understanding of the basic flow physics of propulsion system components." The announcement went on to say that to design higher performance inlets and nozzles that are "quieter, shorter, lighter" there is a need for "benchmark quality data for flowfields including shocks, boundary layers, boundary layer control, separation, heat transfer, surface cooling and jet mixing." These areas nearly all involve shock/boundary-layer interaction in one form or another. Inlet design for supersonic flight, especially for a commercial transport aircraft that must operate at high efficiency and with a wide stability margin, poses many challenges and is an area dominated by shock/boundary-layer interactions. In a mixed compression inlet, high total pressure recovery requires that the terminal shock form just downstream of the inlet throat. However, the terminal shock is very sensitive to disturbances and may move upstream and ultimately out of the inlet, resulting in unstart that can result in large transient forces on the airframe and may cause engine surge. To stabilize the shock, boundary-layer bleed is employed near the throat. The selection of bleed location, hole/slot geometry, suction flow rate, etc., is a complex and difficult problem, and its solution in the past has generally relied heavily on extensive, and expensive, wind-tunnel tests. Based on the work of Zha et al.[19] and others (see Ref. 19 for references) there is some indication now that computational fluid dynamics (CFD) may now be on the verge of playing a powerful role in reducing design cycle time and cost, as well as reducing substantially the wind-tunnel test time needed. Validation of such codes and their extension to progressively more complex geometries and flow situations, such as unsteady or transient flows, will hinge critically on new, closely coupled experimental and computational studies. As will be discussed later, much lip service is paid to such coupling, but its occurrence on a broad scale and over sustained periods of time can prove elusive.

Plume-induced boundary-layer separation can be important in missile design. In this case, the boundary layer separates on the afterbody of the missile rather than at the base itself, resulting in large, unsteady, asymmetric loads. It is a result of the strong adverse pressure gradient generated by the interaction of the expanding plume and surrounding freestream. Shaw et al.[20] have shown that even though the separated flow is enclosed by "two dynamically compliant shear layers rather than by a solid body and a single shear layer" (as, for example, in an unswept compression ramp interaction), the two flows share many common features and may share common physics.

Transverse jet injection into an external supersonic or hypersonic flow generates a complex, unsteady, shock/boundary-layer interaction. Accurate prediction of the shock structure and the turbulence generated by this flowfield are critical in many applications including "scramjet combustors, film-cooled turbine blades, rocket motor thrust-vector regulation systems and high speed vehicles using reaction control jets."[21] Enhanced mixing efficiency in scramjet combustors has been a significant driver of much recent research in the area. The shock/vortex structure and turbulence evolution depend on many parameters, including injection angle, fuel penetration depth, fuel-to-air pressure ratio, etc., which make both experiments and computations difficult, time consuming, and very expensive. In a recent paper, Chenault et al.[21] discuss work in this area. The need for a reliable, robust, and accurate simulation capability is obvious and is another area where a closely coupled experimental/computational approach could yield results.

U.S. Army interest in high-speed, antiarmor, kinetic energy penetrators (Mach 4–8 at sea level) involves many shock/boundary-layer interaction problems and poses many challenges both to experiment and computation. Following discharge from the gun, the sabot, typically consisting of three or four petals, breaks away, and three-dimensional, unsteady, laminar, transitional, and turbulent interactions sweep rapidly across complex geometries moving rapidly apart. Once in flight, lateral thrusters or control surfaces may be used to guide and control such projectiles. Accurate characterization of the transient aerodynamic coefficients is very important and will call for accurate modeling of SWBLI.

It is probably clear from the preceding text that many of the current and future problems will be applications driven and involve complex geometries and flowfields. As will be argued later in this paper, the complexity may be beneficial in the sense of offering the potential of a broader, more general, understanding and should not be shied away from. That is not to say that the need for simpler experiments involving some of the classic planar geometries that have been studied since the very beginning has disappeared. There is a temptation in our culture to pick winners and focus all of our attention and resources on one area or on one method, whereas in practice progress hinges on a multifaceted approach. It is worth noting that in April 1953, Ascher Schapiro wrote in the preface to his famous book on compressible fluid flow[22]: "The most practical approach to the subject of compressible fluid mechanics is one which combines theoretical analysis, clear physical reasoning, and empirical results, each leaning on the other for mutual support and advancement, and the whole being greater than the sum of the parts." If theoretical analysis is taken to include simulation, then this comment is as apt today as it was almost 50 years ago and should be heeded.

Research Cycle

As noted, much of the early work was experimental. One of the best known studies is that of Chapman et al.[23] on laminar, transitional, and turbulent interactions published in 1958. Out of this work came the concept of free interaction. In their words,

> Certain characteristics of separated flows did not depend on the object shape or on the mode of inducing separation. Any phenomenon near separation which is independent of object shape would not depend on geometric boundary conditions which describe the flow downstream, but would depend only on the simultaneous solution of the equations for flow in the boundary layer together with the equations for flow external to the boundary layer. Such flows are termed free interactions.

Chapman et al.[23] argued that the pressure rise in the interaction region could be written as

$$\frac{\bar{P}_w - \bar{P}_{w0}}{q_0} = \frac{2}{\sqrt{M_0^2 - 1}} \frac{\mathrm{d}\delta^*}{\mathrm{d}x}$$

Through use of the boundary-layer momentum equation and order of magnitude considerations, they showed that

$$(\bar{P}_w - \bar{P}_{w0})/l_i \sim \tau_{w0}/\delta^*$$

where 0, designates conditions at the start of the pressure rise, that is, at X_0, and l_i is the length characteristic of the streamwise extent of free interaction. They subsequently showed that pressure distributions through separation for different model configurations and at different Reynolds numbers could be collapsed when the pressure and distance axes were scaled appropriately in terms of the skin-friction coefficient at X_0. The technique worked very well for both laminar flows and turbulent flows, suggesting that the same physical processes occurred in both. Other early analyses include the swept shock work of McCabe[24] in 1966, in which he developed an approximate quasi-two-dimensional theory for conditions across the shock that related the deflection of the surface flow to that at the boundary-layer edge with the objective of defining a separation criterion. Subsequent work in swept shock flows that built on and extended McCabe's ideas has been reviewed by Settles and Dolling and can be found in Ref. 25.

In a general sense, as more sophisticated tools are developed, new opportunities arise to address questions that earlier workers may have raised but could not investigate, or to raise issues that were overlooked in earlier work. Often the new tools result in the discovery of new phenomena for investigation. This cyclic nature is quite evident in studies of shock-induced turbulent boundary-layer separation. From schlieren and shadowgraph photographs, investigators in the 1950s, including Chapman et al.,[23] noted that such flowfields exhibited some degree of unsteadiness, but they did not have the means to study the issue further. Their focus was naturally on mean measurements, including wall pressures measured using conventional means (wall tappings), on surface flow visualization, with some measurements of heating rates, and very limited intrusive probing of the flowfield. As a consequence, key flow physics were overlooked. In the mid-1960s, when high-frequency response transducers and relatively high-speed data acquisition/recording became available, an opportunity arose to explore the unsteadiness. In one of the first, if not the first, studies of the phenomenon, Kistler[26] found that shock-induced turbulent separation upstream of a forward-facing step was characterized by a relatively low-frequency, large-scale pulsation (low frequency relative to the incoming boundary-layer characteristic frequency U_∞/δ). This poses the question of how this could have been overlooked in earlier work. Chapman et al.[23] used high-speed schlieren and shadow photography and noted that "turbulent separations were relatively steady." They reported that "shock waves occasionally appeared to move slightly but no appreciable movement of the separated layer could be detected."[23] With hindsight, it is easy to see that their remarks on the relative steadiness of the turbulent cases were probably incorrect. In such two-dimensional flows, conventional spark shadow or schlieren photography will reveal only minor variations from one photograph to another, leading to the (erroneous) conclusion that a flowfield is essentially steady. However, unless the separation shock motion is uniform across the width of an interaction, the unsteadiness would not be detectable. These techniques average across the flowfield, and random spanwise variations in shock position result in essentially the same image from frame to frame. All that is revealed in such images is a slight rippling, suggesting that the flow is relatively steady. Thus, the free-interaction region in turbulent flows is actually characterized by a translating shock/compression system across which the instantaneous pressure rises abruptly. In the region downstream of X_0, the mean pressure is the result of the superposition of large-amplitude shock-induced pressure fluctuations on the undisturbed boundary-layer pressure signal. The mean pressure increases downstream because of increasing shock frequency and fluctuation amplitude. Although the pressure can be scaled using the free-interaction parameters, the physics implicit in the latter are not what actually occurs.

A review of much of the work on flowfield unsteadiness up until the early 1990s can be found in Ref. 27. The majority of these unsteady measurements were restricted to surface pressures, from which only inferences about the external flowfield could be drawn. Some high-frequency response single-point (and sometimes multipoint) measurements have been made, but, due to flow interference, probes often cannot be placed where needed, or they cannot be made small enough. Furthermore, when intrusive measurements are made, the question of their validity always arises. Thus, although this body of work has brought out the basic character of the unsteadiness and has helped explain some features of the earlier mean flow measurements, it also generated a new set of questions regarding the causes of the unsteadiness. These remain unanswered today, and much work remains to be done in this area.

In the next phase of the cycle, underway now, it is hoped that many of these problems can be overcome, and the outstanding questions regarding the underlying causes of the unsteadiness can be answered. This hope is rooted in the rapid development of new laser-based optical methods, the ability to acquire large volumes of data at very rapid rates, and innovative image processing and analysis methods. Even though very expensive, and far from routine to use, nonintrusive, laser-based imaging systems and high-speed charge-coupled device (CCD) cameras are now becoming more commonplace and offer new, exciting research opportunities. Techniques such a particle image velocimetry (PIV), used alone or in conjunction with high-frequency response surface instrumentation, offer the opportunity to investigate in real time and with high resolution not only time-dependent flow structure but also the evolution of turbulence through the flowfield. With the advent of such powerful techniques, a new era of experimental research is at hand.

If this review is repeated in 2050, the first 50 years of shock/boundary-layer interaction discussed in this paper may well be considered as a period of observation. The new experimental tools, in conjunction with developments such as large-eddy simulation (LES), offer an opportunity for the field to enter a period of explanation. Explanation implies understanding, and with understanding comes the chance to develop robust and reliable prediction methods. With such prediction tools comes the opportunity to develop sophisticated and effective flow control techniques, firmly rooted in flow physics, which can be used directly in design (or for generating correlations for engineering design).

Paper Focus/Purpose

Note that this paper is not a review in the conventional sense: A bibliography of the major studies alone over the past 50 years would take many times the page limit of this paper. For good reviews of the early work, the reader is referred to Green,[28] Korkegi,[29] Stanewsky,[30] Hankey and Holden,[31] Peake and Tobak,[32] and Adamson and Messiter.[33] For more recent work, good starting points are Délery and Marvin,[34] Settles and Dolling,[25] Dolling,[27] Délery and Panaras,[35] Zheltovodov,[36] Smits and Dussauge,[37] and Knight and Degrez.[38] In this paper, an attempt has been made to identify where significant weaknesses exist in our understanding and predictive capability across the board and what might be done to improve matters. The purpose is to present some ideas. As a consequence, very few data are shown, and many important studies are not referenced. Topics discussed include 1) the need for simulation tools that model all of the essential physics; 2) the measurement and prediction of heat transfer, including unsteady effects; 3) understanding flowfield unsteadiness; 4) understanding how interactions are affected if the incoming boundary layer is developing in a pressure gradient, or is three-dimensional, or is transitional; and 5) flow control.

Although progress would doubtlessly be hastened by new techniques, it should be emphasized that we do have at our disposal now many techniques that can be put to good use in addressing outstanding issues. There is a strong temptation to conclude that useful research work can only be done if the tools employed are state of the art and/or the flowfields very complex and the data sets enormous. The challenge, excitement, and glamour associated with such work is real and understandable, but care should be taken to ensure that it does not distract us from addressing some very important, but apparently more mundane, issues.

On a final note, it is obvious that an improved understanding of shock-wave/turbulence interactions is clearly an integral part of each of the topics cited earlier. Andreopoulos et al.[39] have just published a review of work in this area and conclude that "the phenomenology associated with the interactions is not very extensive, and the understanding of the physical attributes is not very thorough." This is an area where much work also needs to be done. The reader is referred to Ref. 39 for details.

Computation

General Comments

Although there remain critical quantities of interest that still cannot be computed with confidence (discussed later), progress made in the computation of SWBLI over the past 30 years can only be described as remarkable. It can only be anticipated that its contributions will increase. It is easy to forget that it was only 21 years ago that Horstman and Hung[40] presented the first detailed comparisons of measured and computed flowfield properties in swept shock interactions generated by a single, sharp fin at angle of attack. The groundwork for their study had been laid in the mid-1970s with the laminar calculations of Shang and Hankey[41] and Hung and MacCormack.[42] The latter had, in fact, extended their work to turbulent flow and computed the Mach 6 experiment of Law,[43] but the comparisons of predictions and measurements were limited to surface properties only. Despite a very coarse mesh by current standards ($21 \times 36 \times 28$, for a total of 21,168 grid points) Horstman and Hung[40] obtained good agreement with the measured pitot pressure, Mach number, velocity, and yaw angle profiles of Oskam[44] at Mach 3 and of Peake[45] at Mach 2 and 4.

The author recalls that at that time there was considerable skepticism that computations of such three-dimensional interactions would be successful. Predictions of two-dimensional interactions such as those generated by unswept compression ramps could only be described as poor, and it was felt that the three-dimensional case would be even more challenging both in terms of capturing the interactive physics (which, it turns out, were not well understood), as well as resolving the flow details due to grid limitations. However, over time and after some carefully conducted studies, it became evident that the dominant physics of three-dimensional and two-dimensional flows differ in important ways, as will be described briefly later. Thus, with the benefit of hindsight it is no real surprise that Horstman and Hung[40] were able to do such a good job.

Over the 20 years since then, flowfields of increasing complexity have been calculated using a large variety of turbulence models, algorithms, and increasingly finer meshes. It is fair to say that, in many flow types, the crossing shock interaction being an example, simulations can now be used with confidence to explore the flowfield structure, its evolution with shock strength, and many aspects of the basic physics. For example, in a recent paper, Gaitonde et al.[46] use the full three-dimensional Navier–Stokes equations in strong conservation form and mass-averaged variables, and the k–ε turbulence model, to explore the turbulent flowfield generated by a symmetric (7×7, 11×11, and 15×15 deg) and asymmetric (7×11 and 11×15 deg) double-fin arrangement at Mach 4, with particular emphasis on the latter. The simulations bring out in extraordinary detail the shock structure, the nature and structure of the vorticity field, and the flowfield evolution with increasing interaction strength. Details of these patterns are discussed within the framework developed earlier for symmetric interactions. Overall, this series of simulations has provided an understanding of the flowfield that could not be obtained experimentally.

More recently, Schmisseur and Gaitonde[47] have extended this work to even stronger interactions (symmetric cases with fin angles of 18 and 23 deg at Mach 5). The results for the lower angle are qualitatively similar to the 15-deg symmetric configurations at Mach 4, but the stronger case (23 deg) exhibited a new critical point topology. With respect to flowfield resolution it is worth noting that compared to Hortsman and Hung's[40] work 20 years earlier, in which they employed approximately 20,000 mesh points, Gaitonde et al.[46] at Mach 4 use approximately 1.12×10^6 points for the symmetric case and 2.13×10^6 for the asymmetric case, whereas at Mach 5 Schmisseur and Gaitonde[47] used up to 5.3×10^6 mesh points.

Current Capability

Under the auspices of AGARD Working Group 18, Knight and Degrez[38] have recently reported results of a "critical survey of current numerical prediction capabilities" for simulation of laminar and turbulent interactions, including the single-fin, double-fin and hollow cylinder flare configurations. The objective of their study was to determine how well current codes could predict quantities that are needed in the design of high-speed vehicles, including flowfield structure and mean and fluctuating aerodynamic and thermal loads. They concluded that for laminar flows "accurate prediction of both aerodynamic and thermal loads" can be made using existing codes.[38] They note, however, that "extremely fine and carefully generated grids are necessary,"[38] especially for strong interactions, and indicate that grid adaptivity is essential. The situation for turbulent flows is not as satisfactory. They conclude that mean pressure distributions in three-dimensional interactions can be computed quite well, with "little variation between computations using different turbulence models."[38] This result is largely attributable to the approximate triple-deck structure of these flows; in the inner deck, a thin layer adjacent the wall, viscous and turbulent stresses, heat transfer, and inviscid effects all play a role. However, in the second deck, which includes most of the boundary layer, the flow is essentially rotational and inviscid. The third, or outer deck, is the inviscid, irrotational flow above the boundary layer. Because, to a first approximation, the surface pressure results from an interaction between the second and third decks, it is not much affected by the choice of turbulence model.

On the other hand, skin-friction and heat transfer distributions are generally poor, except for weak interactions, with different turbulence models producing different results. The differences between measured and predicted heat transfer are not small. Knight and Degrez note "differences of up to 100%" for strong interactions.[38] They also note that the accuracy of pitot pressure and yaw angle profiles "degrades as interaction strength increases."[38] Primary separation can be predicted quite well, but secondary separation is very dependent on turbulence model. In two-dimensional interactions, especially strong ones, the situation is somewhat bleaker. Mean surface pressure distributions are satisfactory only for weak interactions. The poor agreement seen for strong interactions is attributed to two causes. First, Reynolds-averaged Navier–Stokes (RANS) calculations do not model flowfield unsteadiness. As noted earlier, global flowfield unsteadiness can be a dominant feature of such flows, and, without modeling it, not even mean quantities can be computed accurately. Second, eddy viscosity models characterize the turbulence using a single length scale, which is incorrect in separated flow. Furthermore, Knight and Degrez[38] note that many eddy viscosity models employ wall functions "which lose their validity in the neighborhood of two-dimensional separation and reattachment."[38]

Future Work

The results of the review of Knight and Degrez[38] are both illuminating and disappointing. They are illuminating in the sense that they provide a clear picture of what can and cannot be satisfactorily predicted and offer insights as to where the focus of future experimental and computational work should lie. They are disappointing in the sense that some quantities critical to the design of high-speed vehicles/vehicle components such as heat transfer rates (in particular peak heating magnitude and location), still cannot be computed with confidence and that other quantities, such as fluctuating pressure loads, or fluctuating thermal loads, cannot be computed at all. To address these deficiencies, Knight and Degrez[38] recommend the development of LES solvers. This perspective is not unique to the prediction of shock-wave/turbulent boundary-layer interactions. In a recent review of the computation of supersonic cavity flows, Sinha et al.[48] reached the same conclusion.

Unlike direct numerical simulations (DNS), in which all scales of motion that contain significant energy are resolved, LES attempts "to resolve those eddies that are large enough to contain information about the geometry and dynamics of the specific problem under investigation and to regard all structures on a smaller scale as universal following the viewpoint of Kolmogorov" (see Ghosal[49]). In that sense, LES occupies the middle ground between RANS methods, which are relatively cheap computationally, and DNS, which is presently prohibitively expensive, if not impossible, for most aerospace applications. As noted by Speziale[50] "even if such computer capacity became available in the foreseeable future, and that is extremely doubtful, it is questionable as to whether this [DNS] would constitute a satisfactory solution. For example, would one consider as satisfactory a solution to laminar channel flow that consisted of the tracking of 10^{23} molecules." From an engineering perspective, similar concerns arise when considering LES, and whether it or its variants will ever become design tools is a question whose answer will only be known in time. Jameson[51] notes that it is unlikely that designers will ever "need to know the details of the eddies in the boundary layer," but also argues that it is possible that LES may provide "an improved insight into the physics of turbulent flow, which may in turn lead to the development of more comprehensive and reliable turbulence models," which in turn would improve RANS-based modeling.

If the results from LES for several of the classical shock/boundary-layer interaction flows such as those generated by unswept and swept compression ramps, sharp and blunt fins, crossing shocks, etc., could be compiled in a database available over the internet, there would be an opportunity to numerically probe the flow as has been done in the past with DNS of incompressible turbulence. How feasible DNS simulations for one or two canonical cases might be five years from now is uncertain. On the assumption that the simulation is accurate, then time histories of all variables would be available, instead of the very few that can be measured. There is then the possibility that answers to the following issues/questions such as those arising from the detailed experimental studies reported by Zheltovodov[36] could be addressed: 1) What role do three-dimensional effects, such as those triggered by Goertler vortices in the vicinity of separated regions, have on the separated flow and on the flow downstream? 2) What is the nature and magnitude of turbulence suppression in large-scale separated flows, and does relaminarization of the reversed flow occur? 3) What are the mechanisms for the suppression and amplification of turbulence by shock waves, compression waves, and expansion fans? 4) What is the cause of the flowfield unsteadiness?

Whereas most of the effort in the field of shock/boundary-layer interaction has been directed toward physical understanding and modeling, the ultimate aim of this knowledge is not only the latter but also to design. With that in mind, note that RANS methods, despite their limitations with respect to heating rates and fluctuating loads cited are, on account of the underlying flow physics, quite capable of predicting mean pressure distributions (in many cases) and primary separation, and can be used to optimize configurations or components in which SWBLI plays an important role. An example is the redesign of the NASA P2 and P8 scramjet inlets, which were originally designed in the 1970s using the tools of the day (method of characteristics, integral boundary-layer analysis, and algebraic control volume analysis for the SWBLI). Subsequent wind-tunnel tests showed that the cowl shock was not canceled by the centerbody due to poor modeling of the SWBLI. Shukla et al.[52] show that using a conventional RANS model and gradient-based optimization method a redesign resulted in almost complete cancellation of the cowl shock.

The application of LES or very large eddy simulation (VLES) to compressible flows in general, and SWBLI in particular, is very much in its infancy, and it will be many years before simulations become routine. In the meantime, there has been a massive investment in RANS codes, and engineers need predictions and need them rapidly. Thus, even if it is known that critical physics is missing, it is important to know how RANS codes perform in specific flows, what is reliable in the output, and what is not. The deficiencies of RANS modeling as justification to move rapidly forward into LES is quite understandable, but it should not be forgotten that for many applications these techniques are adequate. It would be foolhardy to abandon entirely any further calibration and tuning of turbulence models, etc., for RANS calculations.

It is evident from the recent literature that some very interesting work is being now being done in LES and variants of LES, and there is reason to hope that innovative approaches will evolve that will solve existing problems and address the new ones that will undoubtedly arise as LES is applied to higher Mach number flows. For example, in the normal LES approach, subgrid scale (SGS) models provide closure to the low-pass filtered Navier–Stokes equations and provide the mechanism by which the kinetic energy accumulated at high wave numbers is dissipated. A key question involves the necessary physics that the SGS model must contain to ensure that the interaction between it and the resolved or grid scales (GS) are modeled properly. In a recent paper, Fureby and Grinstein[53] address this issue and show that a new technique called monotonically integrated LES (MILES) may be an alternative to the usual approach. MILES involves the solution of "the unfiltered Navier–Stokes equations with high resolution monotone algorithms in which the effects of the SGS flow physics on the GS flow are incorporated into the functional reconstruction."[53] With such methods, it is claimed that "explicit SGS models can be dispensed with, and the nonlinear, high-frequency filters built into the algorithms act as minimal implicit SGS models."[53] The MILES approach has recently been used by Urbin et al.[54] to simulate a 25-deg compression corner at Mach 3. The initial results look promising, showing instantaneous spanwise rippling of the separation shock front with approximately the experimentally observed ripple wavelength.

In another recent study, Speziale[50] has reexamined traditional LES and Reynolds stress models with "a view toward developing a combined methodology for the computation of complex turbulent flows." More specifically, SGS models are proposed "that allow a direct numerical simulation to go continuously to a RANS computation in the coarse mesh/infinite Reynolds number limit."[50] In between these two limits, LES or VLES would be used, depending on the resolution. According to Speziale,[50] this approach has "the capability of bridging the gap between DNS, LES and RANS." There are doubtlessly other workers developing different approaches. Over the next few years they will be used in many flow types, their strengths and weaknesses brought out, and hopefully progress will be made.

Computational/Experimental Synergy

One action that could help in conducting well-conceived experiments, learning new physics from them, and validating/improving codes is a much closer coupling of experimental and computational work. Aeschliman and Oberkampf[55] of Sandia National Laboratories have been promoting this view for many years, culminating in Ref. 55. Although the advantages of synergistic computational and experimental research appear to be endorsed in all quarters, there have been relatively few instances of highly coupled programs. In the words of Aeschliman and Oberkampf,[55]

> Careful experiments designed and executed specifically for CFD code validation are the recommended source of data for CFD code validation. We consider unsatisfactory the common practice of attempting to validate codes using published data obtained for some other purpose unrelated to CFD validation. Almost inevitably, critical information needed required by the code, boundary and initial conditions especially, will be unavailable.

Support for this conclusion comes from Settles and Dodson's[56] compilation of experimental data in 1991 for a hypersonic shock/boundary-layer interaction database for guiding turbulence modeling and code validation efforts. In their words, "several hundred candidate studies were examined and 105 of these were subjected to a rigorous set of acceptance criteria for inclusion in the database. Twelve experiments were found to meet these criteria, of which only 5 were in the hypersonic regime."[56] Whatever arguments are made for or against tightening or loosening the acceptance criteria that Settles and Dodson[56] adopted, it is telling that in the early 1990s, only five experiments in hypersonic shock/boundary-layer interaction were judged sufficiently accurate and well documented for inclusion in a validation database. At that time, Settles and Dodson[56] recommended that further experimentation was needed in several areas, including 1) interactions involving real gas effects, 2) turbulence data, 3) at least one high-quality hypersonic laminar boundary layer for comparison with computation, 4) nonintrusive flowfield data (both mean and fluctuating), 5) more complex types of building block experiments, such as the double-fin or crossing shock flows, and 6) emphasis on three-dimensional rather than two-dimensional interactions. In their concluding remarks, Settles and Dodson made the strong statement that "future experiments that do not address these criteria should not be conducted at all."[56] Although the author does not agree entirely with that sentiment, given that their search yielded such a short "short list," the viewpoint is certainly understandable.

In the nine years since that recommendation, there has certainly been progress made in most of these areas, notably the fifth and sixth, with momentum and expertise building in the fourth, which offers great potential for the second in the future. As noted earlier, the first item poses particular challenges from every aspect and, to the author's knowledge, relatively little has been done. Questions such as how does vibrational excitation and chemical reaction affect SWBLI and how do equilibrium and nonequilibrium cases differ have received little attention. Facilities in which SWBLI can be generated that have a useful scale, duration, and with real gas effects are very limited. Davis and Sturtevant[57] have reported recently on some separated, laminar, double-wedge interactions investigated in the California Institute of Technology's T-5 tunnel using nitrogen at freestream Mach numbers from about 5 to 9 and total enthalpies from 4 to 28 MJ/kg. They introduce a classification that "divides mechanisms for real gas effects into those acting internal and external to the viscous regions of the flow."[57] Correlations are presented of measured separation length as a function of a normalized interaction pressure rise using "local external flow quantities computed for reacting flow, which scales out external mechanisms but not internal mechanisms."[57] They observed a significant increase in the scaled separated length for high-enthalpy cases and attributed the result to an internal recombination mechanism in the separated shear layer. They also reported that a limited numerical study showed a small decrease in the length scale of the separated flow relative to a nonreacting case with the same external conditions. This is clearly an area where much work remains to be done.

The initiative for promoting a closer coupling of experiment and simulation probably lies in the hands of program managers who have the leverage to force change, but they in turn will need the financial support and understanding from the management of their agencies. Aeschliman and Oberkampf's[55] comments on the "reluctance on the part of program managers to use scarce funds for the validation exercise" argue the case well. They suggest that in the longer term the lack of attention paid to validation represents false economy because the near-term cost must be "weighed against the future, and potentially much larger, economic and social liability of a system failure whose origin is traceable to erroneous results from an unvalidated code."[55]

Complex Flows

Settles and Dodson's[56] recommendation to focus on three-dimensional rather than two-dimensional flows is an important one, not just because such flows reflect better real applications, but because the potential for confusion is often heightened when starting with a special or singular case (two dimensional), then moving to the more general case (three dimensional), rather than vice versa. The years of argument over the terminology, even the existence of three-dimensional separation, is an example where baggage carried from study of the particular case can inhibit an understanding of the general case. A. Zheltovodov of the Russian Academy of Sciences, in a private communication in December 1999, uses as an analogy the typical school curriculum in which students are introduced to scalars, then vectors, then tensors, a process in which confusion often abounds. He suggests that, contrary to intuition, less difficulty may be encountered by starting with the more general (tensors) and then moving to the particular (scalars). After many years of teaching fluid mechanics the author understands that sentiment well. Incompressible flow is generally taught first. Once students have become acquainted with Bernoulli's equation, it is frequently difficult to prevent them from using it along a streamline in compressible flow, even when they have been shown that it can be derived in the limit of small Mach number from the more general isentropic, compressible equation relating P_0, P_∞, γ, and Mach number. If their first acquaintance with the relation between flow variables had been the compressible equation, they would probably have fewer problems remembering that Bernoulli's equation is a particular case of the general. Working with this analogy, Zheltovodov suggests that the time is ripe to reconsider some of our views in SWBLI by focusing more on the general (three dimensional) than the particular (two dimensional).

J. Stollery of Cranfield University in England, United Kingdom, in a private communication in December 1999 also endorses the view that we should concentrate on complex three-dimensional flows. He cites the example of a delta wing with a sweptback, tapered flap and poses questions such as the following: At what flap angle are the pressure and heating rates significantly affected, where does the flow initially separate and how does it develop laterally, and at what flap angle would the flow become significantly unsteady? Stollery notes that these questions are difficult to answer for either laminar or turbulent regimes. How the answers are affected by angle of attack poses an entirely new and challenging series of questions. Some related work has been done in the past using swept compression ramps, but this has been for a nominally two-dimensional incoming boundary layer and with an effectively infinite ramp. Stollery also poses the question of how roughness affects both laminar and turbulent interactions and the issue of relaminarization: When does the latter occur?

Heat Transfer

In many applications, the two most important quantities in SWBLI are the location and magnitude of peak heating. It is well known that in shock/boundary-layer interactions and shock/shock interactions that peak heating can be severe, particularly in hypersonic flow, with peak rates up to 10–100 times that under the incoming attached boundary-layer flow and many times the equivalent stagnation point value. Holden,[58] in 1986, presented a review with an emphasis on problems generated by viscous/inviscid interaction. Many of the issues raised in that paper (peak heating in three-dimensional turbulent interactions, dynamic loads generated in transitional regions of SWBLI, effects of the unsteadiness of separated flows, etc.) are as relevant today as research topics as they were 14 years ago.

Earlier in this paper, reference was made to Knight and Degrez's[38] review of SWBLI in high-Mach-number flows. To reiterate their conclusion, they noted that "heat transfer distribution predictions are generally poor, except for weak interactions, and significant differences are evident between turbulence models. Differences of up to 100% between experiment and numerical results were obtained for strong interactions."[38] An example is shown in Fig. 1. This case is for a crossing shock interaction at Mach 8.3 with both shock generators (sharp fins) at 15-deg angle of attack. The experiment and predictions are compared along a line between the fins, which is about $7.8\delta_0$ downstream of the fin leading edge. Details of the turbulence models and the modifications made to them are given in Ref. 38. Depending on location, the maximum deviation between the experiment and the predictions is from 40 to 150%. Knight and Degrez[38] conclude their review by noting that "to continue making progress in turbulence modeling for shock wave/boundary layer interaction it is essential to obtain accurate experimental data for flowfield turbulent heat flux, and wall pressure and heat transfer fluctuations."

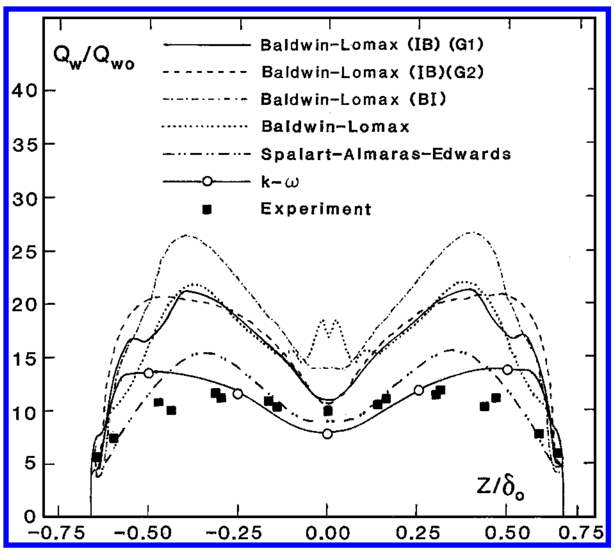

Fig. 1 Predicted and measured heat transfer rate distributions for crossing shock interaction at Mach 8.3; station is $7.78\delta_0$ downstream of fin leading edges; fins are at 15-deg angle of attack.[38]

This latter remark leads directly to the critical question from the physics perspective, namely, how is peak heating generated in these flows? It is probable that the details of the answer depend on flow type, interaction strength, state of the boundary layer, and other geometric and flow parameters. Nevertheless, to illustrate the kinds of questions that need to be addressed in any flow situation, consider an apparently simple case, that of a separated shear layer approaching reattachment on a unswept compression ramp face. Mean wall pressure distributions for such cases (an example at Mach 5 from Ref. 59 is shown in Fig. 2a) show that the pressure gradient and pressure rise are severe, an increase of about $10P_\infty$ in a streamwise distance of about 1–2 δ_0. Compression thins the layer, and turbulence levels rise, as does the temperature gradient near the wall, resulting in high heating. However, if this description was entirely accurate, it is surprising that computational methods are unable to do a better job of predicting the magnitude of the heating. An interesting question is whether some key physics is not being understood and modeled and whether in this case it might be related to separated flows of this type being very unsteady. In other cases, other issues may play a role. For example, in a very interesting recent study of crossing shock interactions, Thivet et al.[60] have investigated why heat transfer is overpredicted using RANS models and two-equation models.

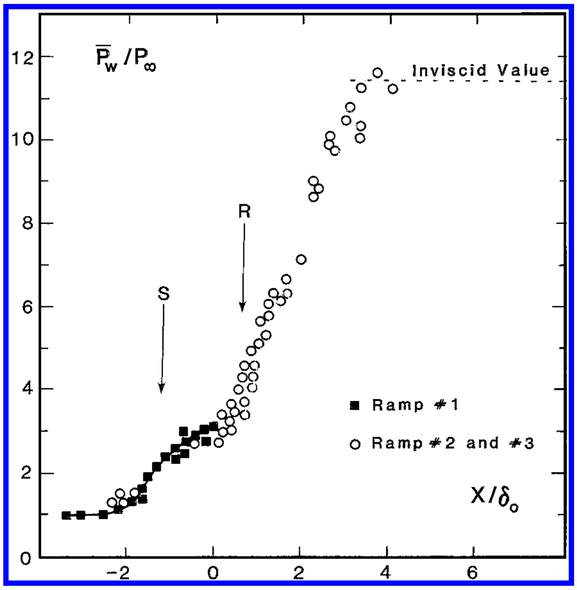

Fig. 2a Measured streamwise mean wall distribution in a Mach 5, 28-deg unswept, compression ramp interaction.[59]

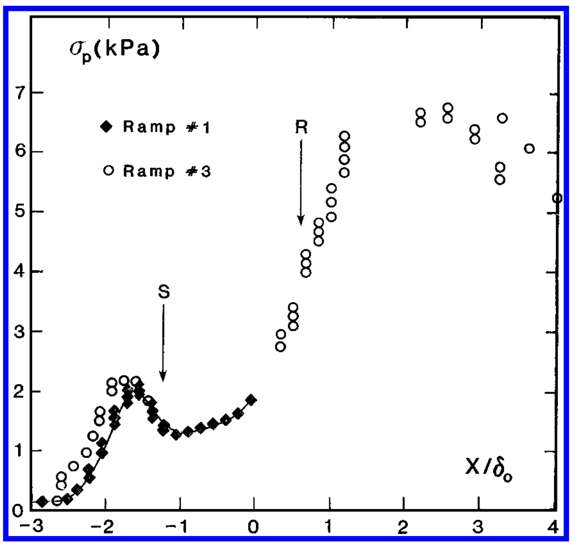

Fig. 2b Measured streamwise distribution of rms of the wall pressure fluctuations in a Mach 5, 28-deg, unswept, compression ramp interaction.[59]

First, their analysis shows that the overprediction is "clearly linked to the attachment to the bottom wall of vortices forming after the primary shock waves."[60] They investigate the hypothesis that two-equation models predict too large an increase in turbulent kinetic energy (TKE) of the outer part of the boundary layer as it crosses the shock and that the increased heating occurs when this excessive TKE is convected to the wall by the strong vortices downstream of the shock. In their study, they make the coefficient C_μ in the viscosity equation $\nu_t = C_\mu k^2/\varepsilon$ dependent on the velocity gradient. The heat transfer coefficients are reduced, although not sufficiently to match the experimental data. They suggest that this may be because "the correction is too weak" or that it may be due to another cause.[60] They note that the increase in TKE along the relevant streamlines is more significant when the entrainment flow "approaches and impinges the bottom wall than when the streamlines cross the primary shock wave, near the fin leading edge."[60] More investigations of this kind, and new experiments in which mechanisms are the focus, are needed to continue progress in this area.

Real-time, continuous measurements of heating rates near reattachment in different flows would provide an understanding of how mean values (which form the bulk of the existing database) are actually generated, how peak heating is generated, and why the peak appears where it does. Appropriate joint analysis of the multichannel heat transfer signals might show the roles that the turbulence and the unsteadiness play. This knowledge would certainly help in showing what must be included in modeling efforts and would also be very important in any studies whose focus was on developing methods to reduce peak heating.

Such an approach has already proven useful in explaining how peak fluctuating pressure loads are generated and where attention should be focused in any attempt to reduce them, or alter their frequency content. For example, Fig. 2b shows the rms of the pressure fluctuations through an interaction generated by a 28-deg unswept compression ramp at Mach 5. There is a rapid increase in fluctuating pressure level on the ramp face with a peak value of about 100 times that under the incoming attached boundary layer. If interpreted within a mean context, it is tempting to consider this rapid increase as being the result of turbulence amplification through the interaction. However, that is not the case. Fluctuating wall pressure measurements and planar laser imaging show that the separated flow undergoes a relatively low-frequency expansion/contraction (from about 2 to 4 δ_0 in streamwise extent).[59,61,62] Figure 3 shows ensemble-averaged wall pressure distributions for two ranges of separation shock-foot intermittency γ, where γ is the fraction of total time that the shock foot is upstream of a given streamwise position. A value of γ in the range 0–0.03 corresponds to the shock foot at the limit of its upstream motion when the separated flow scale is at its maximum. Conversely, γ in the range 0.96–1.0 corresponds to the shock foot at its downstream limit of motion and is when

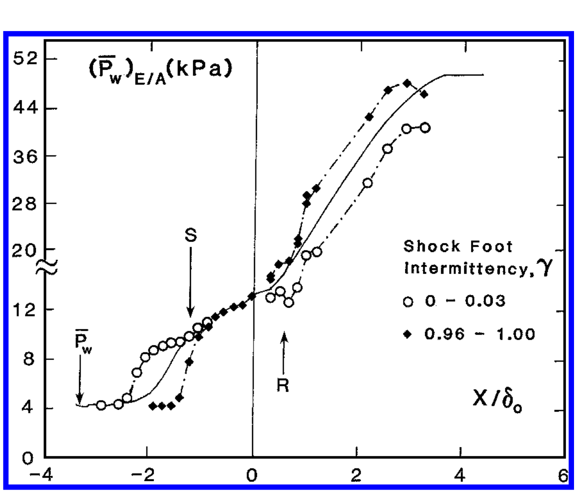

Fig. 3 Measured mean and conditional streamwise wall pressure distributions in a Mach 5, 28-deg, unswept compression ramp interaction. (Solid line is mean value, $\gamma = 0$–0.03 is for separation shock foot at limit of upstream travel, and $\gamma = 0.96$–1.00 is for separation shock foot at downstream limit of travel.[59])

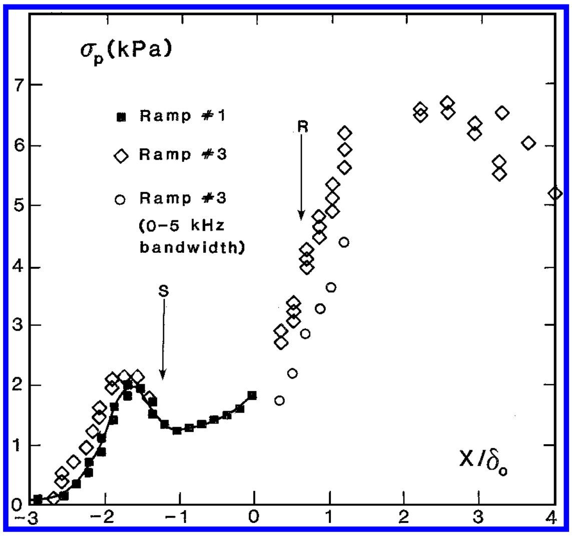

Fig. 4 Same data as Fig. 2b, but included are data on ramp face showing rms of the wall pressure fluctuations from frequencies below 5 kHz.[59]

the separated flow scale is at a minimum. Also shown (solid line) is the overall mean wall pressure distribution obtained simply by averaging the fluctuating wall pressure signals, or that which would be obtained by conventional wall taps. Simply by visual inspection of the reattachment region on the ramp face, it is evident that a large fraction of the fluctuating pressure load is generated by the changes in mean pressure as the interaction expands and contracts. For example, at $X/\delta_0 \approx 2$, approximately midway up the pressure rise on the ramp, the mean pressure is about 34 kPa with excursions about that value of ± 6.9 kPa. Shown in Fig. 4 is the fraction of the rms pressure generated by fluctuations at frequencies below 5 kHz, corresponding roughly to the frequency range of the separated flow unsteadiness. The fraction of the rms at stations between $0.25 \leq x/\delta_0 \leq \approx 1.0$, which is generated by frequencies below 5 kHz, is about 60–70%. It is fair to say that any strategy for reducing fluctuating loads that ignores this phenomenon is not likely to be very successful.

The equivalent data set for the fluctuating heat transfer is not available. In its absence it is difficult, if not impossible, to identify the weaknesses in current modeling approaches, or to propose alternative approaches. Compared to the obvious glamour and excitement of using state-of-the-art, laser-based methods to explore high-frequency turbulence evolution, or supercomputers for LES, a call for a renewed focus on heat transfer seems rather mundane, even unattractive. Nevertheless, after 50 years of work, its prediction remains elusive, and yet its importance is not likely to go away. Indeed, with an ever increasing interest in supersonic and hypersonic vehicles, accurate prediction of heat transfer is likely to be increasingly important. The availability of and decreasing costs of miniature instrumentation make the next few years an ideal time to renew efforts in this area. There is a need for accurate, high-resolution, reliable, robust, high-frequency response heat transfer rate instrumentation that is as easy to install and as easy to use as high-frequency response pressure instrumentation. It should be inexpensive, certainly no more so than fluctuating pressure instrumentation. It should be capable of measuring low heating rates accurately and suitable for use in blowdown facilities, rather than requiring high driving temperatures and short duration facilities.

Flowfield Unsteadiness

General Comments

Shock-induced turbulent separation appears to be inherently unsteady. A review by Dolling[27] summarizes much of the work up until about 1992 on the nature of the unsteadiness and its cause(s). The author is unaware of any comprehensive reviews of the field since that time. As discussed earlier, the fluctuating pressure loads generated by translating shock waves, pulsating separated flows, and expansions/contractions of the global flowfield can very severe enough to cause structural damage and cannot be ignored by designers of supersonic and hypersonic vehicles. Their importance is compounded by the largest loads also often occurring in regions of very high heat transfer. In a 1989 paper by Pozefsky et al.,[63] the authors identify locations on a generic hypersonic airbreathing vehicle at which the estimated time to failure is 1 min or less. At all of these locations, the flowfield is dominated by shock/boundary-layer interaction or shock/shock interaction. In the paper by Pozefsky et al.,[63] the sources used for estimating fluctuating load levels date largely from the 1970s, with some from the 1980s. If the same study was repeated today, there would be relatively few additional sources to draw on and, as far as the author is aware, no codes exist for accurate computations of fluctuating loads. There is a pressing need for more work in this area, both experimental and computational.

In many flowfields the unsteadiness is the dominant phenomenon and, as was seen in the preceding section, the behavior of even the mean flow properties often cannot be understood without some knowledge of the unsteadiness. This knowledge may, in reality, be more of an observation than a deep understanding, but even the former alone can be of great assistance in explaining why property distributions have the shape, length scale, magnitude, etc., that they do. Some knowledge of the flowfield steadiness (or lack of it) is critical in planning how experiments should be conducted, what should be measured (and how), as well as what must be included in any modeling strategy.

Unexplained Results

Experiments from a wide range of facilities from continuous to intermittent, from transonic to hypersonic, have generated a data set that currently cannot be understood within a common framework. Indeed, it is currently not possible to explain satisfactorily many of the results obtained for a given model geometry in a fixed incoming flow. For example, in an unswept, separated compression ramp flow in which the freestream velocity is almost 800 m/s and the incoming boundary-layer thickness is about 18 mm (i.e., a characteristic frequency U/δ_0 of about 40 kHz), the expansion/contraction of the separated flow (from 2 to 4 δ_0 in extent) is at a few hundred hertz.[60] Separation shock motion histories show occasions when the shock foot undergoes large-scale unidirectional motions lasting up to 1 ms. During 1 ms, the bulk freestream flow moves streamwise almost 1 m. During such time, if large-scale turbulent structures are 1–2 δ_0 in streamwise extent, about 20–40 large-scale structures pass through the shock and shear layer. What mechanism is at work such that the passage of 20–40 large-scale structures, of different shape and properties, do not influence the expansion (or contraction) of the separated flow?

Experiments from the broad database show that the variations in the separated flow scale and that the dominant frequencies seem to depend on the incoming flow properties, the particular interaction under study, and the physical dimensions of the model geometry generating the interaction. For example, consider an unswept compression ramp generating a separated flow in a fixed incoming freestream and boundary layer. Experiments at Mach 5 show that the characteristic frequency range of the separation shock increases as the corner line of the ramp is progressively swept back and the interaction changes its character from nominally two dimensional, to cylindrically symmetric (about the corner line), to conically symmetric.[64] The changes are not minor. Dominant separation shock frequencies changed from about 0.3–0.5 kHz to 2–7 kHz as the ramp was sweptback from 0 to 50 deg. Thus, with a given forcing function (incoming boundary-layer turbulence) the response is a function of the interaction structure.

As a second example, consider a circular cylinder in a fixed freestream and fixed incoming boundary layer. If the cylinder diameter is increased the length scale of the separated flow increases as does the length of the region over which the separation shock moves, both roughly in proportion to the change in the diameter. As the physical scale of the interaction increases, the separation shock frequency decreases. For example, the data of Dolling and Smith[65] at Mach 5 show that as the cylinder diameter is changed from 12.7 to 19.1 mm in a fixed boundary layer ($\delta_0 \approx 0.5$ mm), the dominant shock frequency decreases from around 1.6 kHz to about 1.3 kHz. Holding the diameter constant ($D = 19.1$ mm) and increasing δ_0 from 5 to 16 mm decreased the dominant frequency from about 1.3 to about 0.9 kHz.

Kleifges and Dolling[66] also studied blunt-fin interactions and obtained some interesting results. In this study, five 19.05-mm-thick hemicylindrically blunted fins with leading-edge sweepback angles of 0, 8, 18, 30, and 45 deg were used. The results showed that although the mean and rms pressure levels in the region of separation shock motion are unaffected by moderate sweepback (18 deg), the mean and rms pressure at the fin root are reduced by about 40–60%, respectively. This reduction in root loading is coupled with a significant reduction of the interaction length scale (by about 80% in the 45-deg swept case). Leading-edge sweep had little effect on the spectral content of the pressure fluctuations in the separated region, but the spectral content of fluctuations in the intermittent region shifts to higher frequencies for greater sweep angles.

To examine the effects of leading-edge shape, fins with a hemicylindrically blunted leading edge, a 53-deg-half-angle, wedge-shaped leading edge, and a flat-faced fin were used. A 53-deg wedge was used because it had the same upstream influence as the hemicylindrical model. The flat-faced fin is not a practical configuration, but was selected because such a strong interaction might provide useful information on the underlying physics. The hemicylindrical and wedge models were 19.05 mm thick, whereas the flat-faced model was 9.53 mm thick. The latter thickness was chosen to generate an interaction with the same upstream influence as the wedge and the hemicylindrical model. Fin leading-edge shape affected the structure of the separated flowfield, which in turn altered the flowfield unsteadiness. Cross correlations of separation shock/velocity fluctuations with pressure fluctuations in the incoming boundary layer and under the separated flow showed that fluctuations in both regions correlate with and precede the shock motion. The physical extent of the expansion/contraction process appears to depend on the details of the flowfield structure, not on its overall size. Recirculation of large-scale turbulent structures also plays a role in influencing the shock motion, and the recirculation process depends on the type and scale of the separated flow. What these examples show, simply put, is that our knowledge of the unsteadiness is still far from complete. They are essentially observations without explanations. Doubtlessly, when the explanations emerge, these results will fall neatly into a logical framework.

Cause(s) of Unsteadiness

A key question is the cause of the unsteadiness, especially the low-frequency component characteristic of the separated flow pulsation. Is it an inherent feature of all high-speed turbulent boundary layers, whether they are generated in a test facility or in flight, or is it characteristic only of the former? The mechanism by which the boundary layer is generated on a flight vehicle or wind-tunnel model is clearly different in both cases. Generating high speeds in a test facility necessarily involves expanding a high-pressure stationary gas through a nozzle over concave walls. Is it possible that the low-frequency phenomenon is generated by meandering vortices embedded within the test section boundary layer? Are there stagnation chamber resonances, or disturbances, or other mechanisms peculiar to the wind-tunnel environment that feed into the boundary layer, freestream, or separated flow?

Understanding the low-frequency component and determining whether it is peculiar to the wind-tunnel generation of high-speed turbulent boundary layers has far-reaching ramifications for future testing, for interpretation of the existing database, and for CFD. If the low-frequency component is a feature only of test facilities, then, in practice, only the high-frequency component, which appears to be driven by large-scale structures, would be present. Because the latter causes high-frequency jitter as opposed to large-scale excursion of the shock foot, the flowfield would be nominally steady. The bulk of the database is time-averaged data from wind-tunnel flows in which large-scale unsteadiness is known to occur. If the large-scale unsteadiness is facility induced, then it is not a productive use of resources to focus on developing unsteady modeling strategies. Over the years there have been a number of studies focused on shedding light on the underlying cause, or causes, but there has yet to be developed a comprehensive framework in which the results to date can be explained.

From experiments made in a Mach 3 compression ramp interaction Andreopoulos and Muck[67] suggested that the frequency of the separation shock motion scales on the bursting frequency of the incoming turbulent boundary layer.[67] Later work indicated that the single-threshold algorithm they used to estimate shock frequency may have resulted in shock frequencies that were too high. Furthermore, experiments by Thomas et al.[68] showed no "discernible statistical relationship between burst events and spanwise coherent shock front motion."

Erengil and Dolling[69] showed a correlation between the wall pressure fluctuations beneath the incoming boundary layer and the separation shock-foot velocity, from which it was inferred that the small-scale motion of the shock is caused by its response to the passage of turbulent fluctuations through the interaction. They also showed that the large-scale motion is a result of the shock's displacement due to the expansion and contraction of the separation bubble. A physical model of the shock unsteadiness can be produced from these observations, where the expansion and contraction of the separation bubble displaces the shock upstream or downstream, whereas the passage of turbulent fluctuations alters the shock velocity, which integrates to changes in the shock position and accounts for the small-scale, high-frequency unsteadiness. However, the model does not address what causes the low-frequency, large-scale pulsation of the separated flow.

To address this question, McClure[70] and Ünalmis and Dolling[71] made conditional pitot pressure measurements in the upstream boundary layer and showed that the mean pitot pressure at a fixed vertical position was lower for upstream shock locations than for downstream shock locations. This observation led to a simple model in which it was suggested that low-frequency variations in the incoming boundary-layer thickness induce the large-scale shock motion. Chan[72] and Beresh et al.[73] examined this idea using instantaneous planar laser scattering (PLS) from a condensed alcohol fog. Images upstream of the interaction in the incoming undisturbed boundary layer were obtained simultaneous with pressure signals from transducers used to track the shock-foot motion. The PLS images exhibited no significant correlation between the local mean boundary-layer thickness just upstream of the interaction and the shock-foot location.

Beresh et al.[73] also acquired PIV images simultaneous with pressure data, similar to the PLS experiment. The resulting vector fields were ensemble averaged based on the shock-foot location, producing conditional mean velocity profiles through the incoming boundary layer. No measurable difference in the boundary-layer thickness was found for different shock-foot positions, but there were very small differences in the profile shape with the shock-foot location. Overall, the PLS and PIV data provided little support for the thickening/thinning boundary-layer idea.

Similar laser diagnostic techniques were used in a subsequent study by Beresh et al.[61] to examine further the idea that turbulent fluctuations in the incoming boundary layer are responsible for the small-scale shock motion. Time-sequenced pairs of PLS images were acquired that show the passage of turbulent structures through the interaction region. Although turbulent structures greatly distort the outer region of the separation shock, the shock foot does not move appreciably in the same time frame. PIV measurements of the turbulent velocity fluctuations in the incoming boundary layer were obtained by subtracting the mean velocity field from each instantaneous vector field. Velocity fluctuations in each vector field were then averaged to produce a single representative value for that image that measures the overall acceleration or retardation of the boundary layer. These were then plotted against the shock-foot velocity. Previous experiments had suggested a relationship between these two quantities might exist,[67] an idea supported by the LES of Hunt and Nixon[74] that showed an approximately one-to-one relationship between the shock velocity and the incoming turbulent velocity fluctuations. The experimental data, however, exhibited no such trend.

However, these experiments are very difficult to make, and it is difficult to be certain if the lack of correlation is real or due to shortcomings of the experiment. It is possible that the PIV data set was insufficient for statistical convergence. As a consequence, the PIV

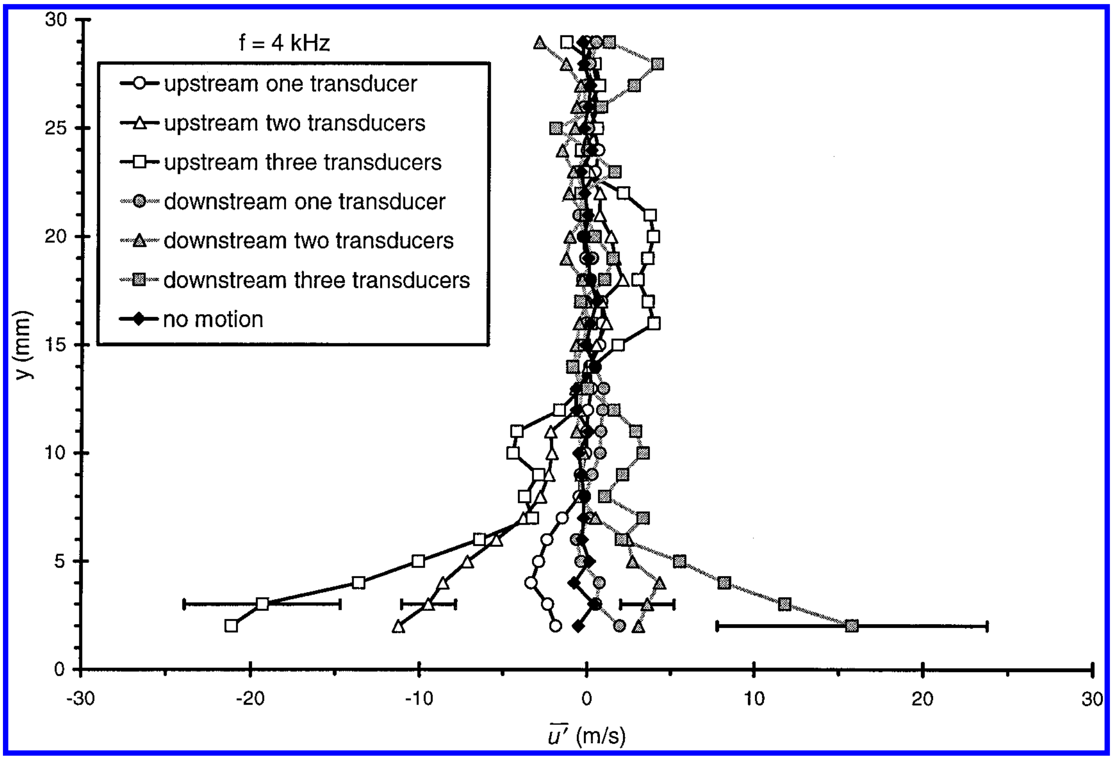

Fig. 5 Conditional ensemble-averaged profiles of the streamwise velocity fluctuations in the incoming boundary layer, conditioned on the separation shock-foot motion within a time period of 250 μs (4 kHz); profiles are for different types of shock motion and distance is measured by the number of wall-mounted transducers the shock foot traverses during the time period. Figure is from Ref. 62.

experiment was repeated and improved and a much larger volume of data acquired. Other improvements in the experiment yielded velocity measurements closer to the wall and an improved determination of the shock-foot motion. To examine the question of whether the boundary-layer thickness varied with the shock position, the velocity vectors were conditionally ensemble averaged and collapsed into velocity profiles for shock-upstream and shock-downstream positions. No difference in the boundary-layer thickness was found, thus showing that the thickening/thinning mechanism is not valid.

However, as shown in Fig. 5, when the velocity fluctuations are conditionally averaged for different types of shock-foot motion, an interesting trend is revealed. Near the wall, negative velocity fluctuations correlate with upstream shock motion and positive velocity fluctuations correlate with downstream shock motion. This correlation is stronger for larger excursions of the shock. Interestingly, no correlation is observed in the outer part of the boundary layer. These results are the first to offer direct experimental evidence of a relationship between the velocity fluctuations in the upstream boundary layer and the motion of the separation shock foot. Positive velocity fluctuations produce downstream motions of the separation shock, which, over a sustained period, integrate to a fuller velocity profile for a downstream shock location. Similarly, negative velocity fluctuations produce upstream motions of the shock and integrate to a less full velocity profile for an upstream shock location. These observations are consistent with the simple concept of a fuller velocity profile providing increased resistance to separation and, thus, a downstream shock position. Furthermore, such variations in the shape of the instantaneous velocity profile may yield changes in the shock position and, hence, produce the unsteady shock-foot behavior.

Wu and Miles[75] have recently reported some interesting work in a Mach 2.5 compression corner interaction using a megahertz rate visualization system. With their system, 30 images per burst can be acquired at megahertz rates with a burst-repeat rate of 9 Hz. They report that "the shock motion is strongly correlated with the incoming boundary layer structure."[75] They noted that the shape of the shock could change from "a single shock to compression fans or groups of shocklets" and that they would "fluctuate at large scale [boundary-layer thickness] in the streamwise direction and high frequency (100 kHz)."[75] Based on studies of the author and colleagues, and mentioned earlier, it should not be inferred from the latter remark that the shock foot and the separated flow pulsate at such high frequencies. In Ref. 62, in which double-pulse PLS images were acquired in a Mach 5 compression ramp interaction, the shock-foot position was monitored simultaneously using pressure transducers. Large, rapid distortions of the outer part of the separation shock were seen, similar to the observations of Wu and Miles.[75] However, they were not accompanied by any change in position of the separation shock foot. Of considerable interest and worthy of further study was Wu and Miles's[75] observation that different boundary-layer structures had a different influence on the shock. Structures referred to as hatchback (those with a square end) had a large influence whereas finger structures (inclined at about 45 deg) had a much smaller effect.

New Studies

As far as flowfield unsteadiness and fluctuating loads are concerned, there are probably two broad classes of experiments that would be useful in differing ways for the design engineer, the physics explorer, and the code developer. For the designer, reliable and reasonably accurate engineering correlations for loading levels, locations of peak loads, and their spectral content would be invaluable. In the near term, unless LES proves successful, it is not likely that such correlations can be developed from simulations. New parametric experiments are needed. The data currently available are very limited in scope and are nearly all for flows in which the incoming boundary layer is nominally two dimensional and in a zero pressure gradient. In many applications it is likely that the incoming boundary layer will be three dimensional and developing in a pressure gradient. How the unsteadiness and fluctuating load levels in interactions are affected is not known. Appropriate instrumentation, data acquisition systems, and data storage devices are now far more widely available and easier to use than in earlier decades, making new, wider-ranging experiments more economically reasonable.

The experiments referred to fall primarily into the observation category. They require care but do not require new data acquisition strategies or analysis methods. The idea is to generate a database of measurements from which the effects of flow parameters and model geometry can be identified and from which useful correlations can be developed. The second set of experiments, which are difficult to define, let alone execute, focus on providing the explanation for experiments providing the observations. The two sets of experiments are clearly synergistic. If carefully conducted experiments showed how peak load magnitude and frequency in a given interaction correlated with freestream velocity and incoming boundary-layer thickness [or whatever the key parameter(s) are], then this would provide invaluable hints on how an experiment can be devised that will highlight the physics. With the rapid development of laser-based imaging techniques and high framing rate CCD cameras, nonintrusive full-field measurements (as opposed to intrusive point measurements) are now possible. Such methods, used in continuous or conditional modes, either alone or in combination with high-frequency response pressure transducers, make possible experiments that earlier investigators could only dream about.

Incoming Boundary Layers

Existing Database

A very large fraction of the experiments done to date have employed nominally two-dimensional, equilibrium, zero-pressure-gradient, incoming turbulent boundary layers. This stems in large part from the constraints imposed by conventional supersonic wind tunnels in which the nozzle usually has a square or rectangular cross section and is followed by a constant-area test section. The test boundary layer is usually the one on the floor or ceiling, or occasionally on a flat plate. In hypersonic flows, axisymmetric nozzles are common and experiments are most likely to have been conducted on a flat plate, or on a hollow cylinder aligned with the freestream. In either case, the boundary layers develop in a close-to-zero pressure gradient. Generally, the incoming boundary layer is only characterized in terms of a mean velocity profile (deduced from pitot surveys and a single total temperature measurement, usually with an assumption of zero normal pressure gradient), from which integral properties and skin-friction coefficient are calculated. The latter is commonly deduced from a fit to the law of the wall/law of the wake or from methods such as that of van Driest II. Freestream and spanwise boundary-layer uniformity, turbulence quantities, etc., are often undocumented or unknown.

In most of these experimental facilities, substantial and very costly modifications would be needed to generate a two-dimensional boundary layer developing in a controlled streamwise pressure gradient. Characterizing even the mean velocity profile development of the incoming boundary layer, let alone the turbulence evolution and its properties at the interaction start, would be time consuming and expensive. Generating a three-dimensional incoming boundary layer whose mean velocity field was well-defined would be even more daunting. Aside from these facility restrictions, which are still firmly in place today, there was some sentiment that the interactions under study were already sufficiently complex that it made sense to understand the flowfield structure and properties for the simplest possible incoming flow conditions before moving on to more complex incoming flow conditions. Now is the time to move forward.

New Work

Because such experiments form the bulk of the existing database, a very large fraction of the computations of these flows has also been made using the same restrictive incoming flow conditions. There has been little work, experimental or computational, to explore how interaction behavior is altered if the incoming boundary is not two-dimensional and in a zero pressure gradient. Such experimental data could be very helpful in highlighting the important interaction physics and confirming (or refuting) ideas based solely on zero-pressure-gradient studies. Such data would also serve as excellent tests of a given simulation approach. For example, even for the nominally two-dimensional interaction generated by an unswept compression ramp interaction, it is not known how interaction length scales, heating rates, skin-friction distributions, etc., are influenced if the incoming boundary layer is still two dimensional but developing in a strong pressure gradient. It is easy enough to argue intuitively that the mean separated flow length scale should increase/decrease with a decelerating/accelerating incoming boundary layer, but predicting the magnitude of the changes is not as simple. Interesting and practical questions abound. For example, with an accelerating incoming boundary layer, will peak heating on the face of an unswept compression ramp be increased or decreased, by how much, and why? How does the change correlate with the magnitude of the pressure gradient, or the length over which it has occurred, or some integrated combination of these and other parameters? Can simple expressions be developed that will relate the peak heating to some normalized pressure gradient parameter? Can available RANS codes and widely used turbulence models even predict the basic trends correctly? Less intuitive are answers to such questions as is the interaction unsteadiness affected? Does the length scale of the separated flow pulsation increase or decrease, or is it unaffected? Does the frequency spectrum of the separated flow pulsation shift up or down, and why? How are maximum fluctuating load levels on the ramp face affected? If the incoming boundary layer is three dimensional, or highly skewed, situations that are likely to occur in practice, the problem is even more complex. To the author's knowledge there are no engineering correlations for such situations, nor have there been any systematic experimental studies or simulations in which such issues have even been addressed.

Progress in nonintrusive instrumentation now makes such experiments more feasible, not only in terms of measuring quantities in the interaction itself, but especially in terms of characterizing the incoming boundary layer (mean and fluctuating velocities). Some carefully documented experiments using incoming boundary layers developing in different pressure gradients, and with three-dimensional boundary layers, would be useful in several respects. First there is simply that in most applications the incoming boundary layer is not likely to be developing in a zero pressure gradient or be two dimensional. If the past is a guide to the future, it is likely that increasing the breadth of the parameter space will not only provide support for some existing ideas, but will also show that issues that were thought to be understood are, in fact, not well understood. Such experiments are also likely to raise new questions that investigators have not thought of posing before. One pending question discussed in the preceding section involves the underlying causes of flowfield unsteadiness. Some relatively simple experiments using boundary layers developing in pressure gradients might well generate interesting results.

Transitional Interactions

Predicting transition to turbulence in supersonic and hypersonic boundary layers and understanding fully how the process is influenced by basic flow and geometric parameters such as Mach number, pressure gradient, curvature, sweep, angle of attack, roughness, bluntness, etc., is a goal yet to be reached. The inability to predict transition with confidence was identified by the Defense Science Board as one of the key technologies lacking in the National Aerospace Plane (NASP) program. In a 1987 report, Reshotko et al.[76] state that "aerodynamic heating is a primary driver in the trade-offs and compromises in the development of configuration and structure for the NASP vehicle." They point out that "the airbreathing propulsion system will have the most severe and complex aerodynamic heating. On the side walls and cowl it is desirable to maintain a laminar boundary layer as far as possible, however the extreme local environment (oscillating shock waves, etc.,) makes it necessary to thoroughly understand the boundary layer behavior to determine how long it can beneficially be kept laminar."[76] It is likely that shock-wave/transitional boundary-layer interaction will occur in inlets as well as other external locations.

SWBLI with a transitional boundary layer is a field in which little work has been done, but one which could, with some carefully conceived experiments, not only show how a transitional boundary layer influences interaction properties, but perhaps shed light on many of today's vexing questions in turbulent flows, from peak heating rates to the causes of global flowfield unsteadiness. At this stage, it does not seem likely that simulation can be used with any measure of confidence to predict such flows. Even generating repeatable transitional flowfields experimentally, making the kinds of measurements that will be necessary, and developing analysis methods for bringing out the physics will be extremely challenging. The author's very limited experience some 10 years ago with transitional fin interactions on a flat plate (which arose purely by accident) provided some indication of the difficulties. At fixed tunnel stagnation conditions, small changes in some flow or geometric parameter(s) shifted the transition front upstream and downstream on the plate from run to run. Admittedly, these experiments were far from being under control in the sense that they were performed in a blowdown tunnel with a relatively high and unmonitored freestream turbulence level. Furthermore, the author recalls that run-to-run visual inspection of the initially sharp leading edge of the flat plate revealed random chipping and blunting across the span due to dust particle impact, a factor which could randomly affect the location of the transition region. Although nothing useful came out of these simple, qualitative tests, experiments in new quiet tunnels under very carefully controlled and monitored conditions could yield useful results. If the transition region relative to a model could be fixed, then at least the incoming conditions might be repeatable from test to test. Under such conditions, some interesting work could be done on how an interaction changes structure and scale and how and why unsteadiness becomes a dominant feature as the interaction changes from laminar to transitional to turbulent. One of the known, interesting features of changing the incoming flow from laminar to turbulent is the (generally) large change in interaction length scale that occurs, providing an opportunity to see cause and effect. For example, the upstream influence of an unswept, semi-infinite circular cylinder in laminar flow is around 9–12 diameters, whereas in turbulent flow it is about 2–3 diameters. The limited data for the transitional case suggest a value roughly in the middle.

Many experiments can be dreamed up using transitional boundary layers that might enhance understanding of global flowfield unsteadiness. None are simple, but given today's instrumentation and data recording and analysis capability, they are possible and could yield very useful insights. In trying to study the causes of unsteadiness in a turbulent interaction, the forcing function, presumably some aspect of the turbulence in the incoming flow, is always turned on. In a transitional flow, if it can be controlled appropriately, there is an opportunity to study how bursts of turbulence, or how short durations of fully turbulent flow entering the interaction initiate and influence the unsteadiness. In the perfect (and relatively easy) world of inventing experiments, one can imagine using an unswept circular cylinder to generate a large-scale laminar interaction. The available data suggest that such an interaction should be steady, although it is possible that some cylinder-induced interactions with multiple pairs of horseshoe vortices have a natural instability. However, assume that it is steady and that the incoming boundary layer has been seeded with particles for PIV measurements. The tunnel stagnation pressure could then be systematically increased such that turbulent bursts are produced in the upstream boundary layer, which are then convected downstream into the interaction. These bursts would, on their passage downstream, convect over a flush-mounted pressure transducer, or hot film, triggering sequential laser sheets producing image pairs from which the streamwise and vertical velocity components of the burst could be obtained, providing some characterization of the incoming perturbation. This same trigger could also be used to initiate data acquisition on N flush-mounted, streamwise-aligned, pressure transducers installed downstream and spanning the interaction region. In this way, or some similar way, the passage and evolution through the interaction of the turbulent burst could be tracked and its effect on the interaction unsteadiness monitored.

In earlier work it was shown that recirculating turbulent structures influence the separation shock motion as well as structures entering the boundary layer from upstream. Cross correlations of shock velocity fluctuations with pressure fluctuations under the separated flow had maxima at negative times, indicating that separated flow fluctuations precede shock/velocity fluctuations. With such measurements it is difficult to separate out their relative importance and also to distinguish clearly cause and effect. In experiments of the preceding type, or better-thought-out variants, it should be possible to determine how different perturbations (in magnitude and duration) directly affect the downstream flowfield and determine if particular perturbations play a critical role whereas others are less important. Answers to questions like this could play a role in developing rationally based control strategies: does it make more sense to try and manipulate the incoming flow or the downstream recirculating flow?

Flow Control

The past decade has seen a great deal of interest in flow control across the entire spectrum of fluid dynamics. This interest is likely to grow. The potential benefits of flow control depend on the application, but, in a general sense, the objective is increased efficiency or improved performance of a vehicle, or of a component, hopefully at a lower cost, or with only a small (and worthwhile) increment in cost. In a recent review, Kral[77] notes that "the design trade-offs of a particular method of control must carefully be evaluated and compromises are often necessary to reach a particular design goal." This makes flow control a particularly challenging endeavor because in many flows of interest it is not known with certainty what the key parameters are, let alone how changes in one parameter will affect others.

Flow control can be broken down into passive and active types. In passive control, an attempt is made to produce a beneficial result without the expenditure of externally supplied energy and includes such well-established methods as the ubiquitous vortex generator, riblets, as well as the venting method cited in the example in the introduction. Active control, on the other hand, is categorized by Kral[77] as being either predetermined or interactive. In the former case, steady or unsteady energy inputs are made through some form of actuator irrespective of the state of the flowfield. In contrast, in an interactive method, the power supplied to the actuator is varied continually, depending on input from a sensor or sensors. The control loop can be either feedforward (open loop), where the sensor is placed upstream of the actuator, or it can be feedback (closed loop). In the latter case, a sensor is also placed downstream of the actuator, and, based on comparison of the output from that sensor and the upstream one, a feedback law is used to control the energy input to the actuator. Kral notes that Moin and Bewley[78] have broken feedback interactive control into four subcategories. The reader is referred to Refs. 77 and 78 for details.

Over the past decade, work in control has grown enormously, driven by the advances in miniaturization of computers, sensors, and actuators. The attraction of active control lies in its potential for a large payoff. Supersonic inlets is one area where the payoff could be large. Currently bleed is used to improve pressure recovery and mitigate flow distortion by reducing separation and unsteadiness. The ducting necessary for bleed incurs a drag, weight, and cost penalty. Furthermore, the inlet must be increased in size to account for the bleed mass-flow losses. An additional penalty of bleed at subsonic conditions is the associated aerodynamic roughness of the holes/slots. An alternative control approach named smart mesoflaps for aeroelastic transpiration (SMAT) is currently under study by a Boeing/NASA John H. Glenn Research Center at Lewis Field/University of Illinois consortium.[79] SMAT flaps, which have a chord length of a few millimeters to a centimeter, are held fixed at the leading edge, but the remainder can flex naturally under pressure loading, or can be made of smart materials and activated in a control loop.

Under a shock/boundary-layer interaction, the cavity under the entire flap assembly reaches a pressure level between the upstream and downstream values. The upstream flaps deflect upward (tangentially injecting mass), whereas the downstream flaps deflect down removing mass from the interaction. In this sense, the technique resembles traditional passive venting, although with SMAT flaps the injection is tangential and in the no-shock condition they seal approximately, providing a drag benefit. However, with SMAT flaps, improved performance may be possible with local active control. In the example just described, the flaps might be made of conventional materials, that is, aluminum, that deflect under external pressure. Alternatively, the flaps could be made of a stress-activated or thermally activated smart material (to provide increased deflection and mass flow). The latter could be controlled by heating elements for closed-loop control of their stiffness. Payoff analyses for a generic Mach 3.5 vehicle at 12,000-m altitude indicate a total aircraft weight and cost savings of up to 18%. Even if the latter is overstated, a payoff of half that value would be impressive. It is evident from this example that, unlike passive control, where the key lies mainly in understanding the fluid mechanics, successful active control calls for a melding of fluid dynamics, controls, materials, electronics, software, optimization, and other disciplines and is very much an interdisciplinary endeavor. Development of laboratory demonstrations poses difficult, but exciting, intellectual and engineering challenges. Demonstrating that such techniques can then be scaled up, made reliable and robust, and survive the harsh environment of full-scale flight will be even more demanding.

Kral[77] proposes a recipe for successfully applying active flow control. It is worth examining the approach to see how it might be applied to SWBLI in general. Step 1 is to specify the control objective (for the preceding example it might be to reduce the unsteadiness). Step 2 is to identify the flow phenomenon that needs to be controlled or leveraged to achieve the objective (in this example, postpone separation or reduce its scale). Step 3 is to select an appropriate actuation strategy (tangential injection to fill out the incoming velocity profile). Step 4, the final one, would be to determine the forcing frequency and amplitude. Implicit in step 2 is that the flow physics is known or, at least, there is some fundamental understanding of how variations in one parameter influences another. In the inlet example, even though the details may be lacking, it known before starting out that to reduce unsteadiness the control approach must reduce the extent of separation. Consider now SWBLI in general in external flows. An obvious question is what do we wish to control. The answer will necessarily be application dependent, but control objectives at high speeds might include reducing peak heating rates, reducing the magnitude of fluctuating pressure loads, reducing the length scale of pulsating separating flows, shifting their frequency spectrum away from critical ranges, etc. On the other hand, in an internal flow, the exact opposite might be required; in a scramjet it might be beneficial to amplify unsteadiness or the turbulence to augment fuel/air mixing. The fundamental problem in considering control strategies for any of the aforementioned problems is that in most of these cases it is not at all clear what should be sensed, nor what an actuator should do.

It can be argued that initiating flow control studies without fully understanding the underlying flow physics will be a hit-or-miss affair and may well waste both time and resources and lead to unpleasant surprises. In this author's opinion an equally persuasive argument can probably be made to the contrary. The nature of research is that progress often occurs as much by chance as by design and often just as much, if not more, can be learned from an experiment that did not evolve as expected as from one where the anticipated result did indeed occur. Improved physical understanding often emerges from parametric studies, that is, changes in Reynolds or Mach number, model geometry changes, and alterations in boundary-layer properties. Such parametric changes highlight the controlling variables and allow hypotheses to be tested. Flow control strategies (pulsed injection, mechanical flaps, etc.) are in one sense no more than an extension of this classic approach.

Summary

In this paper an attempt has been made to 1) identify weaknesses in our physical understanding and predictive capability of SWBLI and 2) offer some suggestions as to where, in the near term, it might be profitable to focus our attention. Examination of the state of the art in the 1950s with that in the late 1990s shows that enormous progress has been made, yet many questions raised/issues addressed in these early studies are still with us today. A major difference between then and now is the tools, experimental and computational, available to explore these issues. It is probably fair to say that these tools are not being fully exploited to address these issues and, as a consequence, progress is slower than it might otherwise be. In this author's view there is a need for focused programs in the areas of 1) LES and variants thereof, with a view to modeling the unsteady behavior and predicting unsteady thermal and pressure loads; 2) improved measuring techniques for heat transfer and increased focus on understanding why current predictive capability for strong interactions is particularly poor; 3) understanding the causes of the large-scale, low-frequency pulsation of separated flows with a view to determining, at minimum, whether this is an inherent feature of shock-induced separation or whether it is somehow driven by phenomena present only in the wind-tunnel environment; 4) interactions in which the incoming boundary layer is developing in a pressure gradient, is yawed, or is fully three dimensional; 5) transitional interactions; and 6) flow control. That is not to say that there are not other important questions to address, or interesting areas in which to work. It is simply to say that a concerted effort in each area, especially in areas 1 and 3, has the potential to propel the entire field forward. The most profitable approach would clearly be one in which computation and experiment are closely coupled.

Acknowledgments

It is said that "it is better to remain quiet and be thought a fool, than to open one's mouth and prove it," and probably no greater opportunity exists for offering this proof than confident statements about the future. In writing a paper such as this, one runs the inevitable risk of developing a high citation count in later years, as much of what is said is either proven misguided, or worse, wrong. Should this paper be read a few years from now it must be remembered that it was written from the vantage point of late 1999/early 2000 and that 20/20 vision is normally only available after the fact. One point in favor of the reader concluding that much here is reasonable is that many of the points raised in this paper came out of discussions, e-mail exchanges, etc., with colleagues who were asked for their views on current problems and future needs. A list of all those who contributed is given here. Their contributions are gratefully acknowledged.

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