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A Standard Test Case for a Low Speed, Turbulent Junction Vortex Flow

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Abstract

The mean flow structure upstream, around, and within a turbulent junction or horseshoe vortex and extending into the wake is reported for an incompressible, subsonic flow. The flow is generated by placing a streamlined (teardrop shaped) cylinder normal to a flat surface in a relatively thick boundary layer. The flow is a particular case in the broad class of complex, separated, three-dimensional turbulent flows.

The total flow field, including the flow through separation and the vortex, and extending into the near wake, has been documented with mean velocity, static pressure, and total pressure measurements using a very carefully calibrated Prandtl-type, biconic five-hole probe. ~~In addition,~~ extensive floor static pressure measurements, emphasizing the region of the vortex system, and static pressure measurements on the cylinder surface are also reported. Flow visualizations for the floor flow and the body surface are ~~also~~ reported.

Measurements of the primitive variables of velocity and pressure are reported on all surfaces bounding the region of the vortex flow. This is consistent with providing boundary conditions on all surfaces surrounding the solution domain for the implementation of a numerical solver for the elliptic, turbulent, three-dimensional Navier-Stokes equations. Measurements of these same variables are provided on one transverse plane and one streamwise plane within the flow field itself to allow for comparisons between the measured and calculated flow variables.

These data are also suitable for use with other approximate numerical solution marching methods using parabolized Navier-Stokes equations to solve such elliptic flows.

This data set can be viewed as a single, coherent, self-consistent data set. It is offered to the computational fluid mechanics community as a standard test case for the evaluation of the capabilities of numerical solvers intended for predicting the flow field in such a complex, separated, three-dimensional turbulent flow. The data set is available for copying to requestor supplied tapes or for transmission via BITNET.

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1. Introduction

1.1 Motivation

The 1981-82 Stanford Conference on Complex Turbulent Flow [1] clearly revealed that however one may categorize and subdivide the broad class of flows generally designated as turbulent and complex, in virtually any particular category there is a notable shortage of experimentally studied flows that are sufficiently unified, comprehensive, and detailed so as to be of broad value to turbulence modelers, flow modelers, and code/technique developers for such flows. This was made clear in the search for standard test cases in various categories where many experimental studies, which provide excellent information on one or a few aspects of a particular flow, lacked the kind of completeness required for use in objectively evaluating the predictive ability of codes. This lack of completeness in experiments allows, or even requires, flow modelers and program developers to make assumptions in their work that could have very large effects on their computed results. This latitude in assumptions clouds the objectivity in evaluating flow models, or predictive capability of computer codes.

The objective of this project was to provide a complete, highly detailed, self consistent and coherent data set of exceptional quality which could serve as a standard case or archive case for one particular complex, separated, three-dimensional turbulent flow.

1.2 Flow Field Description

The complex turbulent separated flow presented in this report is the three-dimensional separated turbulent flow centered about a junction or horseshoe vortex system. This flow is generated by placing a streamlined cylinder normal to a flat surface in a thick turbulent boundary layer as shown in Fig. 1.1.

The total flow system is arbitrarily divided into four regions, which include:

I. The three-dimensional pressure-driven turbulent boundary layer-like flow upstream and around the body but excluding the separated flow.

II. The three-dimensional separation region including the separation sheet/envelope and the three-dimensional horseshoe or junction vortex system which is contained between the separation sheet and the body itself, including the flow forward of and around the body sides to the trailing edge.

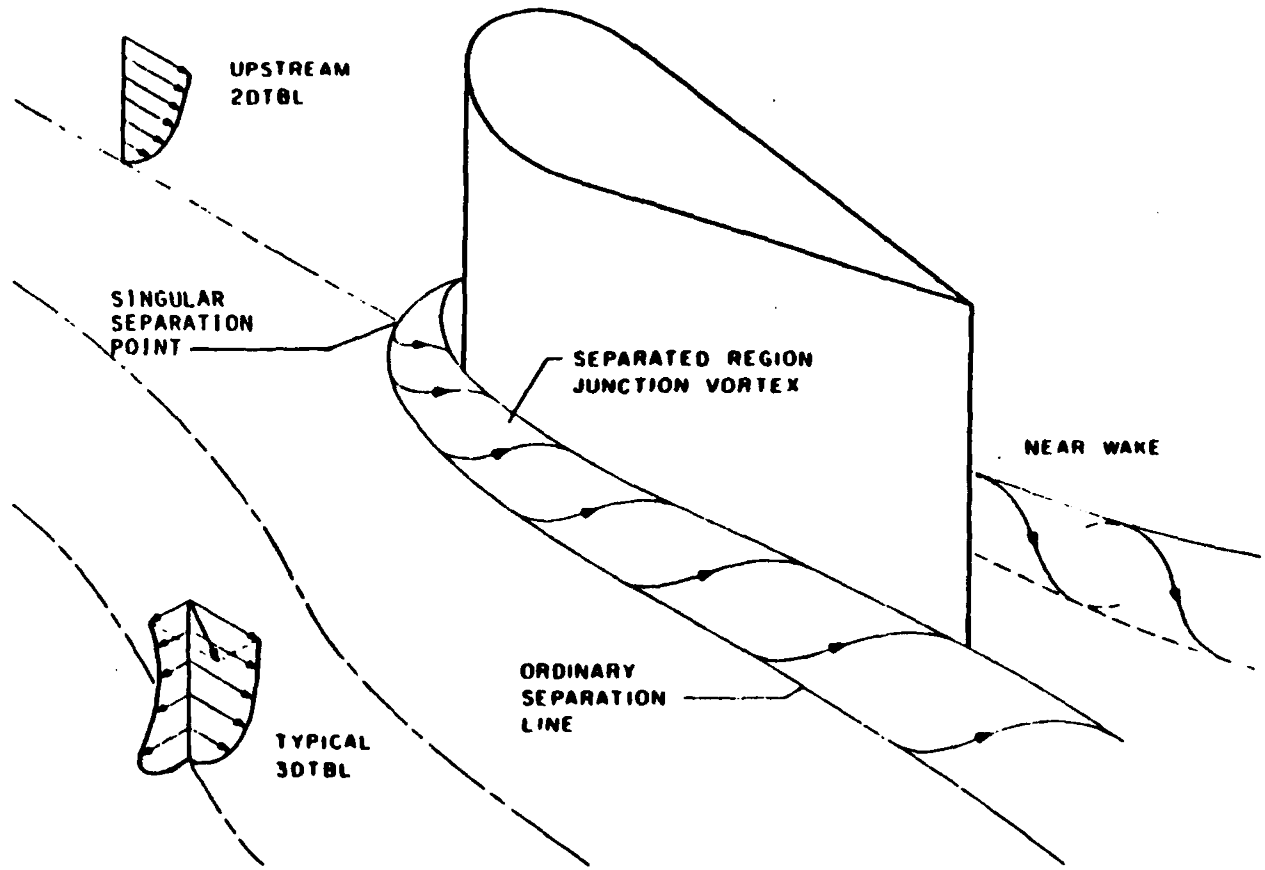

Fig. 1.1 The Overall, Complex Separated Three-Dimensional Turbulent Flow Centered Around a Junction Vortex

III. The near-wake flow dominated by the strong mixing of the tails of the horseshoe vortex system coming off the two sides of the body, as well as the wake from the boundary layers developed on the body sides and mixing with the adjacent boundary layer-like more remote floor flow.

IV. The far-wake flow where the various complex turbulent flows in region III continue to mix and homogenize to some extent toward a more typical boundary layer-like downstream flow.

This type of flow occurs in a wide variety of real world flow circumstances. Among these are the flow around bridge piers in rivers, around buildings and structures in an atmospheric boundary layer, at wing-fuselage junctions, at strut-surface junctions, control surface-body junctions, at strut-surface junctions in turbomachine flow passages, at the leading edge junction between turbomachine blades and end walls, around submarine sail-hull and control surface junctions, and in and around ship hull-strut intersections.

1.3 Measurements

Extensive surface flow measurements were first made to observe surface details of the flow, to guide in the placement of surface instrumentation, and to infer initial transverse stations.

For the fully three-dimensional turbulent junction vortex flow of region II, with considerable overlay into Region I, and the near wake flow of region III, measurements reported here include:

1. The floor surface static pressure coefficient.

2. The body surface static pressure coefficient.

3. The velocity field.

4. The total pressure field.

5. The static pressure field.

6. The computed vorticity field on some planes.

Figure 1.2 shows the surface over which flow measurements were taken for the standard test case. This flow region includes the separated and vortex flow, as well as the near wake flow.

The complexity of the flow through separation and in the vortex of region II suggests that the full, elliptic, turbulent Navier-Stokes equations would be required in a solution. A well posed problem governed by elliptic equations requires boundary conditions on all boundaries surrounding the solution domain. Hence measurements of the primitive variables of (at least) pressure and velocity were made as

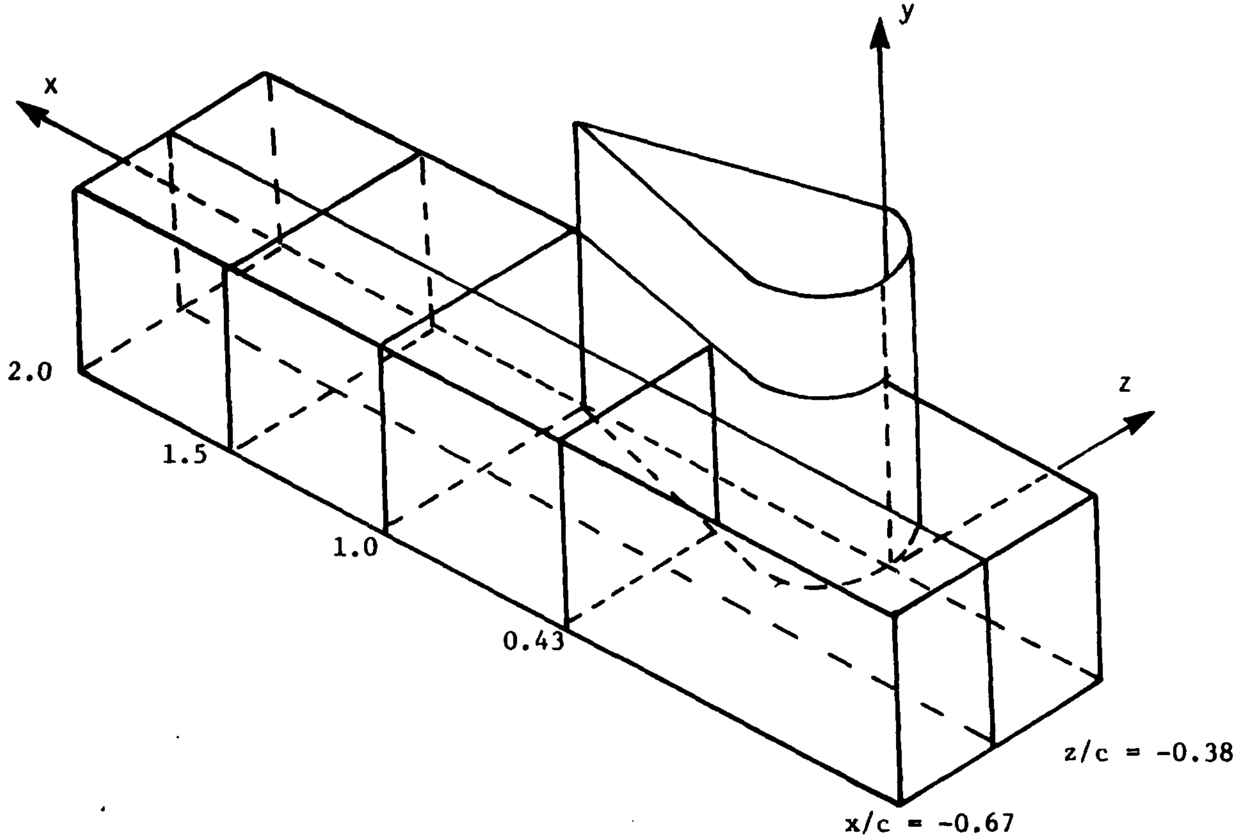

Fig. 1.2 Measurement Planes

described below. More approximate numerical solution methods which more or less march through the elliptic flow, while correcting or adjusting to account for the elliptic character of the flow, also exist. The data set offered is also suitable for use in evaluating such methods.

Measurements were made on:

1. An upstream transverse plane at 67% chord length before the body.

2. A downstream transverse plane at the body trailing edge at 100% chord length.

3. The upstream symmetry plane.

4. A streamwise side plane at 67% chord length away from and parallel to the body centerline.

5. A top plane parallel to the tunnel floor and at 55% body height.

6. The tunnel floor.

7. The body side.

8. A downstream transverse plane at 200% chord length.

9. The downstream symmetry plane.

These planes form a complete box-like boundary surrounding the junction vortex flow. Three additional planes within this flow field are provided for comparisons between the measured data and any computed flow field. These planes include:

10. A transverse plane at 43% chord distance downstream of the body leading edge.

11. A transverse plane at 150% chord distance downstream of the body leading edge.

12. A streamwise plane at 38% chord length away from and parallel to the body centerline, and generally passing through the large junction vortex.

The percent chord values describing the location of these several planes are only approximate. The tabulated data in the appendices of References 2 and 3 identifies all data stations more accurately.

1.5 Utility and Uses of Results

A high quality, fully documented, unified, comprehensive, and self-consistent study of this total complex flow should be valuable in assessing the predictive capabilities of computational codes developed to predict portions of, or the total flow documented here. The data may also be useful in the development of turbulence and flow models. The tabulated data is available for copying to requestor supplied tapes, or transmission via BITNET.

1.6 Acknowledgments

The results reported here are from a long term, ongoing project. Initial support from the National Science Foundation provided for most of the physical facilities, some early instrumentation, and some initial work on the project. Subsequent support from the NASA-Ames Research Laboratory provided for additional instrumentation, the development of the automated data acquisition system, and a portion of the results reported here. The most recent support from the David W. Taylor Naval Ship Research and Development Center provided for completing the documentation of the vortex flow and the near wake of the downstream flow.

2. Facilities and Methods

2.1 Cylindric Body

The interaction between the streamlined cylindric body shown in Fig. 2.1 and the turbulent bundary layer on the floor of the wind tunnel produced the junction vortex flow. The flat sides of the cylinder terminate in a sharp trailing edge and are tangent to the circular leading edge of the body. The cylinder has a leading edge diameter (maximum thickness) of 127 mm, an overall length (chord) of 298 mm, and a height of 229 mm.

2.2 Coordinate System

The righthand orthogonal coordinate system used to describe this flow is shown in Fig. 2.1. The origin of the coordinate system is at the intersection of the floor center line with the leading edge of the faired cylinder.

The x and z directions will be referred to as the streamwise and transverse directions, respectively. The probes were traversed across the flow field in the y direction. Floor data stations are given in millimeters as an (x,z) pair.

2.3 Experimental Methods

The dedicated open circuit, subsonic wind tunnels used for the experiments and probe calibrations are described in detail in reference 2.

Dynamic similarity for the low speed, three-dimensional flow study was achieved by maintaining a constant Reynolds number at the wind tunnel throat. The Reynolds number per unit length,

$$\frac{Re}{L} = \frac{\rho V_*}{\mu},$$

was equal to 1,340,000 per meter, where V_* is the mean velocity at the throat of the tunnel inlet nozzle. The body Reynolds number was 183,000 based on the body thickness or leading edge cylinder radius.

All measurements were made with the body fixed at its reference position. An automated traverse and data acquisition system was used for probe positioning and data collection.

Distributions of the three components of velocity, total pressure, and static pressure were measured by using a 3.18 mm diameter, United

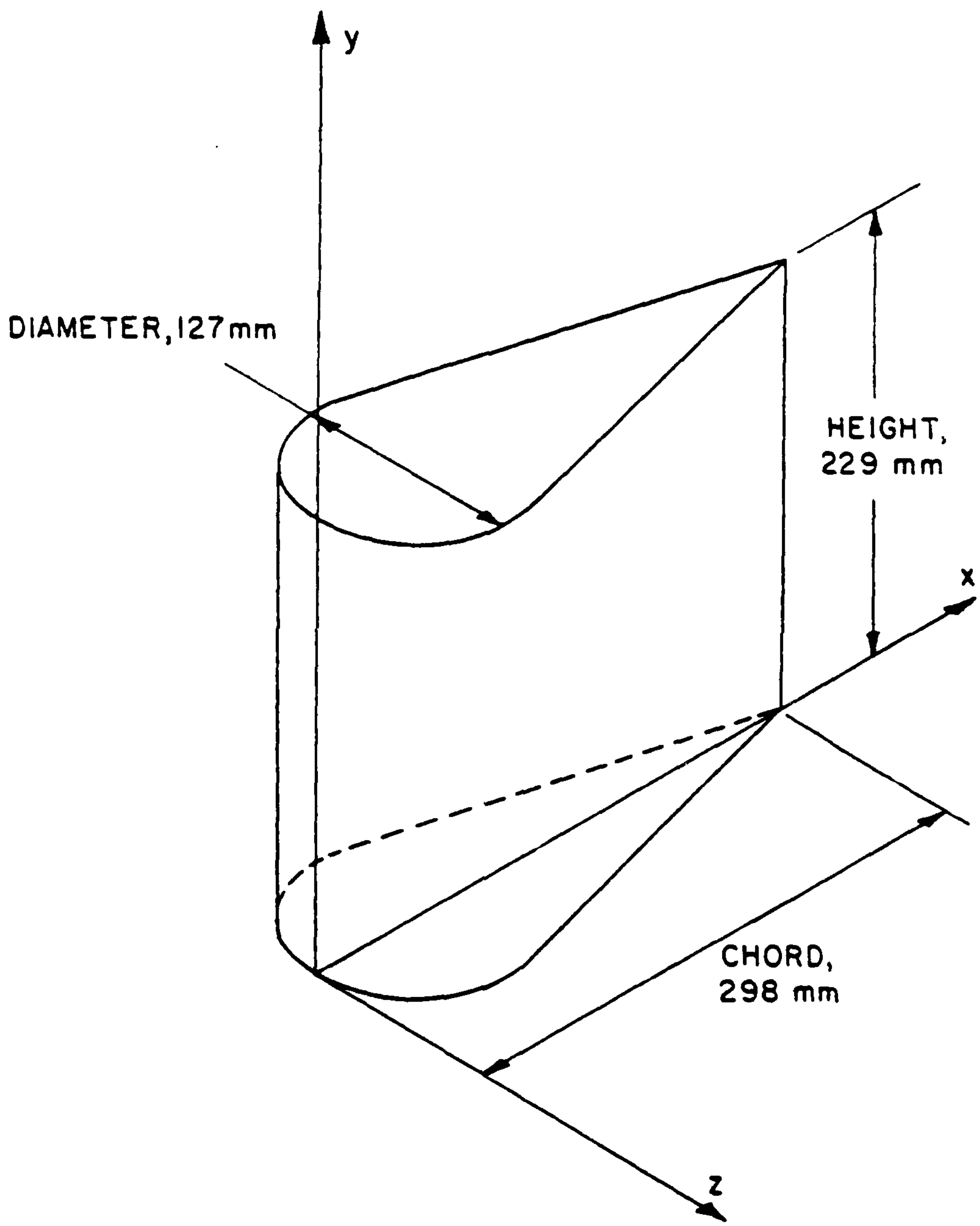

Fig. 2.1 The Streamlined Cylindric Body

Sensor Corporation, type DC, five-hole biconic, Prandtl-type pressure probe. Flow visualizations and surface pressure measurements were also reported.

More details about the data acquisition system, flow visualization techniques and the five-hole probe calibration and measurement methods can be found in reference 2.

3. Results

Detailed results of the surface flow visualizations, the surface pressure measurements, and the five-hole probe measurements for the 13 planes shown in Fig. 1.2 and available in Pierce and Harsh [2], Pierce, Kim and Harsh [3], and Pierce, Kim, Nath, and Shin [4].

The surface flow visualizations generally were used to observe qualitative features of the flow, but these did provide quantitative information on such features as the location of separation points on the floor and body sides, and the physical size of the junction vortex growth as seen by the floor.

Both the surface pressure results and the five-hole probe results are presented in a variety of graphical forms, and in detailed tabulations as well. A rigorous calibration procedure was followed for the measurement system. The five-hole probe was carefully and extensively calibrated in the null-yaw method. Regression analyses, with over 30 candidate models, were used to obtain the calibration functions for the probe. A formal and rigorous error analysis was performed, and statistically meaningful uncertainties are presented with each tabulated data value reported for both the surface pressure results and the five-hole probe results.

The results of the surface flow visualizations, the surface pressure measurements, and the five-hole probe measurements are compared and examined relative to each other in some detail. A high degree of self-consistency was found among the various measurements.

While not a part of the funded project reported on here, the available BITNET files contain extensive laser Doppler velocity measurements provided from an independent study of the plane of symmetry flow using the same body and tunnel facilities as reported here, and at the identical unit Reynolds number value used to insure dynamic similarity. These results also include statistically meaningful uncertainty values for each reported measurement. The LDV data was obtained using a modified DISA (now DANTEC) two-color, two-channel system with frequency shift to allow velocity direction discrimination. The LDV allowed a better spatial resolution of the flow, especially near the solid surfaces. The LDV measurements were confined to the plane of symmetry providing detail measurements in the neighborhood of the one singular separation point detected, and through the dominant vortex core where local velocities sometimes exceeded the limits of the five-hole probe calibration functions. Since these LDV data supplement the five-hole probe data and hence are included in the available BITNET files.

4. Summary

The mean flow structure upstream, around, and within a turbulent juction or horseshoe vortex and extending into the wake is reported for an incompressible, subsonic flow. The flow is generated by placing a streamlined (teardrop shaped) cylinder normal to a flat surface in a relatively thick boundary layer. The flow is a particular case in the broad class of complex, separated, three-dimensional turbulent flows.

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