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Supersonic and Hypersonic Shock/Boundary-Layer Interaction Database

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An assessment is given of existing shock wave/turbulent boundary-layer interaction experiments having sufficient quality to guide turbulence modeling and code validation efforts. Although the focus of this work is hypersonic, experiments at Mach numbers as low as 3 were considered. The principal means of identifying candidate studies was a computerized search of the AIAA Aerospace Database. Several hundred candidate studies were examined and over 100 of these were subjected to a rigorous set of acceptance criteria for inclusion in the database. Nineteen experiments were found to meet these criteria, of which only seven were in the hypersonic regime ($M > 5$). The backup document for this paper (Settles, G. S., and Dodson, L. J., "Hypersonic Shock/Boundary-Layer Interaction Database," NASA CR 177577, April 1991) contains these data in both tabulated and machine-readable form. Suggestions for future experimental needs in this field are also given.

Introduction

IN modern hypersonic programs it has been recognized from the outset that computational fluid dynamics (CFD) must play a major role. Indeed, the future of high-speed air and space transportation depends critically on our ability to predict solutions of those aerothermal problems which are too difficult or expensive to test in ground-based simulation facilities. Great strides have recently been made in the ability of CFD methods to do this, but it is clear that substantial improvement is still needed.

Although not the only problem obstructing further advances in CFD, turbulence modeling is recognized to be one of the major ones. A closed solution of the governing Navier-Stokes equations for turbulent flows of practical consequence is still far beyond our grasp. At the same time, the simplified models of turbulence which are used to achieve closure of the Navier-Stokes equations are known to be rigorously incorrect. Although these models serve a definite purpose, they are inadequate for the general prediction of viscous/inviscid interactions, compressible turbulent mixing, transition, chemical nonequilibrium, and a range of other phenomena which must be predictable in order to design a hypersonic vehicle computationally. For this reason, turbulence modeling is a key issue in the continuing effort to push forward the boundaries of knowledge of high-speed flight.

Because of the complexity of turbulence, useful new turbulence models are synthesized only when great expertise is brought to bear and considerable intellectual energy is expended. Although this process is fundamentally theoretical, crucial guidance may be gained from carefully executed basic experiments. Following the birth of a new model, its testing and validation once again demand comparisons with data of unimpeachable quality. This report concerns these issues, which arise from the experimental aspect of turbulence modeling for high-speed flows.

A high-speed turbulence modeling workshop was held at NASA Ames Research Center, June 7 and 8, 1988. This workshop had the goal of identifying ways to improve turbulence modeling for hypersonic flows, with specific applicability to the NASP program. Both theoretical and experimental issues were discussed in detail. In the course of this discussion, questions arose about the quantity and quality of existing (mostly pre-1970) experimental data which bear upon the issue of hypersonic turbulence modeling. Specifically, it was pointed out that existing surveys of high-speed flows (e.g., Ref. 1) list several hundred experiments that have been carried out at hypersonic speeds. Thus, it was claimed, sufficient experimental data were already in hand for the purpose of turbulence modeling. However, some attendees of the workshop questioned whether any significant number of these existing experiments could meet the high standards necessary for modern code validation and turbulence modeling, especially insofar as nonintrusive flow diagnostics and high-speed data acquisition hardware have only recently become available.

Since this question could not be resolved immediately, one of the conclusions of the workshop was that the need existed to review critically the database of existing hypersonic experiments for its suitability for turbulence modeling and code validation. Accordingly, an effort was begun early in 1989 by the Pennsylvania State University Gas Dynamics Laboratory to perform this critical review and to assemble the required database. The effort was sponsored by the NASA Ames Research Center as part of an overall task to develop improved compressible turbulence models. This paper summarizes the results of that effort.

Database Subject Area

The choice of the specific subject area for this high-speed database collection and assessment effort was made in favor of a few critical issues directly relevant to turbulence modeling. Our purpose in this effort is to define a database for the specific goal of the advancement of modern turbulence models, not to conduct a broad-based survey of all previous work in the field of hypersonics.

Accordingly, discussions with NASA personnel led to the following list of specific topics for the database: 1) shock wave/boundary-layer interactions, 2) supersonic shear layer mixing, and 3) high-speed attached boundary layers with pressure gradients. The initial database collection and assessment effort considered only topic 1. A brief justification of the choice of this topic follows.

Shock/boundary-layer interactions are recognized as the premiere pacing issue of modern CFD and turbulence modeling for high-speed flows. The reasons for this lie in the prevalence of such interactions in both external and internal practical aerodynamic problems, as well as their fundamental level of difficulty. As a practical example, the interaction of shock waves with boundary layers underlies the efficiency (if not the viability) of all high-speed inlets for airbreathing propulsion. As a fundamental example, note that these flows embody mixed hyperbolic and elliptic domains with boundaries not known a priori, and that the problem

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of turbulent boundary-layer separation (not even "solved" in incompressible flow) is included in shock/boundary-layer interactions. For these reasons the most advanced CFD codes have traditionally been tested against such interactions, though very little has been done so far to test CFD methods or validate codes against hypersonic interactions.

Specifically, the coverage of the present database collection and assessment effort with respect to shock/boundary-layer interactions includes both supersonic ($M \sim 3$ and above) and hypersonic data, both two-dimensional and three-dimensional data, and both unseparated and separated turbulent boundary layers (though the emphasis is on the latter). Consideration also includes not only perfect-gas behavior, but real gases and (where appropriate) chemically reacting flows as well. It is recognized, however, that very little if any data of the latter two types exist within the chosen subject area.

Database Collection

Our philosophy of collecting the necessary data for this study hinges on the following four strategies: 1) take full advantage of pre-existing database reviews, surveys, and compilations; 2) conduct machine searches to identify likely candidate studies cited in the literature; 3) make use of NASA, National Technical Information Service, AIAA, and other technical library resources to obtain data reports as necessary; and 4) contact investigators, both former and current, as necessary to obtain sufficient documentation on selected candidate studies.

During the initial phase of this effort we have studied a variety of prior reviews and surveys on shock/boundary-layer interactions and related subjects (e.g., Refs. 1–19). The library holdings of the Penn State Gas Dynamics Laboratory, which has maintained a long-term research effort on this topic, were also thoroughly reviewed. However, the major data collection effort took the form of a computerized literature search.

We have searched primarily the AIAA Aerospace Database, which comprises File 108 of the Dialog computerized database system. The aerospace database covers publications and reports since 1962 on aerospace-related subjects, and includes both International Aerospace Abstracts (IAA) compiled by the AIAA and Scientific and Technical Aerospace Reports (STAR) compiled by NASA. Considering the strong aerospace flavor of the present subject matter, it was felt that this database was an obvious choice and that searches of other science and engineering databases would be unlikely to turn up significant additional material of relevance.

Before beginning this search process, the *NASA Thesaurus*[20] was consulted for appropriate keywords. A group of known references to be included in the database was retrieved from the aerospace database to determine which keywords were used. As it happens, there is no single keyword entry in use for "shock wave/boundary-layer interaction," and the actual keywords choices describing pertinent references varied widely. The keywords "shock wave interaction" and "interactional aerodynamics" were the most prevalent. At the time the search was conducted, the aerospace database contained 3379 references (here referred to as set 1) indexed by one or the other of these two keyword phrases. However, an examination of a random sampling of these revealed a low percentage of useful entries for present purposes.

Our next step was to search for citations with one or more of the keywords: boundary layer, turbulent boundary layer, supersonic boundary layer, or hypersonic boundary layer. This subset (set 2) of the aerospace database contained 27,122 citations. The intersection of sets 1 and 2 (998 citations) is thus the set (set 3) which might be described as shock wave/boundary-layer interactions, at least insofar as keyword descriptors are concerned. However, examination of a random sampling from set 3 still revealed many inappropriate citations for the present purposes. It seemed that the combination of keywords used thus far was necessary but not sufficient to fully and exclusively characterize the literature citations which we sought.

We next decided to narrow the range of consideration still further by requiring that, in addition to the cited keywords, descriptors related to shock/boundary-layer interactions must also appear in the title or abstract of the citation. A long list of such possible descriptors was compiled and linked by Boolean "or" terms, such that the presence of any one of them would produce a "hit." Upon searching titles and abstracts of the aerospace database for this list, set 4 consisting of 815 citations was found. The intersection of sets 3 and 4 resulted in 436 citations (set 5).

Examination of a random sampling of citations from set 5 now revealed a high incidence of apparently pertinent references. A final step was taken to narrow this list still further by excluding those citations in which the keywords laminar, transonic, and computational fluid dynamics appeared. This was done because these three descriptors typically characterize studies which are not pertinent to the present (turbulent, supersonic and hypersonic, experimental) context, though it carried the slight danger that combined studies of interest might be excluded. The result of this operation on set 5 was set 6, containing 279 citations.

The abstracts of every citation in set 6 were examined manually to determine their relevance. This process depended heavily upon our experience in shock/boundary-layer interaction research to identify likely candidate experiments. In cases for which a decision could not be reached from the abstract alone, a hard copy of the full document was obtained and examined manually.

The result of this process was the final set (set 7), which consisted of 105 apparently distinct experimental studies of shock wave interactions with turbulent boundary layers at Mach numbers of 3 or higher. Set 7 was subjected to the database assessment procedure described next.

Database Assessment

This was the critical step of the study, in which the decision was made as to which of the possible candidate experiments identified earlier actually merit inclusion in a database to be put forth as a standard for CFD code validation and turbulence model development. Our philosophy at this stage was that we were looking only for those few experimental studies of unimpeachable quality and direct pertinence to the subject at hand. It would be a mistake, we felt, to give the benefit of doubt to questionable experiments when such a course of action might cause future turbulence modeling efforts to be misled. Also, we drew guidance from Coles,[21] a distinguished predecessor at this task, who noted that those data turn out to be most useful in which only one factor is varied at a time and that there appears to be a certain level above which measurements can be described as being of "professional quality."

We thus subjected the 105 candidate studies of set 7 to a test based on rigorous criteria for this purpose. The criteria are grouped in two categories: "necessary" and "desirable." Candidate experiments were required to pass all the necessary criteria in order to be considered further. However, even then, failure to meet any of the desirable criteria could still result in rejection of a candidate experiment on the basis that it failed to contribute anything truly useful to the goal of the database.

A list of the eight necessary criteria is given below in the hierarchical order in which they were applied.

1) *Baseline applicability*: All candidate studies must be experiments involving turbulent flows in either the supersonic or hypersonic Mach number range (i.e., $M \sim 3$ or higher). Further, these studies must address the subject area of shock wave/boundary-layer interactions.

2) *Simplicity*: All candidate studies passing this criterion must involve experimental geometries sufficiently simple that they may be modeled by CFD methods without enormous difficulty. Flows through complex inlet scale models or over the surfaces of complete three-dimensional flight configurations are rejected at this point, for example. Stated in other words, this criterion is a filter that passes only "building-block" experiments.

3) *Specific applicability*: All candidate studies passing this criterion must be capable of providing some useful test of turbulence modeling. For example, any study which provides only a surface pressure distribution over an arbitrary surface in hypersonic flow is rejected as insufficient to further the goals of turbulence modeling. To be a useful test case, such a study would at least require additional data such as flowfield profiles or heat transfer/skin friction

distributions. (Some experience and judgment were called for in the application of this criterion.)

4) *Well-defined experimental boundary conditions*: This criterion was applied in the mathematical sense of the boundary conditions of an equation, which must be fully specified before a particular solution can be had. For high-speed experiments, the criterion requires at least that all incoming conditions (especially the state of the incoming boundary layer) be carefully documented. For turbulent incoming boundary layers, either known upstream transition conditions (to allow a boundary-layer calculation to be made) or else at least the mean documentation of the incoming profile must be provided. Similarly, all studies claiming "two-dimensional" flow must show data indicating the extent of spanwise flow variations.

We recognized at the outset that this criterion alone might eliminate a large proportion of past studies from further consideration. However, without it, the resulting database would fail to be useful for its intended purpose.

5) *Well-defined experimental error bounds*: To pass this criterion, the experimenter must provide an analysis of the accuracy and repeatability of the data, or error bars on the data themselves. Further, such accuracy indications or error bounds must be substantiated in some rational way beyond their mere statement. This criterion helps to assure that a proper code validation exercise can be conducted with the subject data, in that discrepancies between experiment and computation can be meaningfully interpreted.

6) *Consistency criterion*: If, during the consideration of a candidate study, mutually inconsistent results are discovered, then that study is not considered further for the database. This criterion amounts to a special corollary of the preceding criterion.

7) *Adequate documentation of data*: Candidate studies are examined to determine whether or not their data are documented sufficiently to allow quantitative results to be included in the database in tabulated and machine-readable form. In some cases the experimenters were contacted directly to ascertain if machine-readable data were available. Candidate studies failing this criterion are eliminated.

This criterion applies in particular to studies whose documentation is available only in plotted form. If such plots are quantitatively unreadable within reasonable error bounds as already mentioned (taking note of the scale distortions which often occur during publication), then the data cannot be considered useful for the present database. (Coles[21] read data from plots in only two cases. We have not done so at all in the present study.)

8) *Adequate spatial resolution of data*: To pass this criterion, experiments must present data of sufficiently high resolution, compared with the scale of the flow in question, that the key features of the flow are clearly resolved. Failure to do so results in data which are inadequate to provide a proper test for turbulence modeling. Some experience and judgment were also called for in the application of this criterion.

In addition to the enumerated necessary criteria, the following desirable criteria were also used to determine which candidate experiments were included in the database.

1) Turbulence data: In addition to purely mean-flow measurements, turbulence data such as Reynolds stresses and velocity or mass-flux fluctuation levels are considered highly desirable.

2) Realistic test conditions: Of those flows passing the necessary criteria, special preference is given to cases with Mach numbers in the hypersonic range, nonadiabatic wall conditions, real-gas effects (though no such experiments were found), or related characteristics typical of actual hypersonic flight.

3) Nonintrusive instrumentation: All other conditions being equal, preference is given to experiments wherein nonintrusive instrumentation (e.g., optical measurements) were employed to acquire the data. This preference is based on the automatic elimination of certain error and boundary-condition concerns which arise from the use of intrusive flow probes.

4) Redundant measurements: Further preference is given to experiments in which redundant data are taken, establishing the values of flow quantities by more than one method. This is considered to be a strong demonstration of the quality and error bounds of the data.

5) Flow structure and physics: Finally, preference is also given to those experiments which, in addition to providing quantitative data, also reveal flow structures and physical mechanisms. This criterion promotes the potential for higher level CFD comparisons with the salient characteristics of the flows in question, rather than merely with unstructured flow profiles.

The individual studies of set 7 subjected to the given criteria are listed in the Reference section of this paper as Refs. 25–129. Each of these studies was given a detailed assessment through examination of its source material. During the evaluation procedure a tabular evaluation matrix was kept of decisions in each assessment category for every study considered. This evaluation matrix and the tabulated data of the accepted experiments are too lengthy to be included in this paper. Readers are referred to our backup document[22] for this material. The accepted studies are listed in Table 1 with icons showing the test geometries represented. Tabulated data for each accepted study are included in Refs. 22 and 23, along with diskettes containing the complete data in machine-readable form.

It happened that several pertinent experiments were in progress at the time that the original database compilation occurred. We had occasion to consider the results of these experiments at a later date and found that several of them met the criteria for inclusion in the database. For completeness, these results are also indicated in Table 1 and are listed as Refs. 130–147 in this paper. The details of these late additions, along with their machine-readable data and some corrections to the original data diskette, may be found in Ref. 23.

Results and Conclusions

Only a few of the "finalists" in set 7 passed a sufficient number of the assessment criteria to be accepted into the database. Of these, we observed the trend that far more acceptable studies fell in the supersonic Mach number range (Mach 3–5) than in the hypersonic range (above Mach 5). Since this became clear early in the assessment phase, somewhat more stringent standards were applied to supersonic than to hypersonic studies. Also, the paucity of true hypersonic data resulted in all such studies being accepted in which at least the eight necessary criteria were met.

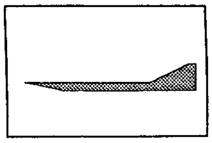
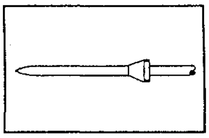
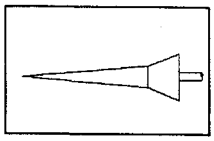
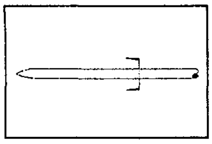
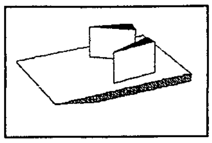
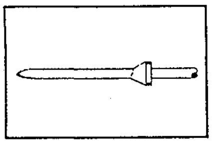
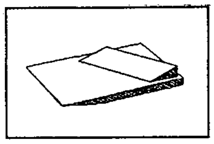
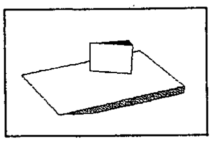
The majority of rejections of candidate experiments occurred due to criterion 3, specific applicability. These experiments were not able to add information of significance to the database, often because the interactions were too weak to be useful or because only surface pressures were measured. Further, few experiments actually reported error bounds (criterion 5), and the lack of any attempt to document the state of the incoming boundary layer was a common disqualifier (criterion 4). Finally, several otherwise-acceptable candidates had to be rejected because their data were simply not available in a useful form (criterion 7).

A single general conclusion may be drawn from this effort: high-quality data on supersonic and hypersonic shock/boundary-layer interactions, suitable for use in turbulence modeling efforts, are extremely scarce. The existing data do not begin to satisfy the current need. Thus the authors strongly suggest that new, detailed, carefully planned experiments, designed to satisfy the criteria listed, are needed. Suggestions for these experiments are listed in the next section. In particular, no useful real-gas data were found in the current database assessment.

The following advice is offered to those who would compute the test cases put forward here. First, one should attempt to match the initial conditions of the experiment as closely as possible. The experimental boundary-layer profile can be matched by any reasonable method, but match local rather than global freestream values at its edge. Finally, one should not attempt to solve the entire test-body and wind-tunnel environment, since some of the models are large and complete transition and freestream conditions may not be known accurately.

The unsteadiness of shock/turbulent-boundary-layer interactions has been documented (e.g., Refs. 2 and 16), but is still not well understood. To date, no computational approaches are known to address this issue. Insofar as the preponderance of accepted datasets treat only the mean-flow properties, the assumption is im-

Table 1 Accepted experiments

	Ref.: 40, 41 Author: Coleman, G. T. Geom.: 2-D Corner Mach number: 9 Data: p_{wall}, c_h	Ref.: 145-147 Author: Kuntz, et al. Geometry: 2-D Corner Mach number: 3 Data: p_{wall}, LDV surveys	Ref.: 112, 53 Author: Smits, et al. Geom.: 2-D Corner Mach number: 3 Data: p_{wall}, c_f, surveys	Ref.: 127 Au: Zheltovodov, et al. Geom.: 2-D Corner Mach number: 3 Data: p_{wall}, c_h, surveys
	Ref.: 75 Author: Kussoy, et al. Geometry: Axisym. Ogive-Cylinder-Flare Mach number: 7 Data: p_{wall}, c_h, surveys	Ref.: 37, 51 Author: Dunagan & Brown Geometry: Axisym. Ogive-Cylinder-Flare Mach number: 3 Data: p_{wall}, surveys		Ref.: 63, 64 Author: Holden, M. S. Geom.: Axisym. Corner Mach number: 11, 13 Data: p_{wall}, c_h
	Ref.: 77 Author: Kussoy, et al. Geometry: Axisymmetric Impinging. Shock Mach number: 7 Data: p_{wall}, c_h, c_f, surveys		Ref.: 141 Author: Kussoy & Horstman Geometry: Crossing Shocks Mach number: 8.3 Data: p_{wall}, q_{wall}, flowfield surveys	Ref.: 142-144 Author: Garrison & Settles Geometry: Crossing Shocks Mach number: 3 and 4 Data: p_{wall}, c_f, surveys
	Ref.: 36 Author: Brown, et al. Geometry: Axisym. Ogive-Cylinder-Skewed Flare Mach number: 3 Data: p_{wall}, surveys (LDV)		Ref.: 109 Author: McKenzie, et al. Geometry: 3-D Swept Corner Mach number: 3 Data: p_{wall}, surveys	
	Ref.: 39, 80 Author: Law, C. H. Geometry: 3-D Fin Mach number: 6 Data: p_{wall}, c_h	Ref.: 73 Au.: Bogdonoff, et al. Geometry: 3-D Fin Mach number: 3 Data: p_{wall}, surveys	Ref.: 70 Author: Kim, et al. Geometry: 3-D Fin Mach number: 3, 4 Data: p_{wall}, c_f, surface-flow	Ref.: 137, 138 Author: Lee & Settles Geometry: 3-D Fin Mach number: 3, 4 Data: c_h
	Ref.: 134-136 Author: Rodi & Dolling Geometry: 3-D Fin Mach number: 4.9 Data: p_{wall}, q_{wall}, surface-flow traces	Ref.: 130-132 Author: Kussoy & Horstman Geometry: 3-D Fin Mach number: 8.2 Data: p_{wall}, q_{wall}, c_f, flowfield surveys	Ref.: 139, 140 Author: Hsu & Settles Geometry: 3-D Fin Mach number: 3, 4 Data: flow density maps	

plicitly made that the recognized unsteady character of such interactions does not preclude a mean-flow approach to their understanding.

Finally, the same effort which produced the shock/boundary-layer interaction database reported here also resulted in a similar database on compressible turbulent shear layers and attached supersonic and hypersonic boundary layers in pressure gradients. These results are beyond the present scope, but may be found in Ref. 24.

Need for Further Experimentation

Figure 1 shows a graph illustrating the Mach and Reynolds number conditions of the accepted database experiments compared with a typical trajectory of a NASP-type vehicle. Although full-scale Reynolds numbers have been reached in some of the experiments, this has not been done adequately at Mach numbers high enough to simulate realistic flight conditions, where hypersonic flow and turbulent boundary layers are expected. Moreover, in terms of total enthalpy, none of the experiments match true flight conditions.

Based on the results of this study, the following list conveys our recommendations for further experimentation in supersonic and hypersonic shock/boundary-layer interactions: 1) interactions involving real-gas effects; 2) flowfield turbulence data; 3) one or more high-quality hypersonic laminar boundary-layer experiments for comparison purposes; 4) nonintrusive flowfield data (mean as well as fluctuating); 5) more complex types of "building-block" interactions, such as the double-fin or crossing-shock-type interaction; and 6) emphasis on three-dimensional rather than two-dimensional interactions.

Finally, we offer the following observation. Although new experimental data are certainly needed in this field, it serves little

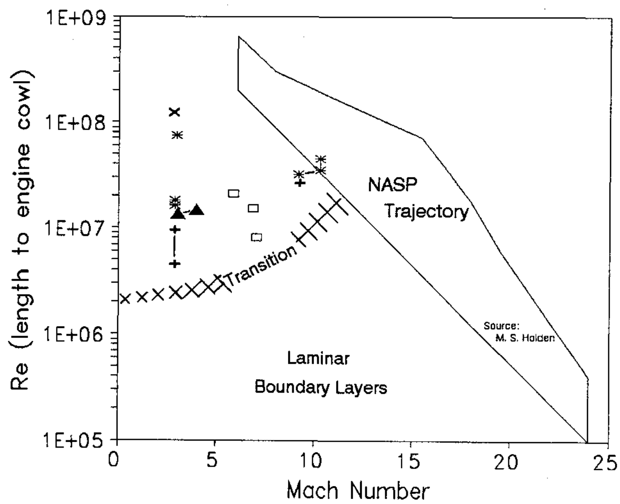


Fig. 1 Mach and Reynolds number ranges of accepted data.

purpose to obtain such data in experiments which are inadequately defined. This database collection effort found large numbers of such experiments already existing, but essentially useless for code validation or turbulence modeling purposes. The necessary criteria, discussed earlier, are truly necessary to define a useful experiment for these purposes. There is no valid reason to fail to address all of these criteria in the planning and execution of future shock/boundary-layer interaction experiments. To insure the quality of future database candidates, a peer review process would be helpful.

Acknowledgments

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