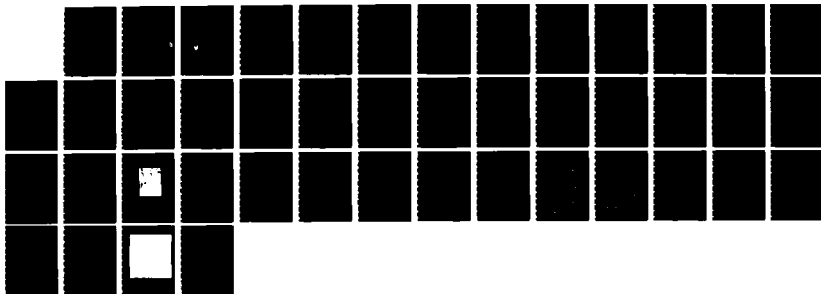AD-A175 833 | THE STUDY OF SHOCK WAVE AND TURBULENT BOUNDARY LAYER | 1/1
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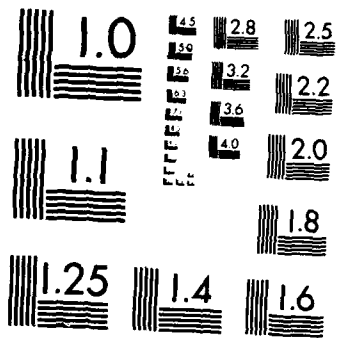UNCLASSIFIED | 1767-MAE AFOSR-TR-86-2175 F49620-84-C-0086 | F/G 20/4 | NL

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non-steady characteristics
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The three-dimensional shock wave turbulent boundary layer interaction generated by several shock generators defined solely by angles has been carried out at a Mach number of 3. Interactions with thin boundary layers were used to obtain overall characteristics, while interactions with thick boundary layers permitted detailed high resolution surveys. Investigations of the interactions were carried out by mean and high frequency surface pressure distribution measurements, surface flow visualization, and mean

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Princeton University

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Final Scientific Report

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Department of
Mechanical and
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Abstract

The three dimensional shock wave turbulent boundary layer interaction generated by several shock generators defined solely by angles has been carried out at a Mach number of 3. Interactions with thin boundary layers were used to obtain overall characteristics, while interactions with thick boundary layers permitted detailed high resolution surveys. Investigations of the interactions were carried out by mean and high frequency surface pressure distribution measurements, surface flow visualization, and mean total head, yaw, and static pressure distributions through the flowfield. Major new data sets were obtained for the interaction of the shock wave generated by a 20° fin, and by a 24° wedge swept at 60° to the incoming flow. A series of tests were carried out to examine new concepts of three-dimensional interactions and extensive "non-steady" results were obtained from the high frequency surface pressure distributions.

Close coordination of the experiments with major computational efforts, carried out by Knight of Rutgers and Horstman of NASA, support new concepts of flow structure and physics for these complex interactions.

Section 1. Introduction

The present report covers the program of research on three-dimensional shock wave turbulent boundary interactions carried out during the two year period August 1984 thru July 1986. The research was a continuation and expansion of the previous studies under OSR support. Most of the results have been distributed in a series of reports and publications and presented at national and international meetings. (See Publication List, Section 6.)

The present report is a brief overall summary of the activity under the subject contract and the key contributions made to our understanding of this complex phenomena. The staff and students that were involved in the program and the significant scientific interactions which took place, particularly with computational programs elsewhere, are also noted. Although the computational program was not directly part of the subject contract, it was an important element in our research, both in the design of the experiments and in the analysis of the results.

Section 2. Overall Objectives and Work Statements

Previous studies under OSR support concentrated on developing an overall view of the three dimensional shock wave interactions caused by a range of geometries under various conditions to try to define the basic parameters and general features. The subject study focussed primarily on trying to better understand the physics and flowfield modeling by extending detailed studies of the 10° sharp fin and the 24° wedge swept at 40° to other configurations which generated stronger interactions. The phenomena of flow unsteadiness, explored for the first time in our previous OSR studies, received major emphasis along

with a closely coordinated experimental and computational study (carried out at Rutgers and NASA-Ames). Continuing analysis of the extensive data sets and expanding data base (now including flowfield static pressures and new optical views) resulted in a new evaluation of some of our earlier studies. In the second year of this study, a new emphasis was placed on surface phenomena with the addition of a grant, from Wright-Field Flight Dynamics Laboratory, to develop high resolution, high frequency, heat transfer techniques. When developed, these techniques will supplement the high frequency static pressure measurements obtained in the current program, and provide a new critical measurement to test computation and aid in applications.

The specific work statement for the first year is noted below:

Work Statement for the period August 1, 1984 - July 31, 1985

1. Extension of the sharp-fin studies at Mach 3 to stronger shocks, that is, to angles of attack as far above 10° as possible. Measurements will include surface flow visualization, mean wall pressure distributions, as well as rms wall pressure levels.

2. Exploratory studies of particular flow areas such as the inception region, and the region near the corner of the swept wedge flows.

3. Initial phase of an in-depth study of a sharp-fin flow at Mach 3. Data will include wall pressure fluctuations, exploratory phase velocity measurements using wall pressure transducers, and measurements of longitudinal mass-flow fluctuations using hot wires.

4. Initial development of measurement techniques to measure the instantaneous direction of the flow near the surface. This tool will be applied to the flows described above as it becomes available.

5. Continued close interactions with computational groups, especially Dr. C. C. Horstman at NASA-Ames and Prof. D. Knight of Rutgers University.

The work statement for the second year is noted below.

Work Statement for the period August 1, 1985 thru July 31, 1986

TASK 1: Fundamental Investigation of the Structure of Three-Dimensional Flows.

Task 1.1 Investigation of "strong" interactions

Flowfield survey of 24/60 degree swept wedge. Detailed study of the flowfield details near feature lines and in the inception region where preliminary computations have been poor. Preliminary investigation of flowfield steadiness using arrays of pressure transducers. Preliminary application of topology to three-dimensional interactions.

Task 1.2 Instrumentation development for three-dimensional flows

Development of condensation flow visualization, the measurement of flowfield static pressures and qualitative normal velocities. Preliminary use of surface films as well as multiple viewing angle optical systems (schlieren and shadowgraph).

TASK 2: Interaction Between Experiment and Computation

Extended flowfield survey of 20 degree sharp fin and 24/60 wedge (as needed or indicated by computations). Close interaction with computational groups to validate calculations and suggest new experiments to achieve a better understanding of the flow physics.

TASK 3: Initial Use of New Low Turbulence Variable Geometry Facility

Initial operation of the new facility, calibration, and character-
ization of the flow at Mach 3. Examine the effect of low turbulence flow on
attached and separated flows over two-dimensional wedges by comparison with
tests in 8" x 8" High Reynolds Number Tunnel.

Results of the program are briefly outlined in the following sections,
grouped to match the work statements above, with reference to the complete
publications where available

Section 3. Outline of Work Accomplished

The discussions of the details of the work accomplished will be grouped
using the framework of the work statement for 85-86. In each case, the inclu-
sion of the appropriate statements from the 84-85 work statement are covered
in the discussion.

Task 1. Fundamental Investigation of the Structure of Three-Dimensional Flows

1.1 Investigation of strong interactions

Included in this section are the studies covering items 1-3 in the 1984-85
work statement. Four major experimental studies were carried out during the
subject period.

a) Exploratory studies, Ref. 1, had shown that, with a variable angle fin,
fin deflections as high as 22° could be obtained. The 20° sharp fin was
selected for a major program to determine full flow details for comparison with
previous detailed information at 10° deflection. (Publications 7, 12, 17.)

b) The 24° wedge, swept at 60°, was studied in detail to provide a comparison with the 24° wedge swept at 40°, Ref. 2, with particular attention to the new feature observed at the corner for the 60° swept configuration. (Publications 10, 13.)

c) Several configurations were examined in detail, using high frequency surface pressure gauges, to focus on the questions of the flow unsteadiness and the comparison to previous two-dimensional studies. (Publications 1, 3, 11, 15.)

d) A detailed comparison of three different shock generator configurations generating the same shock wave was carried out to evaluate the "independence principle". (Publications 8, 14, 16.)

The following series of analysis of previously generated experimental data were also carried out during the subject period.

e) Re-examination of the upstream influence scaling and similarity laws carried out primarily to study the limits of the conical cylindrical boundary proposed in earlier studies. (Publication 6.)

f) The use of surface flow visualization techniques in the topological modelling of the 3-D interactions, and the connection to flowfield details was also examined. (Publication 5.)

g) An examination of the concept of three-dimensional "separation", as compared to two-dimensional characteristics, was initiated on the basis of the flowfield results, comparisons with computation, and topological considerations. (Publication 9.)

h) A review of our state of knowledge of these complex interactions as of 1985 was undertaken. (Publication 4.)

i)   Work under the previous contract on flowfield scaling for sharp fins
was published during the period of the present contract.   (Publication 2)

1.2   Instrumentation development for three-dimensional flows

This also covers Item 4 of the 1984-85 Work Statement.   The primary emphasis
under this task was the development of a flowfield static pressure probe.   The
probe was developed in conjunction with the 24/60 wedge studies and, after use
on this configuration, was applied to the studies of all succeeding config-
urations.   Efforts to determine qualitative normal velocities by comparing the
experimental measurements and computations were also carried out.   The initial
phase of the development of thin surface films for flow direction, heat
transfer, and skin friction measurement required the construction of a vapor
deposition facility, shown in Figure 1, and considerable effort in the depo-
sition, etching and installation of such films was undertaken.   The first phase
of multiple viewing angle optical systems was undertaken on the 20° sharp fin
interaction with first observations being made normal to the test boundary
layer.   The test surface boundary layer developed on the optical window through
which the observations were made.   The final test program did not permit time
for new work on condensation flow visualization, although preliminary work
started with the construction of a micro-pump for fluid injection.

Task 2.   Interaction Between Experiment and Computation

This work covers Item 5 in the Work Statement for 1984-85.   During the
first year, the primary interaction concerned the 20° fin studies.   Numerous
meetings took place, both on the design of the experiment, detailed examination
of experimental results, and comparison of the computation and experiments.

This resulted in Publication 7 and, since then, in the work of Publication 12 and 17. During the second year the emphasis was on the 24° wedge swept 60°. Again there were a series of meetings, data transfer, and detailed comparison of computation and experiment. The initial computations were started with the thin boundary layer data obtained some time ago. The final results of the 24/60° tests were transmitted during the second year and the results of the interaction have been detailed in Publications 10 and 13. Extensive discussions took place during the entire period on the requirements imposed on the experiments which would be crucial for the computations, and the requirements from the computations needed to analyze the results obtained from the experiment.

Task 3. Initial Use of New Low Turbulence Variable Geometry Facility

There was no progress under this task during the reporting period. A major breakdown in the air supply system for the 8" x 8" High Reynolds Number Tunnel caused a delay of 6 weeks in testing, significant funding shifts, and a major disruption of the test program. First priority was placed on Tasks 1 and 2.

Section 4. Brief Summary of Major Results

Following the format of Section 3, the following section briefly summarizes the major results of the subject program.

Task 1

1.1a: The exploratory studies of Reference 1 showed that fin angles as high as 22° could be obtained if a variable geometry system was used. Publications 7, 12, and 17 provide the experimental details for the major program carried out on a 20° sharp fin. Detailed mean surface static pressure distributions,

surface flow visualization and total head and yaw angle profiles were obtained along streamwise and spanwise cuts through the interaction. Examples of the detailed total head and yaw surveys at a station between the initial distur- bance and the theoretical shock wave are shown in Figs. 2 and 3. From these extensive surveys, total head and yaw contours, as shown in Figs. 4 and 5, give a description of the overall flow structure. The surface pressure distri- butions, obtained from surface static pressure orifices, are shown in Fig. 6. This experiment provided details on the flowfield generated by the strongest shock yet investigated for a fin. Analysis and comparision with computation are discussed in the following sections.

1.1b: Earlier studies, Refs. 2 and 3, have described the flowfield over a 24° wedge swept at 40°. This configuration generated a pressure distribution which had the typical sharp increase near the beginning of the interaction, a plateau region which extended past the corner, and then a sharp increase on the wedge. Reference 2 indicated that the 24° wedge, at higher sweep angles, generated a sharp feature located close to the corner. This has been inter- preted by some as the generation of a vortex in that region. During the present study, a detailed examination has been made of the 24° wedge swept at 60°, with very special attention paid to the details in the corner. New probes (including static pressures) and higher resolution provided a quite complete flowfield study which has been supplemented by high frequency pressure measurements to define the steadiness of the interaction (discussed in a later section). Details of the flowfield were carried out along two surveys planes, one normal to the theoretical shock, the other parallel to the upstream direction, the usual survey made in previous studies. The mean and fluctuating

pressures on the surface (in a plane normal to the shock) are shown in Fig. 7. The feature in the corner can be clearly seen in the mean pressure distribution. In addition, the surface features of upstream influence (UI), the coalescence line (c), the shock location in the freestream ($x_s = 0$), and a line defined as attachment or divergence of the surface streamlines (a) are all clearly noted. From the very detailed surveys, contour maps of yaw angle and Mach number were determined, Figs. 8 and 9. Comparisons between these contour plots, results available for a 30° wedge swept at 60° from another study (Publication 14 and 16), show the change in the structure that occurs when the wedge angle is increased. Although the general features remain the same, significant changes in the flowfield are noted. The vortical structure in the flowfield found for lower sweep angles and for both conditions at 60° sweep are similar although there are significant differences in the flowfield. There is no indication from the surveys of any significant flowfield structure in the corner, in spite of the sharp changes in the pressure distribution. Additional comments about this feature are made in the following section on the comparison of experiments and computations.

1.1c: The study of shock wave turbulent boundary layer interactions with a view towards examining their steadiness has been a key element of the subject research program. Earlier work, Refs. 4 & 5, have shown the unsteady nature of such flows using high frequency surface pressure gauges. In the present study, concentration on three-dimensional shock wave boundary layer interactions has provided the first extensive data set on this phenomena. Arrays of high frequency static pressure gauges were used to examine the flows generated by variable angle fins, semicones, swept compression corners, and 2-D ramps.

Both mean surface pressures, rms values, and space time correlations and conditional sampling analyses have been carried out. With the systems used, the mean static pressures measured by wall orifices are reasonably checked by time-averaging the high frequency fluctuating values. The general characteristics of the fluctuating velocities are shown in Fig. 10 for several geometries, generating approximately the same strength shock wave. The physical characteristics obtained from surface flow visualization and from the geometry are noted on the figure (the upstream influence point, UI, the convergence lines for the different geometries, c, the location of the inviscid shock wave, and the model corner). A general characteristic is that there is a peak in the rms distribution between the upstream influence line and the line of convergence from the surface flow visualization. In addition, it appears as though, for the same strength shock wave, the general characteristics of the fluctuating pressures are quite similar. One is led to the conclusion that the inviscid shock strength appears to be the main governing parameter for a large part of the interaction. The sharp rise in rms at the start of the interaction indicates the unsteadiness, and the similarity in the shape of the rms distribution suggests that the same mechanism may be responsible for the unsteadiness in each case. It is hypothesized that the unsteadiness is caused by the "lumpiness" of the incoming turbulent boundary layer. These unsteady measurements show an element of the interaction which was neglected in computation, and may be an important element, particularly in the determination of skin friction and heat transfer through the interactions. Although the cause of the unsteadiness has been hypothesized as being due to the incoming

boundary layer, there is as yet, no direct linkage between boundary layer structure and the observed unsteadiness in the present program.

1.1d: On the basis of an examination of the pressure distributions and surface flow visualization for a wide range of geometries, Publication 8, the similarity of these data sets for shock waves of the same strength led to the concept of the "independence principle." It proposed that the three-dimensional shock wave boundary layer interactions were primarily characterized by the strength and orientation of the imposed shock wave (even though quite different geometries might generate the same shock structure). Further probing of this proposal was carried out by examining the flowfield and surface conditions through both mean and time-resolved static pressures. A 17.5° fin, a 25° half angle semicone, and a 30° wedge swept at 60°, were chosen for detailed study based on their similar shock strengths and shock shape. The mean pressure distributions measured on the surface for these three interactions and the interaction for a 24° wedge swept at 60° (a slightly smaller pressure ratio) are shown in Fig. 11. Up to the position of the inviscid shock, the similarity between the initial part of the interaction is quite good. The nonsteady wall pressure distribution, given in rms terms, is shown in Fig. 12 where again the three geometries show very similar characteristics. The flowfield studies of yaw and Mach number are also quite similar up to the location of the shock, Figs. 13 and 14. The overall vortical structure of the flowfields and the similarity with three different geometries is also quite striking, further supporting the premise that the initial part of all of these three-dimensional shock wave boundary layer interactions is determined by the shock strength and orientation.

1.1e: In earlier work under OSR support, the concept of conical and cylindrical flows and a sharply defined boundary between them seemed a reasonable explanation on the basis of the data then available. As the research programs have progressed, new information and new concepts became available, and more detailed interactions of computation and experiments were undertaken. Many of the proposed models and flowfield structures were re-examined in detail in the light of the present programs. The present analysis, Publication 6, shows that the previous conical/cylindrical designation and boundaries are only approximations, and that the conical proposal is only locally applicable. However, the present data sets, with only limited Reynolds number variation and physical limitations cannot clearly define a "far" flowfield suggested by Wang and Bogdonoff. There is a clear need for further work in this area to clarify the questions which have been brought up.

1.1f: There have been continuing efforts to use surface flow visualization and topological modeling of three dimensional interactions to construct models of the flowfield. Publication 5 notes the lack of correlation between surface observation and the flowfield determined from probing techniques. It also notes the unsteadiness of these interactions as areas where there are difficult conceptual problems which have to be resolved if these flows are to be readily understood.

1.1g: Several earlier experimental studies have continued during the past two years. The comparison with computations and the determination of the sensitivity of the computation to turbulence modeling has brought the concept of three-dimensional separation into question. Analysis of specific detailed two-dimensional and highly swept three-dimensional shock wave turbulent

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boundary layer interactions has resulted in a series of observations which are
counter to much of the usually accepted physical modeling, Publication 9.
1) Three-dimensional flows are found to be radically different than the
classical two-dimensional flows which have been the basis for interaction
structural modeling in the past. There are major differences in scale,
unsteadiness, dissipation, computability, and viscous or inviscid importance.
2) Three-dimensional flow interactions are of large scale compared to their
two-dimensional counterparts for shock waves of the same strength. The
gradients normal to the shock wave are much less for the same shock strength,
and the extent of the interaction is relatively independent of shock strength
in three dimensions. The unsteadiness of three-dimensional flows is only about
half that of the equivalent two-dimensional interaction. Computations show
little effect of turbulence models, indicating that these flows are primarily
inviscid-rotational dominated, in contrast to two-dimensional flows. 3) The
term three-dimensional "separation" is not a realistic designation of flows
which have been so described on the basis of surface flow visualization.
None of the direct measurements, calculations, or computations have established
any significant vertical velocity components close to the surface, and compu-
tations without dissipation can describe the flow structure (in contrast to
two-dimensional separation). 4) A vorticity rearrangement model is proposed
for the basic physics of the interaction on the basis of calculation and the
observed experimental data in contrast to the viscous interaction model which
is the usual description.

1.1h: A general review of our state of knowledge of three-dimensional shock
wave turbulent boundary layer interactions was presented in Publication 4. The

classification of weak and strong interactions was proposed, with a series of recommendations for future work which would help to clarify the basic physics of such flows.

1.1i: A report summarizing our knowledge of flowfield scaling for fin induced shock wave turbulent boundary layer interactions was presented in Publication 2. This work was completed under previous OSR support and the publication of the paper during the period of the subject contract is simply a reflection of the time required for publication.

1.2 Instrumentation Development for Three-Dimensional Flows

Our earlier studies of three-dimensional flowfields were carried out with "cobra" probes, a combination of yaw and total head probes. By nulling the probe, the flow direction was determined and the correct total pressure was obtained. During the first year of the present program, we developed a small static pressure probe. This probe was checked and calibrated and, during the second year, was used in the extensive 24° wedge 60° sweep study. Since that time, the probe has been used also in the three configurations used to generate the same strength shock, the 17.5° fin, a 30/60 swept wedge, and a 25° half angle semicone. The measurement of the flowfield static pressure, which was accurate to approximately 0.10" from the wall, extrapolated well to the measured wall static pressure. The static pressure and the total pressure permitted the calculation of the flowfield Mach number and the velocity (using the approximation of an adiabatic wall). This data set provided new physical insights, i.e. the flow interaction was all supersonic, and the static pressure distributions gave an indication of a complex wave system in the flow.

Normal velocity determination close to the wall gave no significant indication of any vertical velocity, a condition supported by all of the computations. There were no significant normal angles of the flow near the wall, even directly above the line of convergence determined from surface flow visualization.

Surface thin film development, originally started to get high frequency surface flow direction, was expanded with Wright Field support with the aim of developing high resolution high frequency heat transfer gauges. The study started with an examination and analysis of the current techniques and extended to many discussions with micro-chip and circuit board designers. On the basis of these discussions, we constructed a vapor deposition facility to get some "hands-on" experience and to build some experimental gauges. The facility, Fig. 1, has been in operation about 6 months and has provided an inexpensive way to obtain experience with thin film gauges, although the final design will probably be made commercially to our specifications. Substrate characteristics, deposition characteristics and bonding, etching, masking, and contacts, have all been investigated. A commercial TSI gauge has been purchased and this gauge, a high frequency static pressure gauge, and a manufactured gauge are being investigated in the pilot and 8" x 8" tunnels to obtain operating characteristics and performance under full wind tunnel conditions.

The first phase of the multi-angle viewing of three-dimensional interactions was carried out on the 20° sharp fin. Schlieren, shadow, and sharp focussing schlieren, were used to study the three-dimensional interaction by viewing the interaction normal to the original boundary layer. The fin model was mounted normal to a window in the bottom of the tunnel. A second window in the top of

the tunnel permitted an optical view parallel to the fin, normal to the wall on which the interaction took place. An example of the results is given in Figure 15. We were unable to detect any sign of the upstream influence or the line of convergence. The plane shock wave from the fin is clearly seen, and a structure parallel to the fin which we have not yet been able to connect with any of the flowfield structures. The regular and sharp focussing schlieren system (in our first attempts) did not give much more information than the noted shadow photograph. These first studies will be supplemented in the new facility where we hope to combine this view with optical paths parallel to the fin angle, and also with the use of conical schlieren, to try to better visualize the flow structure. This effort will require, however, significant efforts in the next program.

Task 2

The computations of the 20° fin captured the general qualitative details of the flow, although there were significant deviations in the details close to and on the surface (Publications 7, 12, 17). The comparison of the computational results with each other and with the experiments indicated that a large part of the flow appeared to be insensitive to the turbulence model and was primarily driven by inviscid-rotational characteristics. The differences between the two calculations and the experiments close to the wall indicates that the turbulence model is probably crucial in this region. Based on the reasonable correlation between the experiments and the computations over a significant part of the flowfield, extensive flowfield modeling was accomplished by streamline tracing. A large part of our current understanding of the flowfield structure was formed by the combination of experimental results

and calculated flow streamlines. The general nature of the vortical flow and the questions of a model of this vortical flow (which is inviscid-rotational) has proved very important in our subsequent studies. The concept of a _vorticity_ interaction rather than a v_iscous_interaction has led to concepts of possible control. The detailed observations near the surface have led to considerable efforts on the concepts of "separation" in three-dimensional flows, i.e. Publication 9. Concentrating on the flow close to the wall has also made it clear that the flowfield measurements made to date are not the crucial ones if we are trying to evaluate the effect of the turbulence models. Large differences in local eddy viscosity in the outer part of the flow, as the result of different turbulence models, appears to have little effect. On the basis of this observation, greater emphasis is now being placed on the determination of _skin friction and heat transfer_, quantities which we now realize will be crucial in the determination of turbulence modeling appropriateness.

The second major computation-experiment focused on the 24° wedge swept 60°. Previous computations of the 24° wedge swept at 40° gave reasonable qualitative results but considerable discrepancies with regards to details. The computation was not as good at predicting the results as with the 20° fin. The 60° sweep test had revealed, in earlier studies, a major characteristic at the corner (noted in our previous discussions of the experimental program) and the major concentration during the second period of the subject contract was to provide a detailed computational-experimental interaction on this configuration. While the experimental data was being developed, preliminary computations were made of this configuration using previous thin boundary layer results. These were rather large differences between the computations and the

available data (primarily pressure distributions and surface flow visualization). Detailed interactions between the computations and the experiments were not completed by the end of the subject contract, although an abstract, Publication 10, was submitted to the January 1987 AIAA Reno Meeting. The preliminary indications of the computation are that the general vortical structure for this configuration is similar to that seen for the 24/40 swept wedge and for the 20° fin. The sharp variations in the pressure distribution near the corner is not connected with the generation of a vortex in that region, either on the basis of the computations or the experiments. Rather it appears to be due to the high speed flow on the ramp approaching the corner at a high enough angle to generate the significant feature. The lack of a vortex in the corner for the swept wedge model and for the sharp fin studies gives a preliminary indication that the vortex feature included in most models is probably incorrect. This demonstrates the strong effect of combining computations and experiments in finding the true flowfield.

Section 5. Scientific Staff and Interactions

Andreopoulos, Yiannis, Research Staff Member and Lecturer. (Left September 1985 to accept position at City College of New York.)

Bogdonoff, Seymour M., Professor; Director, Gas Dynamics Laboratory.

Mao, Ming-fang, Visiting Research Engineer from China.

Ruderich, Raimund, Research Staff Member. (Left August 1986 to accept position in Germany.)

Smits, Alexander J., Associate Professor; Co-Director, Gas Dynamics Laboratory.

Tan, David K. C., Research Staff Member. (Left May 1985 to accept position at Flow Industries, Kent, Washington.)

Wang, Shuyi, Visiting Research Engineer from China. (Returned February 1986.)

Graduate Students

Chankaya, K. - Master's candidate

Kimmel, R. - Ph.D. candidate.

Shapey, B. L. - Master's Candidate.

Tran, T. T. - Ph.D. candidate.

Trevas, D. - Master's candidate.

Scientific Interactions

During the 2-year period of the subject contract, staff and students carrying out the research program interacted strongly with many organizations and individuals outside of the Gas Dynamics Laboratory. The research program was a focus for a significant group involved in studies or applications of shock wave turbulent boundary layer interactions. Many discussions were very helpful in the formulation of plans for the experiments, interpretation of results, and clarification of concepts.

Outside of the many usual contacts at technical meetings, visits and seminars at other research and industrial laboratories, and visits and seminars by others at the Gas Dynamics Laboratory, several very strong and important interactions continued in collaborative efforts which had a significant impact on the research program. Probably most important was the early development of links with the strong computational group at NASA-Ames, through Dr. C. C. Horstman, and later the close connection established with Prof. Doyle Knight at Rutgers. These two groups are probably the foremost researchers working on the development of computational techniques for the solutions of the Navier-Stokes equations and the application of these solutions to high-speed complex interactions. Many meetings and telephone discussions were important elements

in the planning of the tests and computations, and in the review and critique

of both the data sets generated and the efforts of the computation to duplicate

the results. The results of theinteractions have ended up in several jointly

authored papers. These papers are rather unique and very important in the

development of not only understanding, but engineering techniques to use the

results in practical applications. The problem of turbulence modeling in such

interactions is one of the most difficult unsolved problems in fluid mechanics.

The inadequacy of the present turbulence models, in some cases, or the insen-

sitivity of the phenomena to the turbulence model in others, could only be

determined by the detailed comparison of specific experiments and computation.

The interactions and collaboration with Prof. George Inger of the University

of Colorado, provided an additional input of analytic study based on triple

deck theory and attempts to model the complex flows of the interactions under

consideration.

Section 6. Publications

July 1, 1984 thru July 31, 1986

1. Tan, D.K.M., T. T. Tran and S. M. Bogdonoff, "Surface Pressure Fluctuations
in a Three-Dimensional Shock Wave/Turbulent Boundary Layer Interaction," AIAA
23rd Aerospace Sciences Meeting, January 14-17, 1985, Reno, Nevada. Paper
#85-0125. (Acknowledged to previous AFOSR support, F49620-82-0018).

2. Dolling, D. S. and W. B. McClure, "Flowfield Scaling in Sharp Fin-Induced
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10. Knight, D. D., C. C. Horstman, R. Ruderich, M.-F. Mao, and S. M. Bogdonoff, "Supersonic Turbulent Flow Past a 3-D Swept Compression Corner at Mach 3," AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987. Accepted for presentation.

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17. Shapey, B. L., "3-D Shock-Wave/Turbulent Boundary Layer Interaction for a 20° Sharp Fin at Mach 3," MSE Thesis #1760-T, Mechanical and Aerospace Engineering Department, Princeton University, October 1986.

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Figure 1. Vapor deposition facility (with chamber raised) developed
for thin film construction.
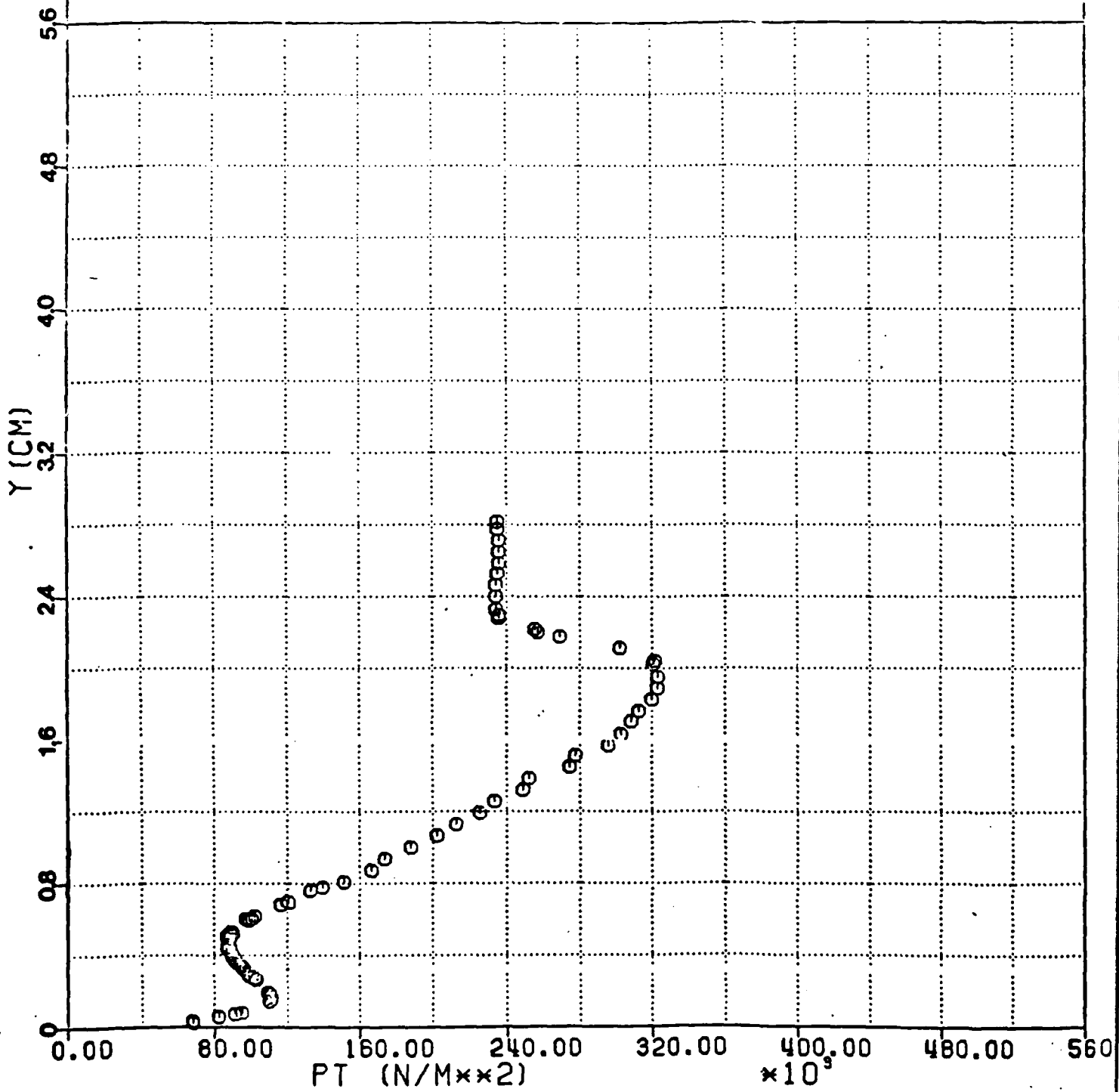
Figure 2. Example of a total head profile through the 20° fin interaction.

STATION 5
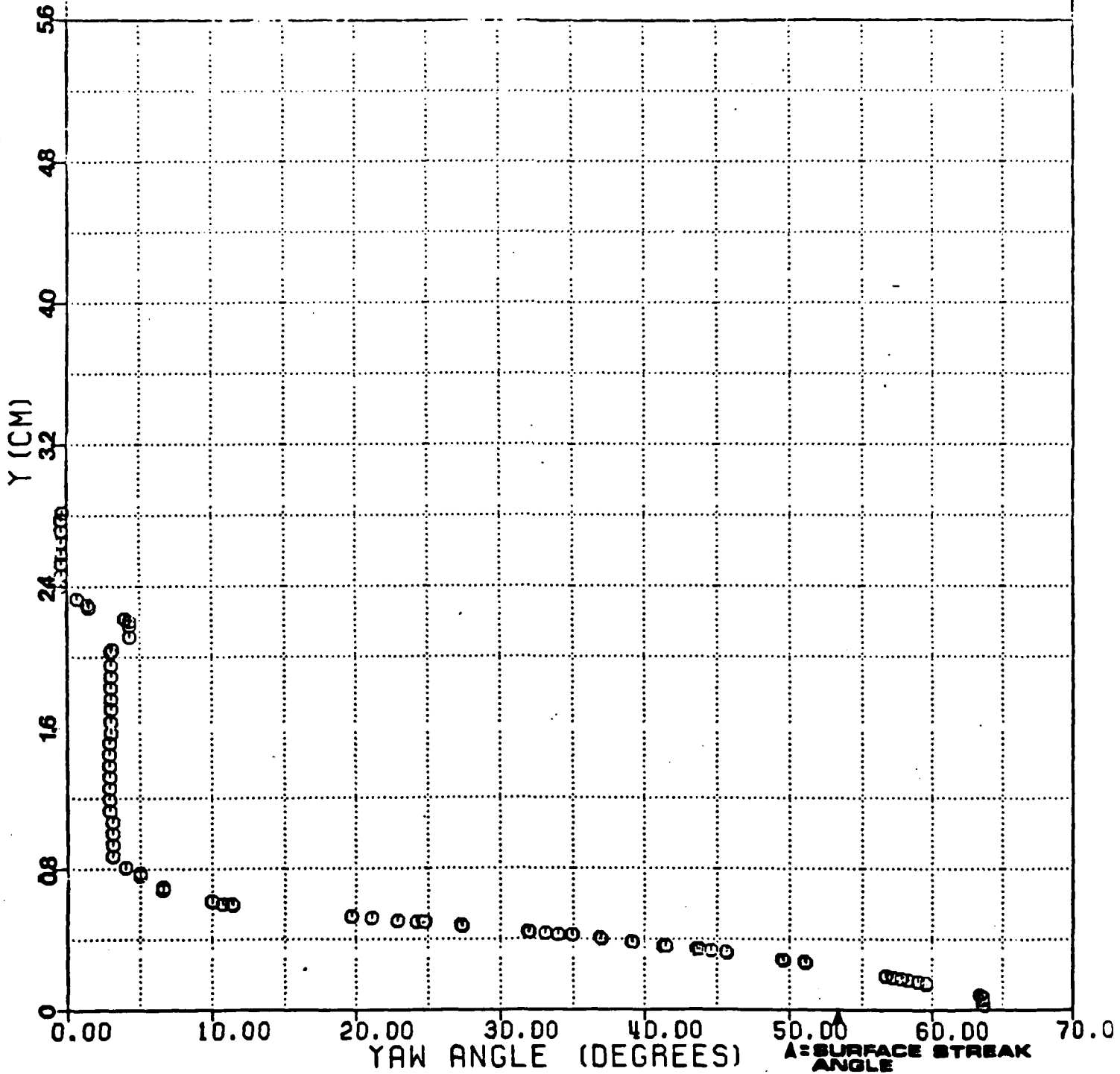
Figure 3. Example of a yaw angle profile through the 20° fin interaction (same station as Fig. 2).
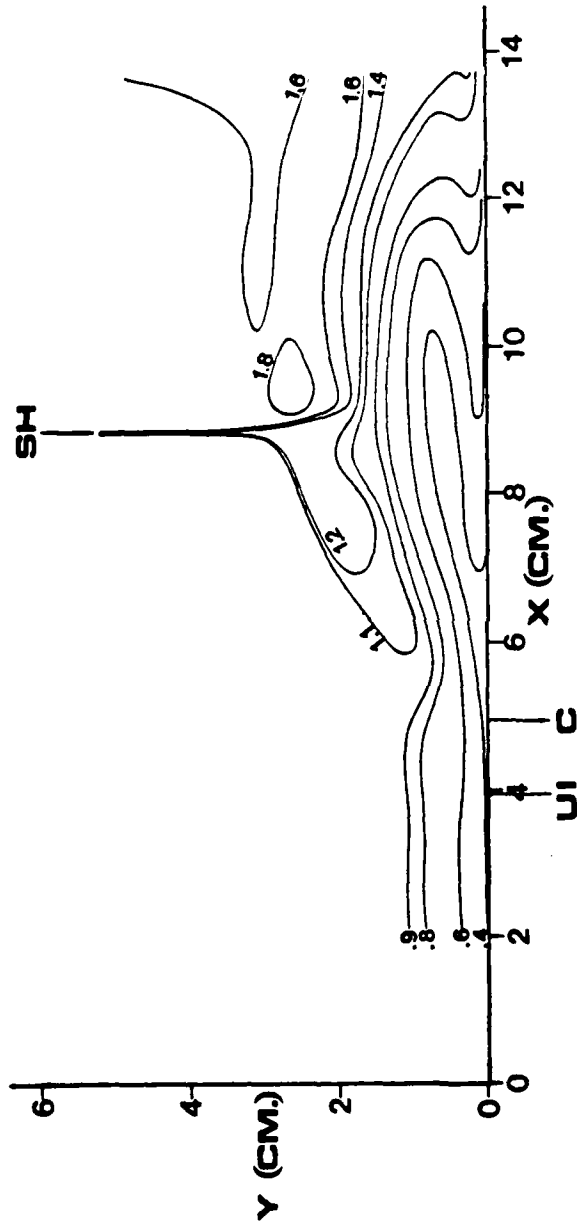
Figure 4. Normalized total head contours through the 20° fin interaction.
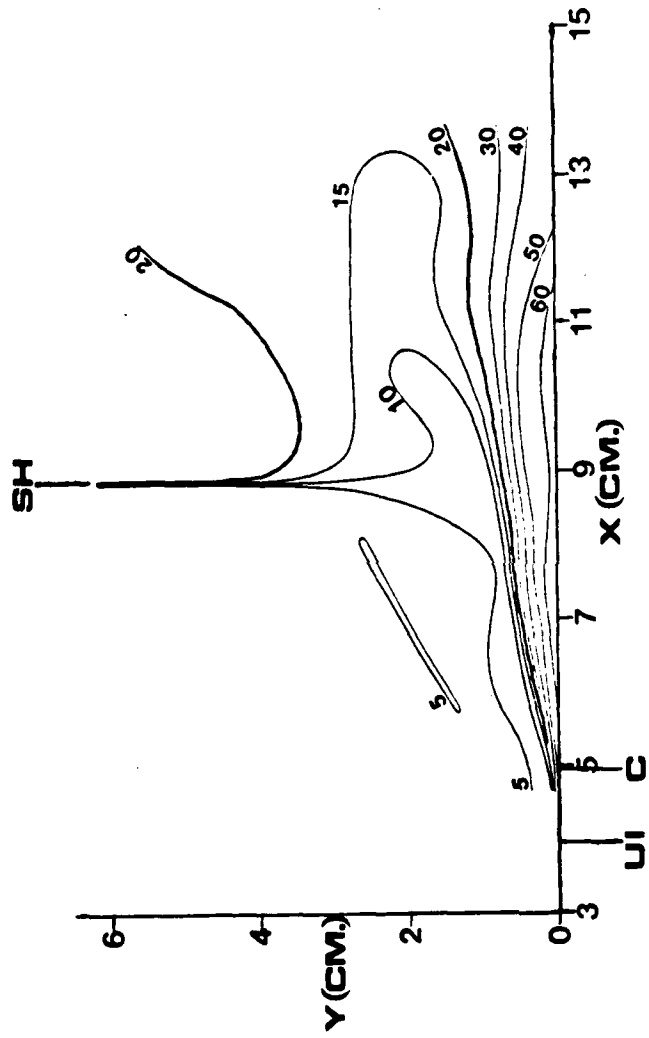
Figure 5. Yaw angle contours through the 20° fin interaction.
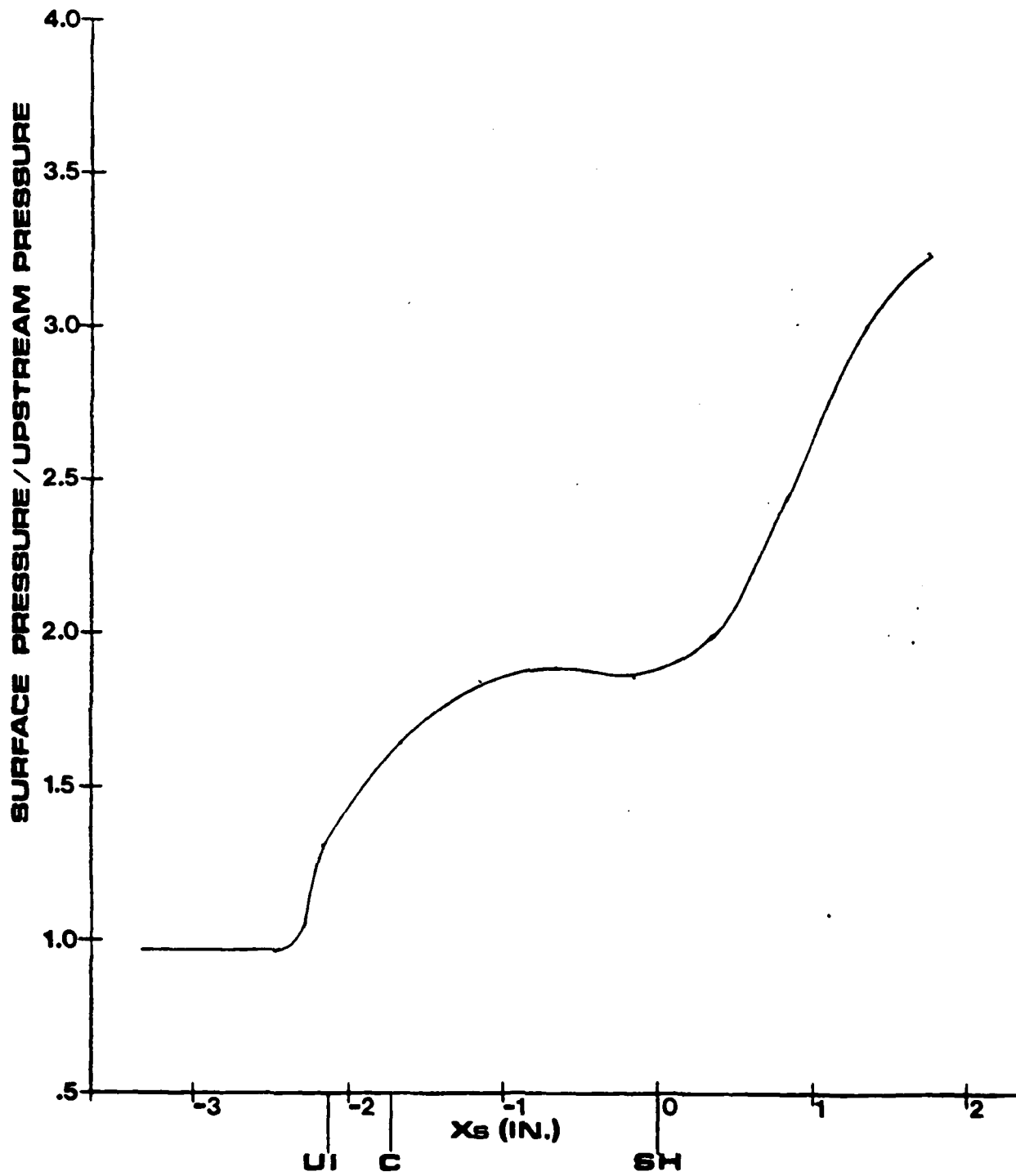
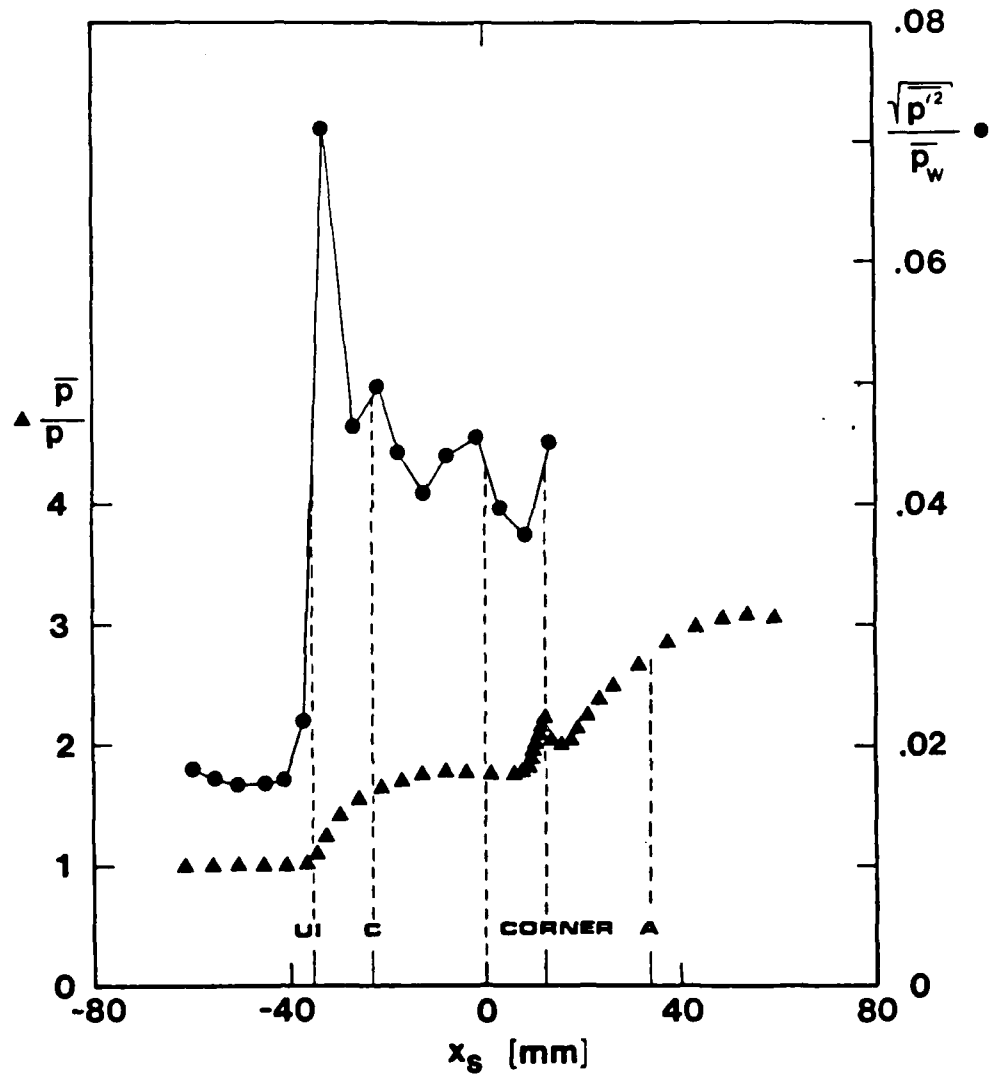Figure 6. Pressure distribution on the wall for a 20° fin interaction.

Figure 7. Mean and Fluctuating Pressure on the Surface in the Normal Plane $Z_s = 144.5$mm of the 24-60° Model.
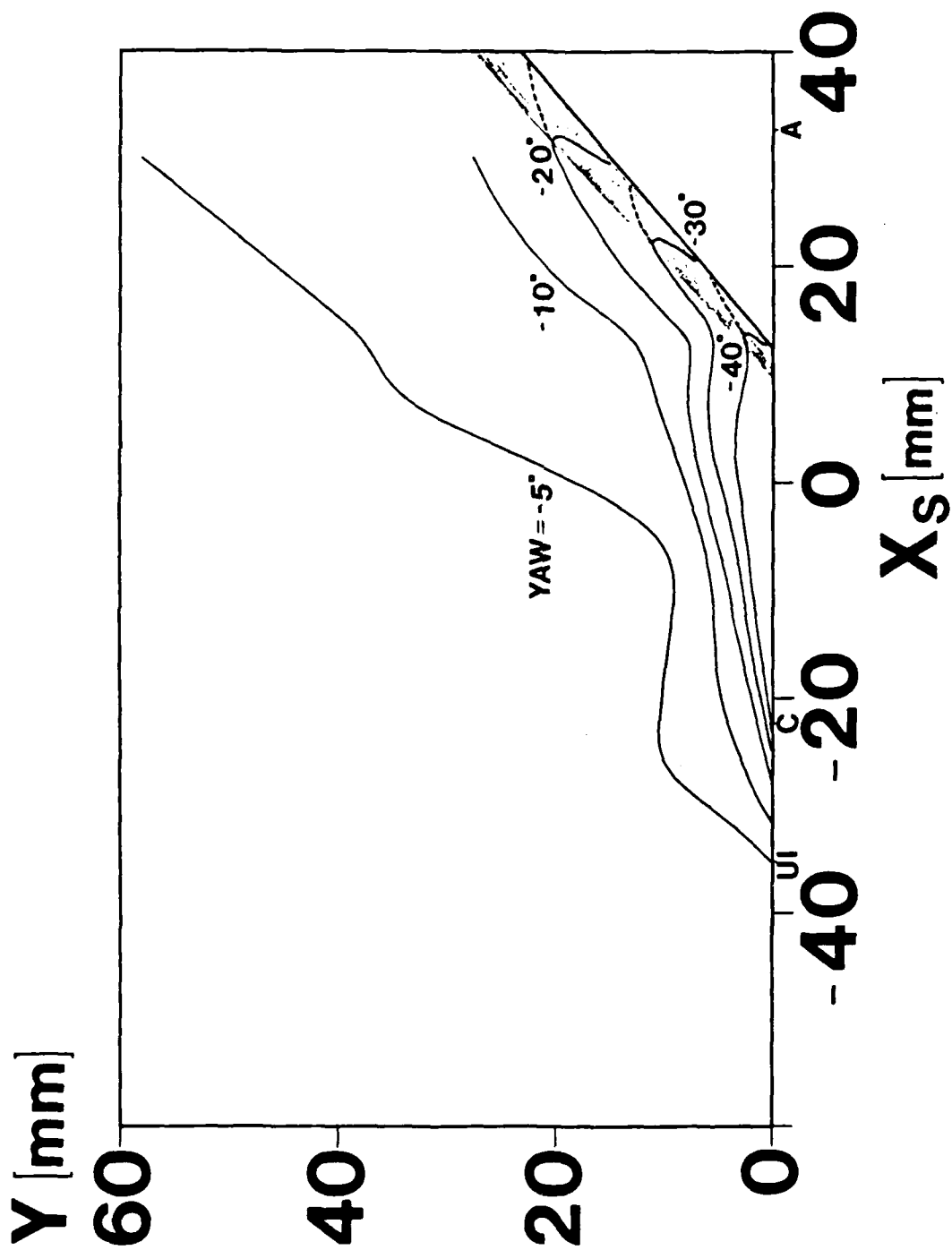
Figure 8. Yaw Angle Contour Map in the Normal Plane (24-60° Model).
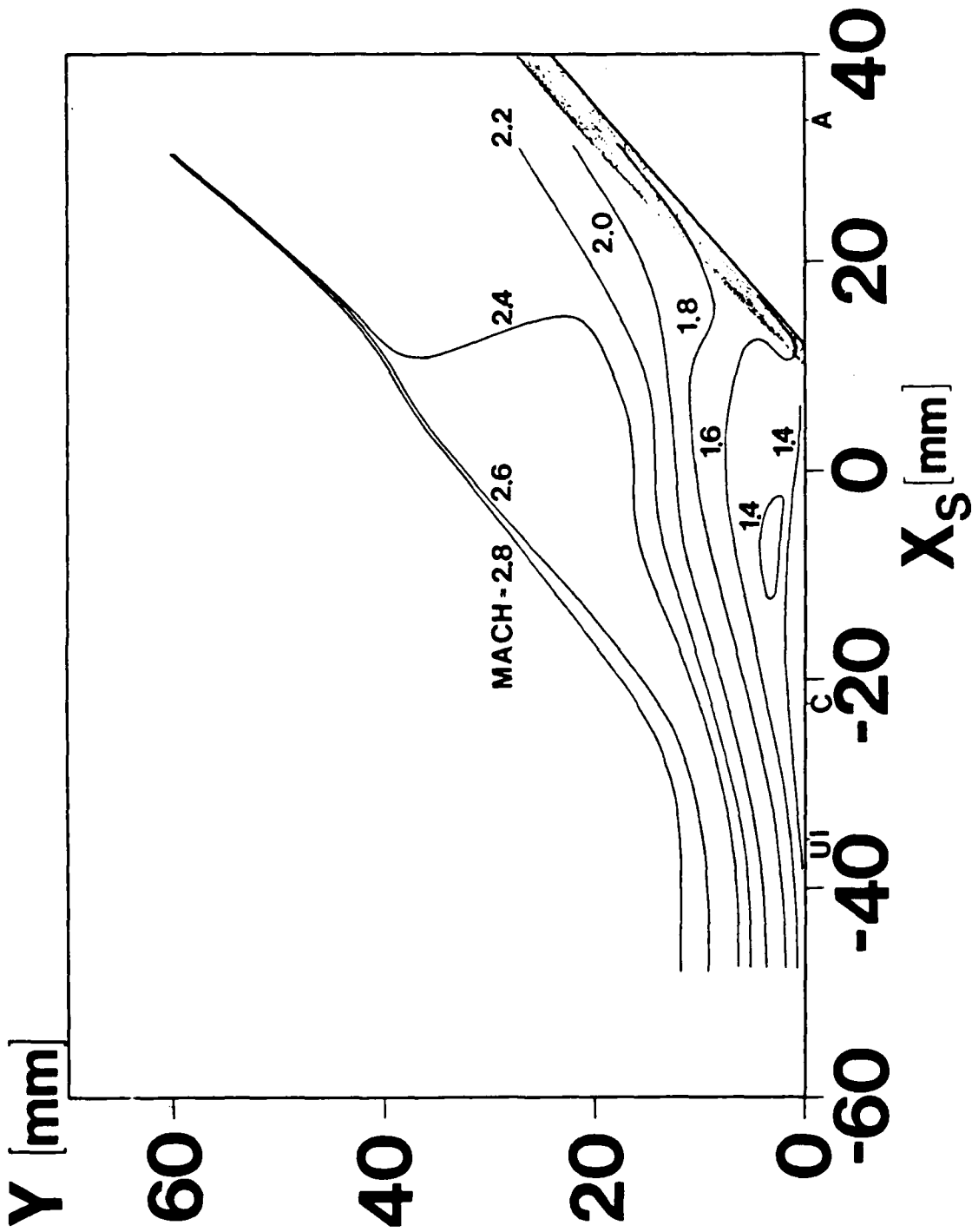
Figure 9. Mach Contour Map in the Normal Plane of the 24-60° Model.
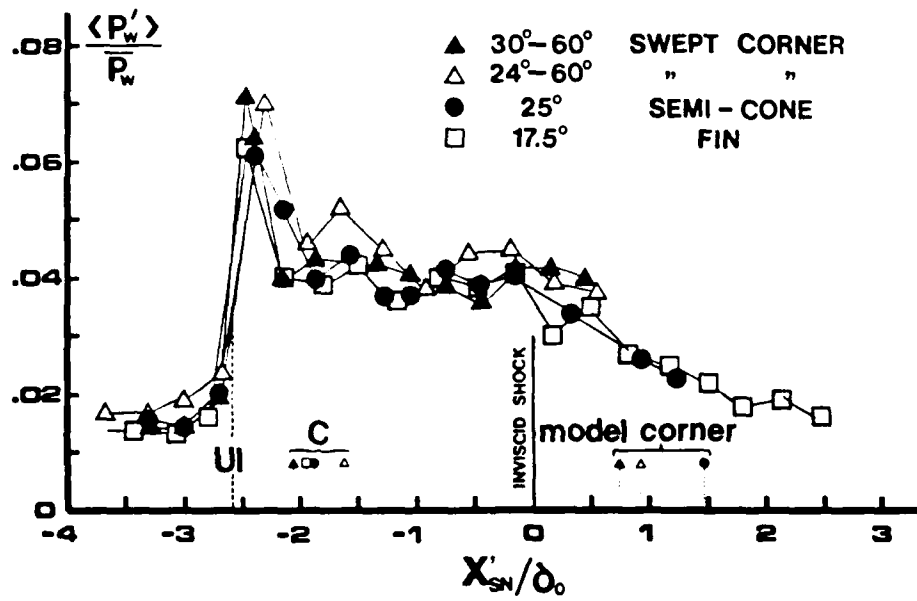
Figure 10. Normalized rms Distributions for Various 3-D Geometries
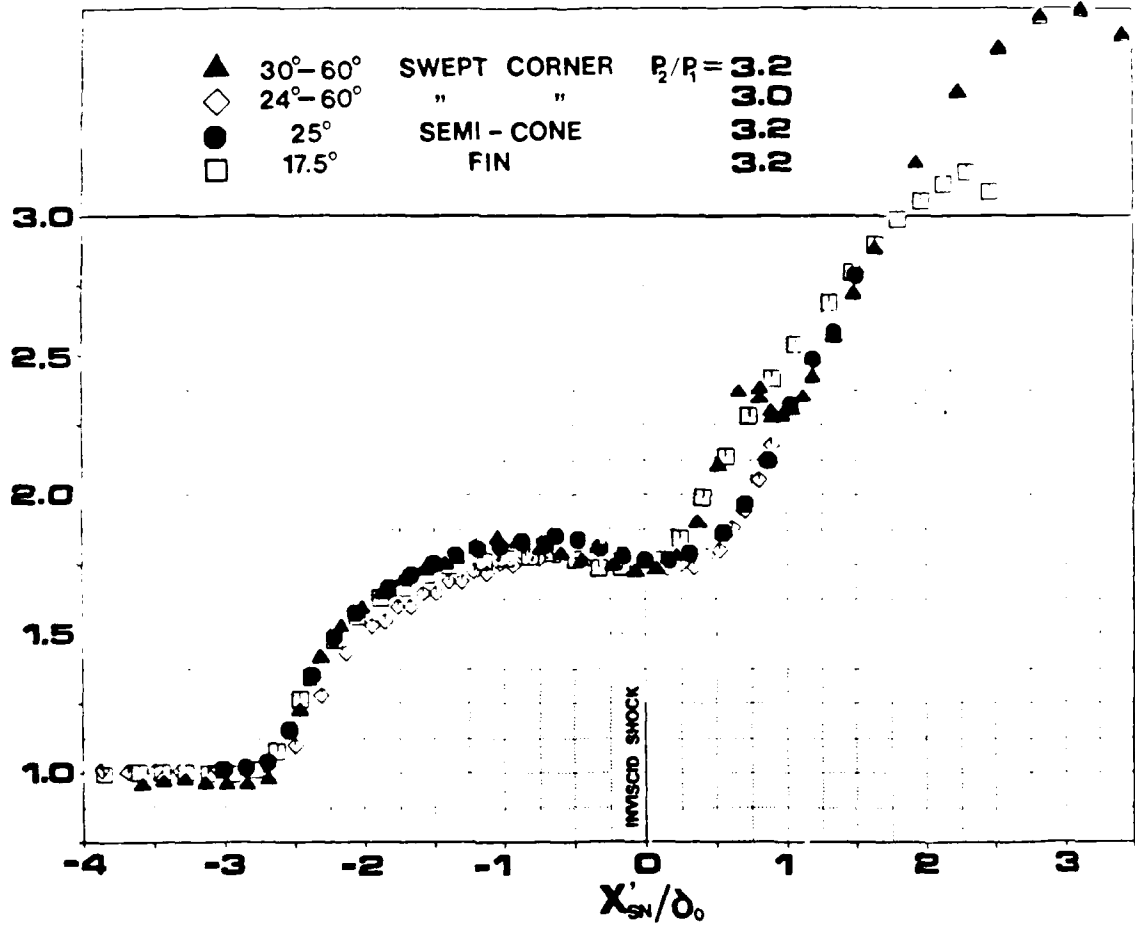
Figure 11. Mean Wall Pressure Distributions for Various 3-D Geometries
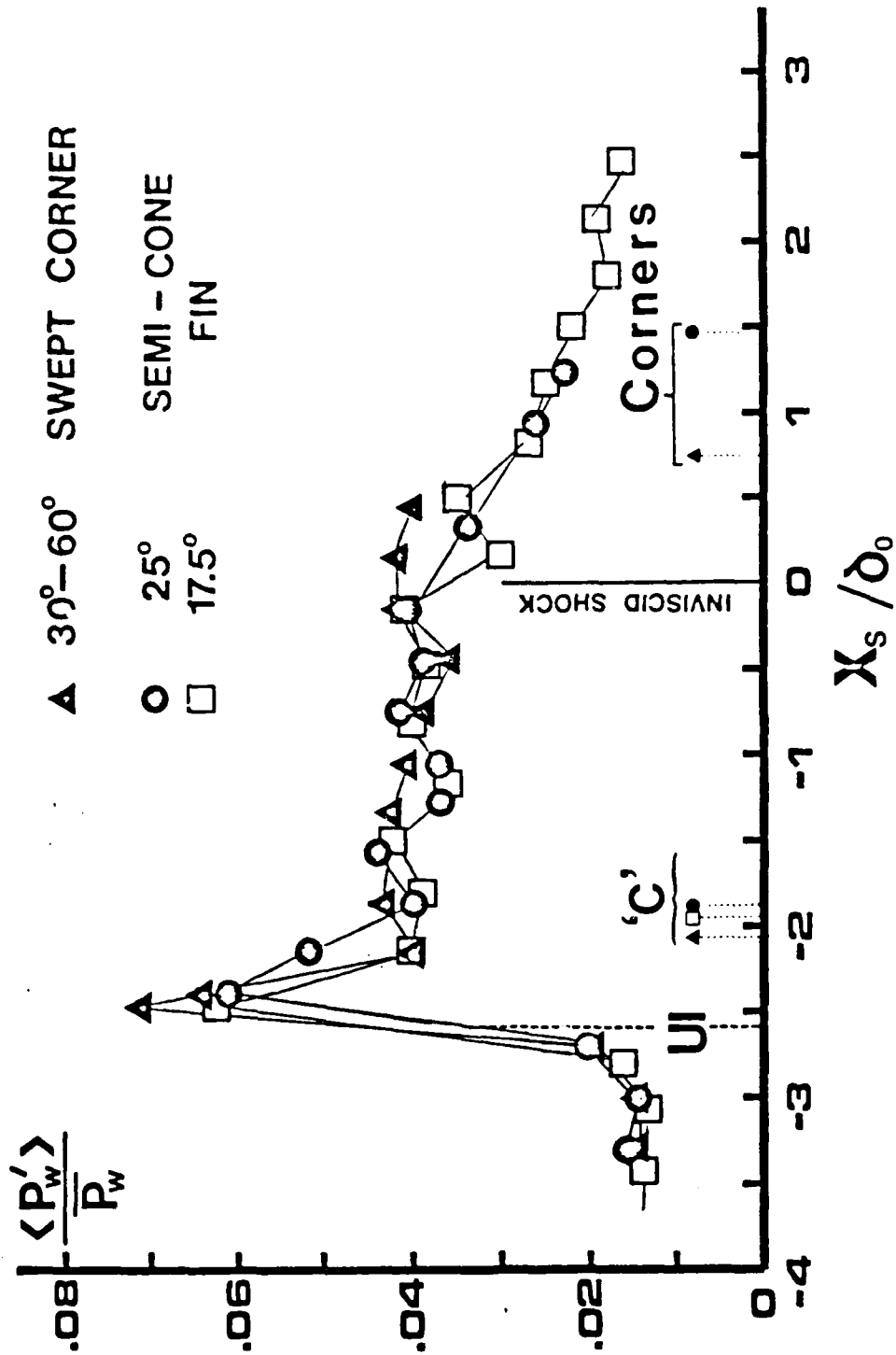
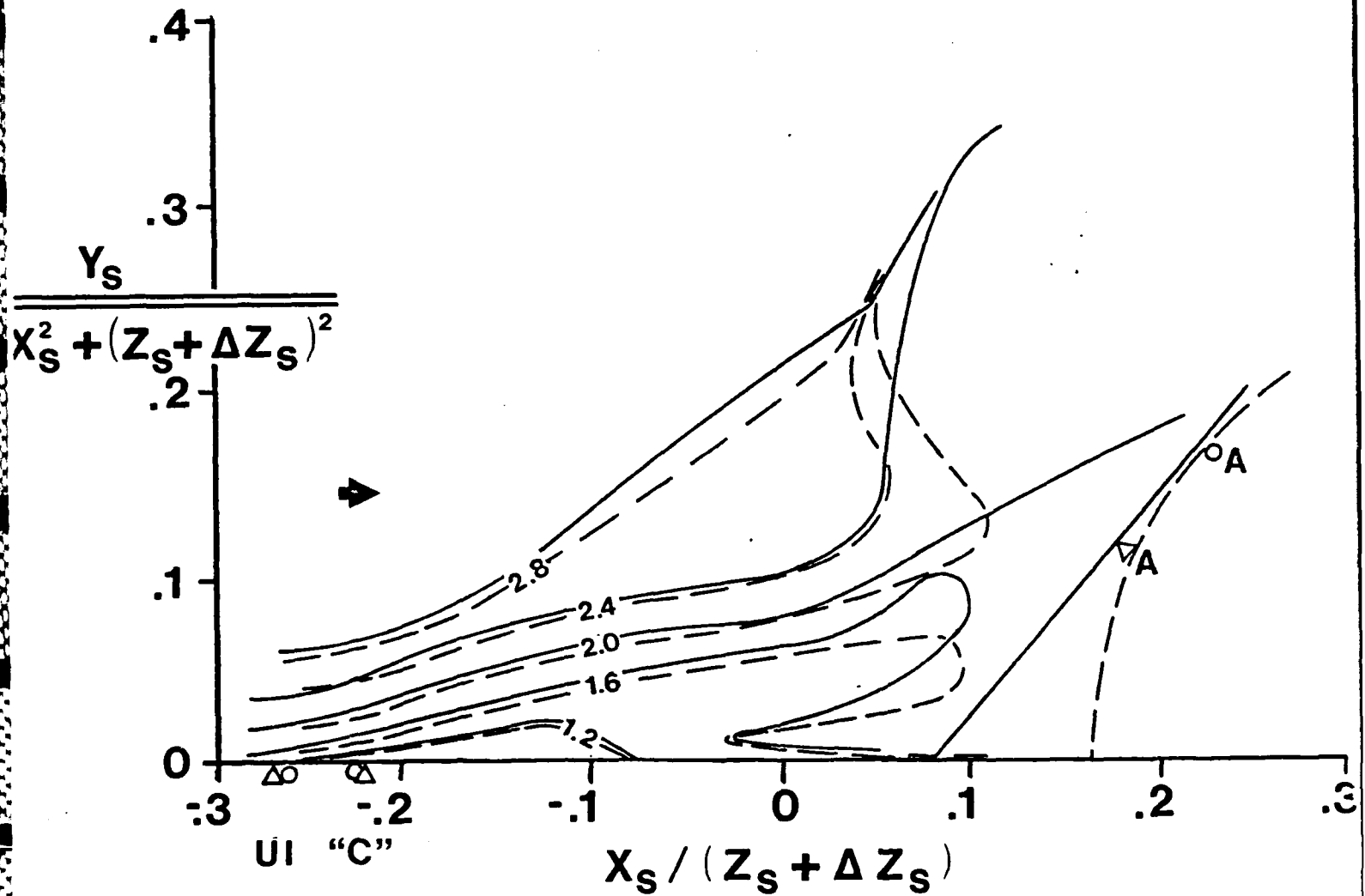Figure 12. Wall pressure RMS for several geometries generating the same strength shock wave.

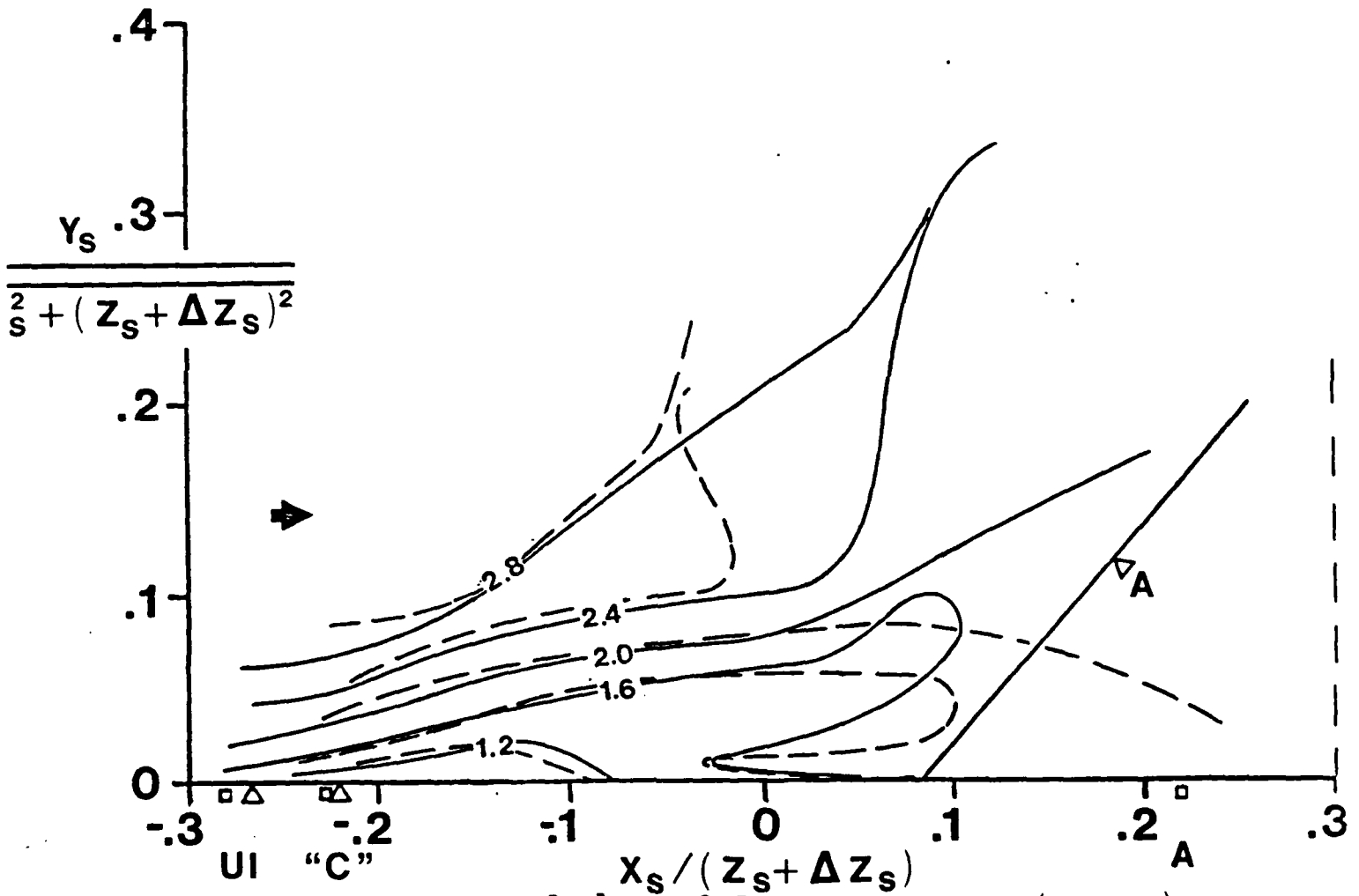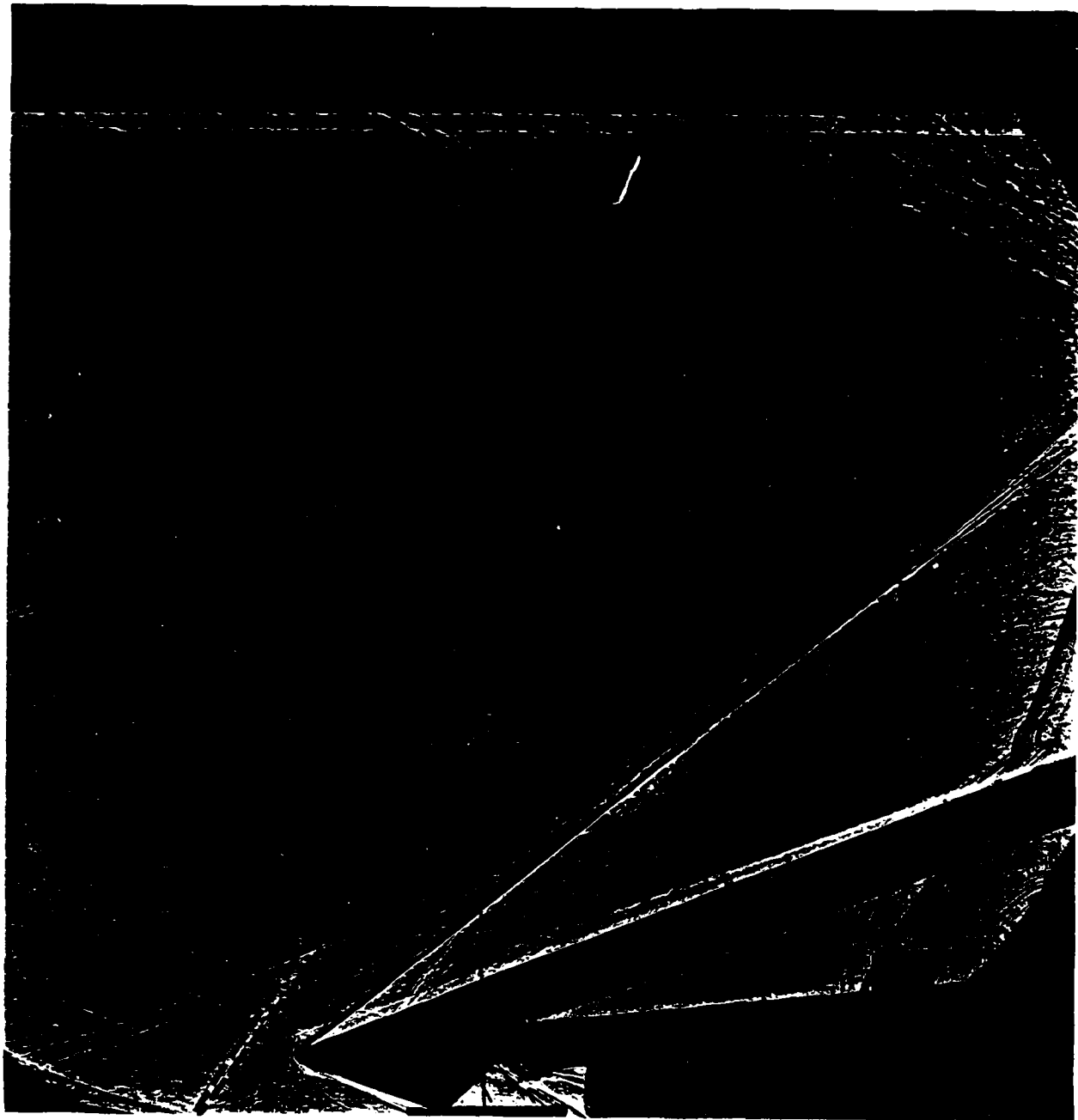FIGURE 13. $\alpha = 30°$, $\lambda = 60°$ Swept corner (solid) and $\gamma = 25°$ semicone (dashed) Mach contours.

FIGURE 14. $\alpha=30°$, $\lambda=60°$ Swept corner (solid) and $\alpha=17.5°$ fin (dashed) Mach contours.

δ_o

Figure 15. Shadowgraph Picture of 20 Degree Fin Interaction

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