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An Experimental Study of Fluctuating Pressure Loads Beneath Swept Shock/Boundary-Layer Interactions

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by

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Semi-Annual Progress Report for NASA Grant NAG 1-1070
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Submitted to:

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PENNSTATE Gas Dynamics Laboratory

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Abstract

This experimental research program is providing basic knowledge and establishing a database on the fluctuating pressure loads produced on aerodynamic surfaces beneath three-dimensional shock wave/boundary-layer interactions. Such loads constitute a fundamental problem of critical concern to future supersonic and hypersonic flight vehicles. A turbulent boundary layer on a flat plate is subjected to interactions with swept planar shock waves generated by sharp fins. Fin angles from 5° to 25° at freestream Mach numbers between 2.5 and 4 produce a variety of interaction strengths from weak to very strong. Miniature Kulite pressure transducers mounted in the flat plate have been used to measure interaction-induced wall pressure fluctuations. These data will be correlated with proposed new optical data on the fluctuations of the interaction structure, especially that of the "λ-shock" system and its associated high-speed jet impingement. The results of this study will be used to provide both a physical model and a Computational Fluid Dynamics (CFD) validation database for swept shock/boundary layer interaction-induced fluctuating pressure loads on aerodynamic surfaces. This work is proposed as an extension of NASA Grant NAG 1-1070, under which the wall pressure fluctuation measurements have already been carried out.

Introduction

The possible failure of aerospace structures due to acoustic fatigue has become an important issue for study at NASA's Langley Research Center and elsewhere, especially with the advent of renewed practical interest in supersonic and hypersonic flight regimes. A body of evidence exists (eg, Refs. 1 and 2) to suggest that severe acoustic loads can occur on high-speed flight vehicles. These loads are known to arise from such flow phenomena as jet noise, combustion, turbulent boundary layers, unsteady shock-wave motion, and the interactions of shock waves with boundary layers.

This evidence further suggests that flow-induced local acoustic loads as high as 190 dB are possible and have been observed in the past. Such loads are of such severity as to pose an immediate threat to the structural integrity of a high-speed flight vehicle, especially when high thermal loads are simultaneously present.

On June 2-3, 1988, a Workshop on Fluctuating Pressure Loads was held at the NASA-Langley Research Center. It became clear at this Workshop that, while a general connection is recognized between certain fluid dynamic phenomena and resulting high acoustic loads, the detailed physics of acoustic energy generation and propagation across turbulent boundary layers to impinge on aerodynamic surfaces is poorly understood. A better understanding was needed as the next step in dealing with current and future aeroacoustic fatigue problems of high-speed flight. The present research program under NASA Grant NAG 1-1070 grew out of that Workshop and is aimed to satisfy, in part, that need.

The Penn State Gas Dynamics Laboratory specializes in basic experimental research on high-speed viscous/inviscid flow interactions, with particular emphasis on the development and use of modern non-intrusive optical flow diagnostic instrumentation. Of particular interest in terms of fluctuating pressure loads is our ongoing research study of shock wave/turbulent boundary layer interactions. These interactions are ubiquitous on the aerodynamic control surfaces and in the propulsion inlets and exhausts of both current and proposed high-speed flight vehicles. However, especially in the case of three-dimensional (swept) interactions of shock waves and turbulent boundary layers, very little is known about acoustic energy generation, propagation, and impingement on adjacent aerodynamic surfaces.

The goal of the currently-proposed research is therefore to gain a better understanding of these phenomena in support of NASA-Langley's program to assess and eventually control aeroacoustic loading on advanced flight vehicles. As a secondary goal, we hope to provide high-quality, detailed experimental data which will be of use in the validation of CFD predictions of such interacting flows.

Progress Report for the Second Year of Grant NAG 1-1070

As shown diagramatically in Fig. 1, a flat plate is being used to generate the turbulent boundary layer and a fin mounted on this plate generates the swept shock wave which interacts with the boundary layer. The fin angle, α, then controls the strength of the interaction for a given incoming-flow Mach number.

Flush-mounted miniature "Kulite" pressure cells have been used to measure fluctuating surface pressures under these swept shock/boundary layer interactions. These transducers are known to have a flat frequency response up to approximately 50 kHz, and a resonance frequency of the order of 100 kHz. While not able to resolve the turbulent pressure fluctuations in the incoming boundary layer, the Kulite cells can faithfully reproduce the relatively low-frequency shock oscillations observed in shock/boundary-layer interactions [3].

The Kulite-cell data were taken for the fin angles α = 10, 16, and 20 degrees at Mach 3 and 16 and 20 degrees at Mach 4, covering a significant range of shock wave strength. The results have been reduced and analyzed to yield rms fluctuating pressure levels, frequency spectra, and point distribution function (pdf) plots. In all cases the location of the Kulite cell with respect to the interaction is denoted by the conical angle β measured from the leading edge of the fin.

The results of the rms surface pressure distributions are shown, in comparison with the mean wall pressure distributions, in Figs. 2 and 3. (Note in these Figs. that each succeeding rms distribution is shifted up by 0.1 psi with respect to its predecessor for clarity. A similar shift of p_w/p_{inf} = 0.5 has been done in the case of the mean wall pressures.) The rms distributions reveal some interesting humps or peaks which we are still trying to understand. Nonetheless, in general, p_{rms} rises from the beginning of the interaction to its rear (ie to the fin). The highest level measured was 0.3 psi, which corresponds to a sound pressure level of about 160 dB. This certainly places such interactions in the category of significant acoustic-load generators.

An example of the many pdf distributions obtained is shown in Fig. 4. The six distributions shown are denoted by the angle β in the upper right corner of each plot. These serve to illustrate that the measured pressure fluctuations are essentially Gaussian, which was the case for all such pdf's examined thus far.

Finally, six example spectra from a given interaction are shown in Fig. 5. The spectra are plotted in the same coordinates used by Dolling et al. These spectra will require much scrutiny before their physical significance is fully understood. However, it is clear that significant changes in the frequency distribution of fluctuating energy occur beneath a swept interaction.

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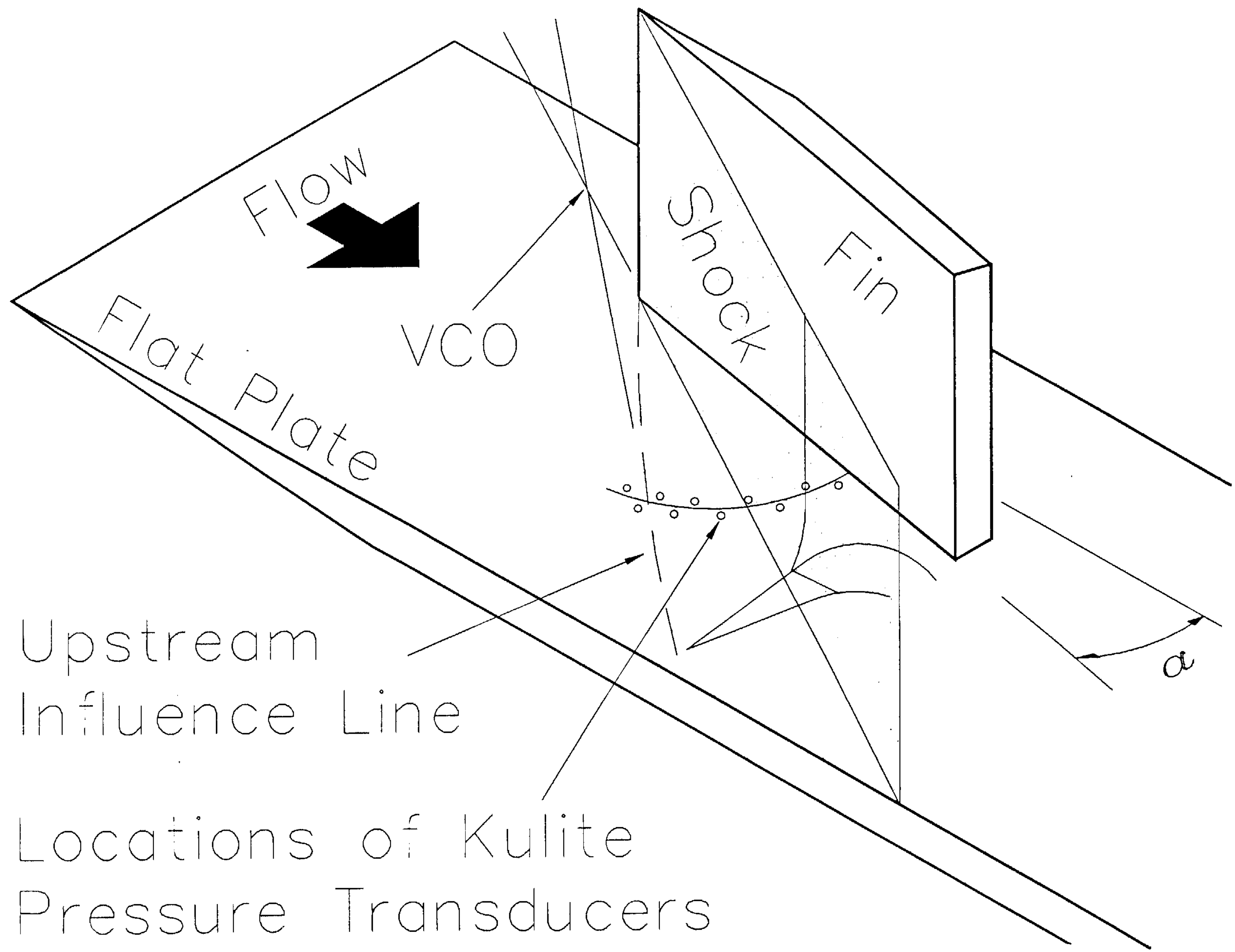

Fig. 1 - Diagram of Test Model for Swept Shcok/Boundary-Layer Interactions

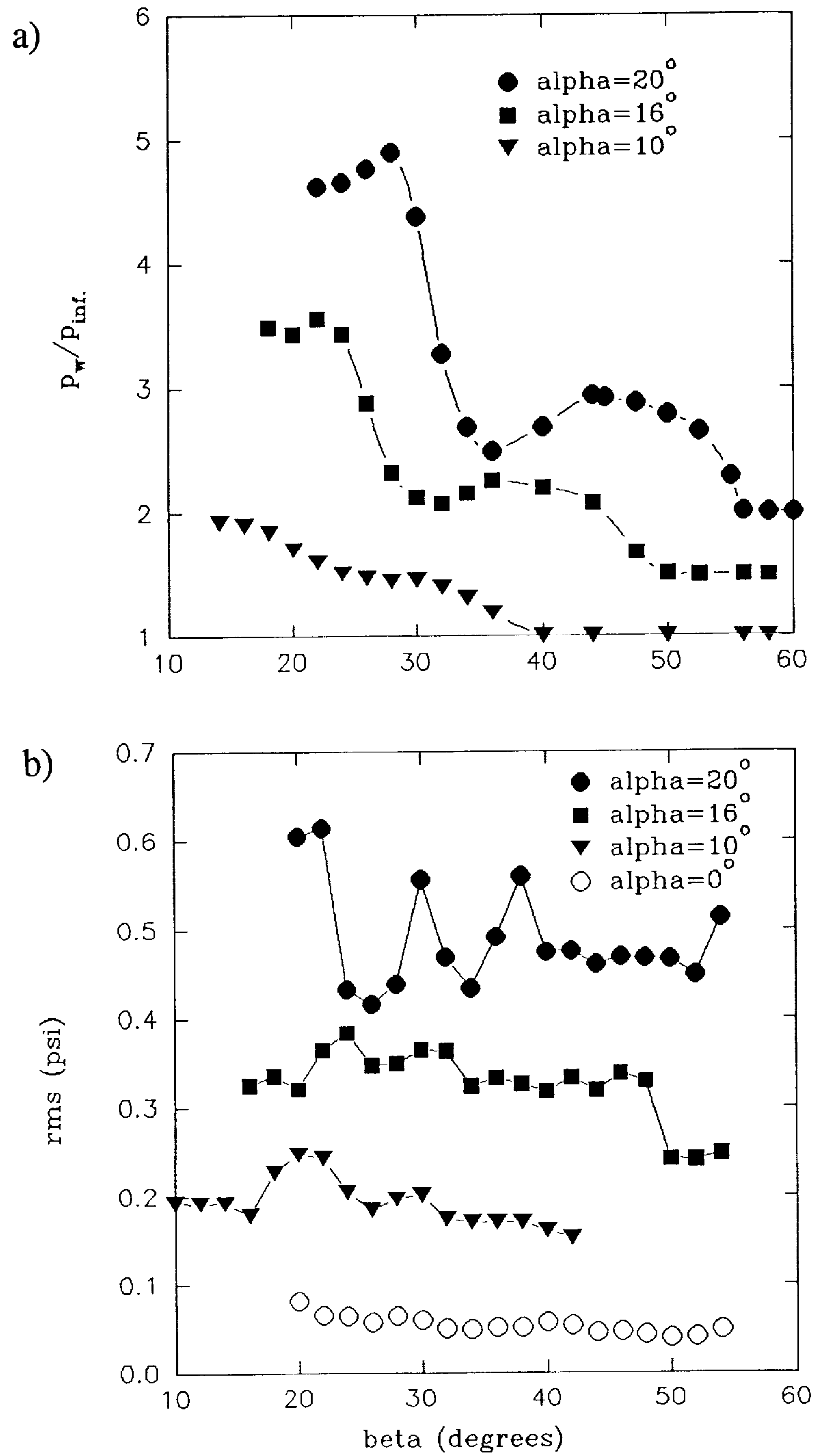

Fig. 2a M=3 Mean Wall Pressure Distributions
2b M=3 RMS Wall Pressure Distributions

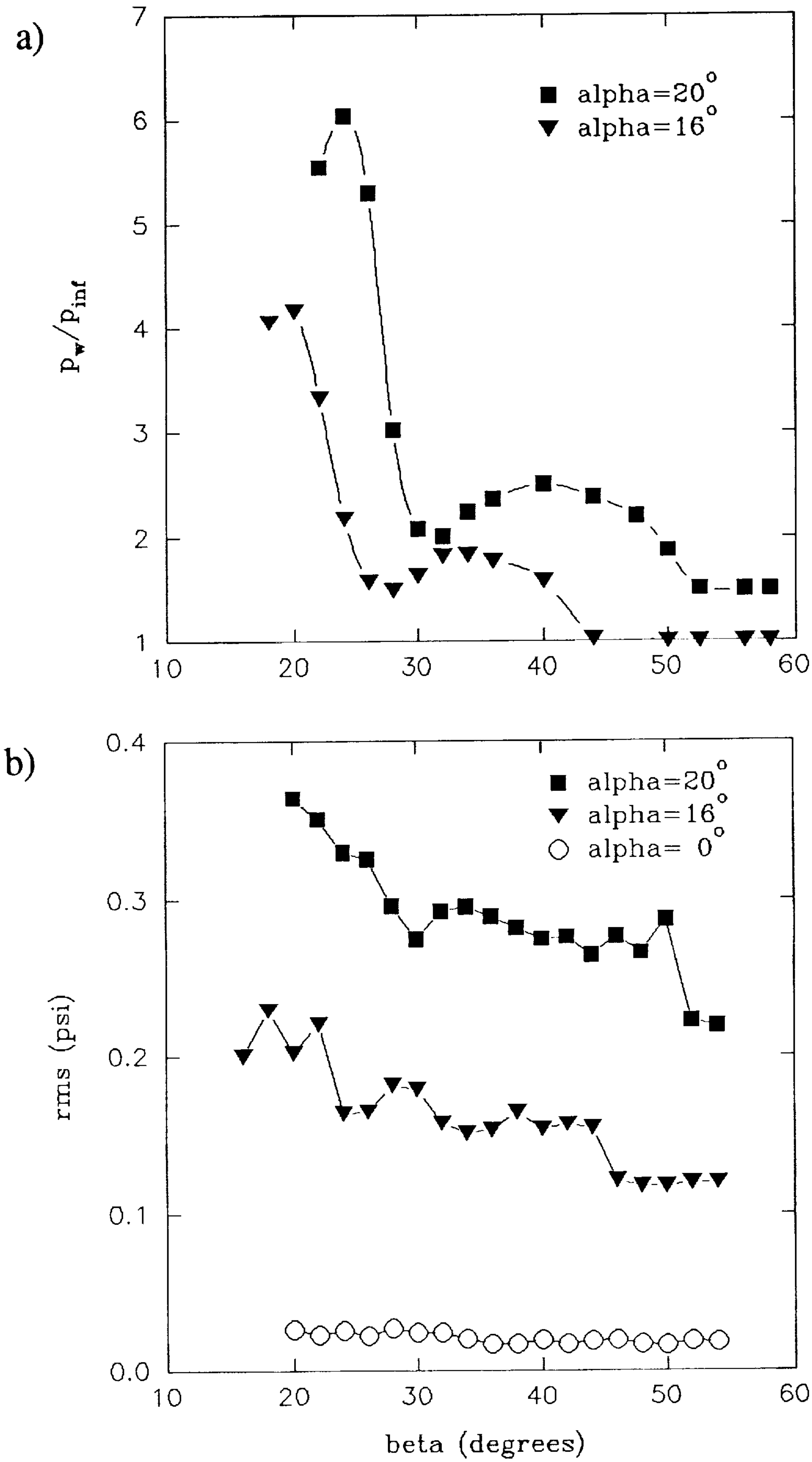

Fig. 3a M=4 Mean Wall Pressure Distributions
3b M=4 RMS Wall Pressure Distributions

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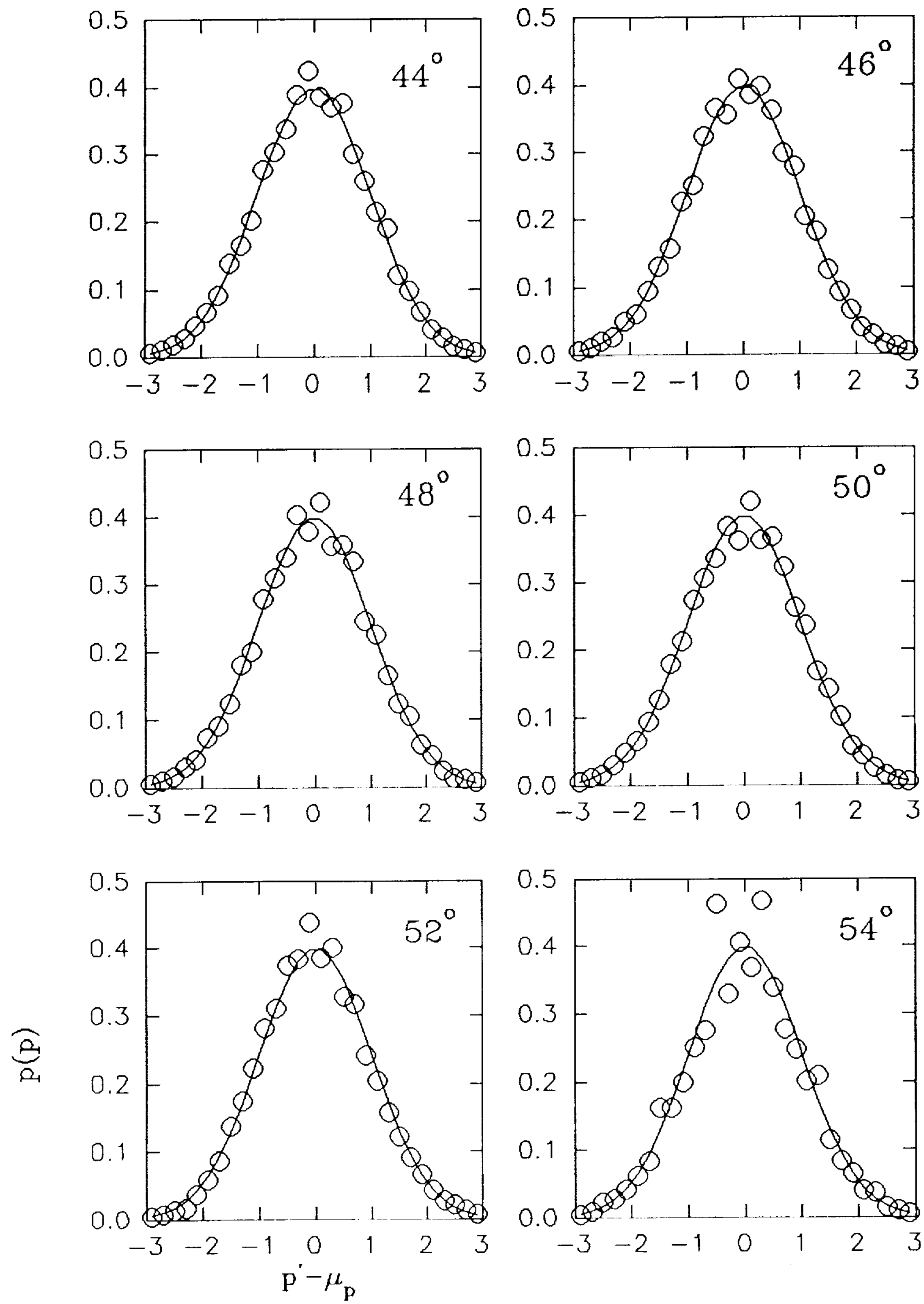

Fig. 4 - Example Probability Distributions for $M_\infty = 4$, $\alpha = 20°$

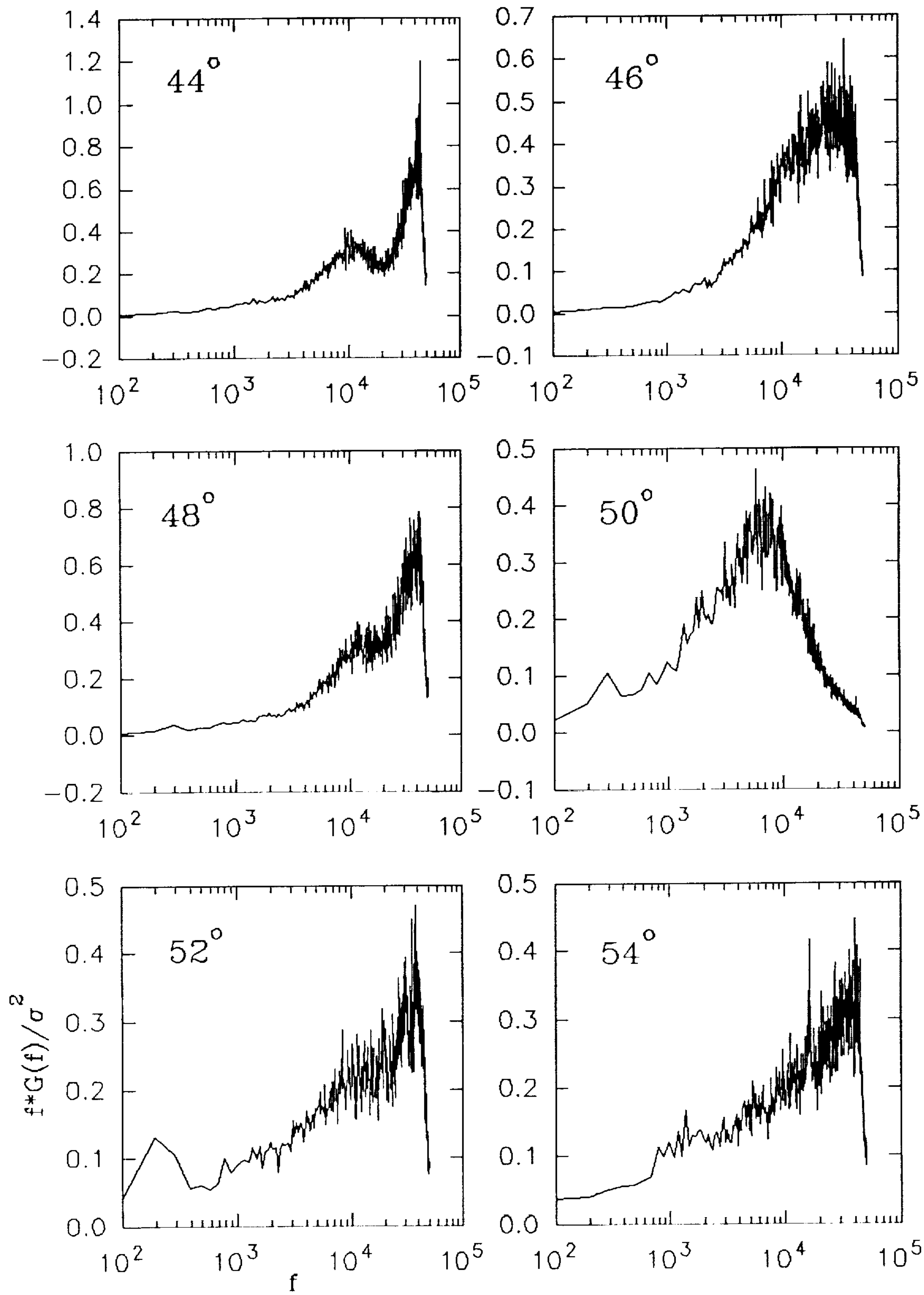

Fig. 5 - Example Power Spectral Density Functions for $M_\infty = 4$, $\alpha = 20°$

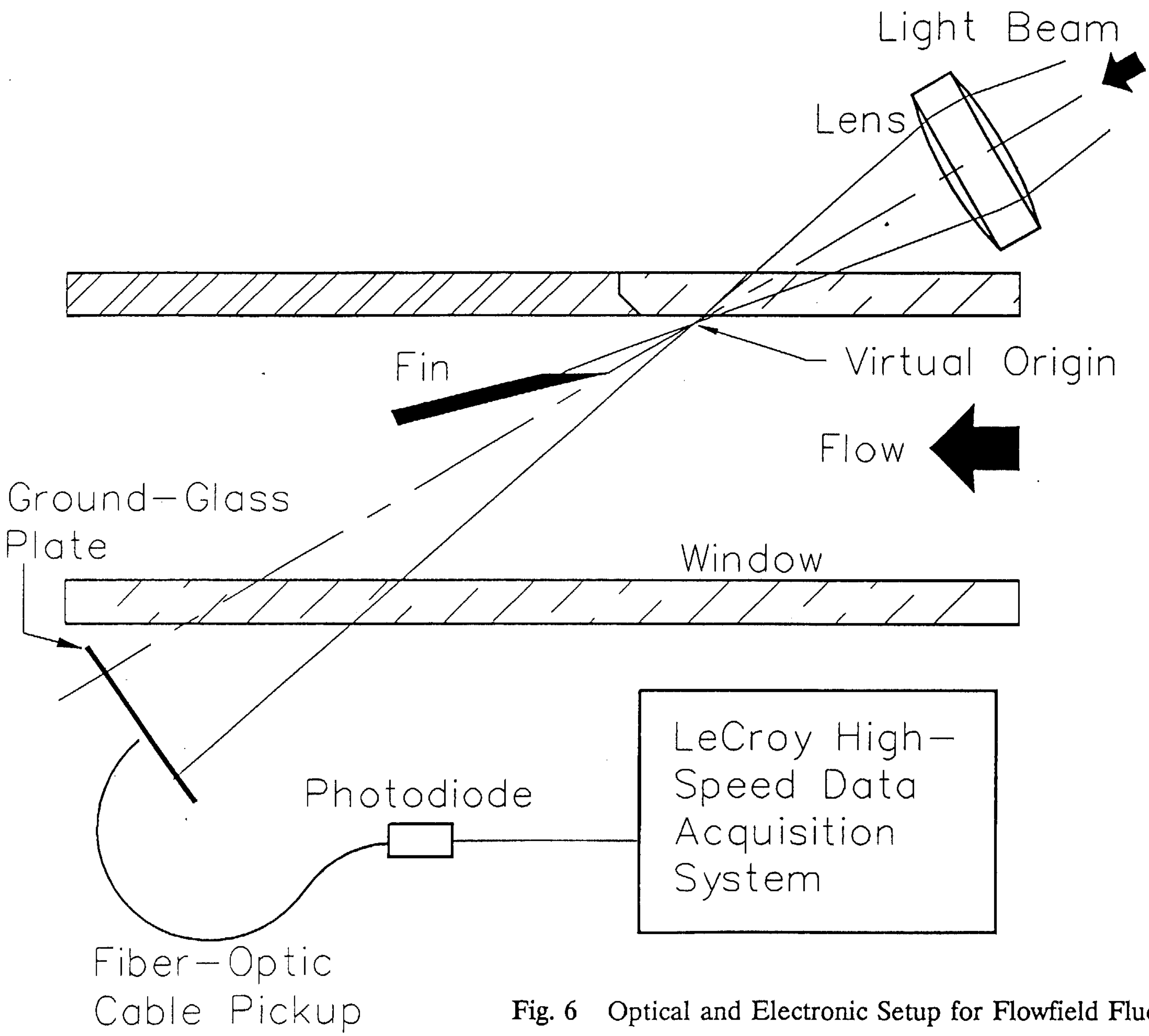

Fig. 6 Optical and Electronic Setup for Flowfield Fluctuation Measurements