some streamwise distance along the diffuser, regardless of the frequency of the applied disturbance.

(*c*) The degree of fluctuation amplification within the boundary layer ranges from one percent to over one hundred percent of the local core flow amplitude.

(*d*) If the distances of the fluctuation amplitude maxima from the wall of the diffuser are plotted versus stramwise distance, the distance of the amplitude maximum from the wall increases with streamwise distance regardless of the frequency of the applied disturbance.

Time Mean Diffuser Performance. As shown above, the velocity fluctuation amplitude within the boundary layer can be over twice as large as the local core flow amplitude. Despite the existence of these amplified fluctuations within the boundary layer, the time mean velocity distributions were not measurably altered. Fig. 9 shows the variation of momentum and displacement thickness with dimensionless disturbance frequency. In general, there is an insignificant alteration of these characteristic thicknesses, meaning that the diffuser mean pressure recovery is insignificantly altered.

Conclusions

Turbulent boundary layers experiencing an adverse pressure gradient in a conical diffuser have been subjected to a controllable periodic oscillation over a tenfold range of dimensionless frequencies, and amplitudes less than ten percent of the time mean diffuser inlet velocity, for well defined inlet conditions. The following results evolved from this investigation:

1 Amplitudes of the diffuser core flow velocity fluctuation and wall pressure fluctuation decay rapidly in the streamwise direction for all frequencies of applied disturbance, reflecting the absence of diffuser stall.

2 Depending on the frequency of the applied disturbance the amplitude of the velocity fluctuation within the boundary layer can exceed that of the local core flow value by as much as 100 percent.

3 At applied disturbance frequency ($St_L = 1.0$, $(St_\theta)_{inlet} = 7.2 \times 10^{-4}$) the amplitude distribution of the velocity fluctuation within the boundary layer grows in an orderly fashion with streamwise distance, and the phase of the fluctuations consistently leads the local core flow fluctuations.

4 At relatively high applied disturbance frequency ($St_L = 7.33$, $(St_\theta)_{inlet} = 5.28 \times 10^{-3}$), the distribution of the velocity fluctuation amplitude across the boundary layer can exhibit more than one peak, and the phase of these fluctuations lags those of the local core flow fluctuations.

5 Mean velocity profiles, and consequently overall time mean diffuser performance, change insignificantly when a disturbance is applied, regardless of frequency of the disturbance.

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DISCUSSION

J. A. Miller[3]

The authors are to be complimented on this timely and important first foray into the behavior of oscillating turbulent boundary layers in adverse pressure gradients. Several years ago this writer in cooperation with Dr. L. Carr attempted to extend the investigation of Despard and Miller[4] of separation in oscillating laminar flows to include turbulent flows. Unfortunately the perversity of the turbulent boundary layer precluded our being able to force the site of separation to coincide with the location of the instrumentation. Unpublished preliminary results of that work show good agreement with the authors' results. Moreover the present results should certainly provide a valuable benchmark for our contemplated investigation of turbulent boundary layers in the neighborhood of separation.

As is almost always the case with investigators deeply involved in their research, the authors have failed to underscore the really significant aspects of their results, the very large fluctuation amplification within the boundary layer and the very strong

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dependency of phase response on Strouhal number. Both of these effects are much greater than has been previously reported in oscillating boundary layer flows.

Finally this writer would inquire of the authors whether or not their apparatus can be modified to produce fluctuation amplitudes in the range $0.1 \leq \tilde{U}/\bar{U} \leq 1.0$ in which the important nonlinear effects begin to manifest themselves? Unfortunately many technical applications fall in this more difficult regime.

A. K. M. F. Hussain[5]

The measurements reported in this well-written paper are clear and new, and appear to be reliable. However, the bases for the choices of the diffuser angle and the frequency range are not clear. It appears that the frequencies and amplitudes of pulsation studied are low enough that no appreciable changes in the mean flow characteristics, including pressure recovery, are to be expected in the small angle diffuser. Some noticeable effect may appear when the time scale of perturbation is comparable to that of the diffuser inlet boundary layer or when the excitation amplitude is large or when the diffuser angle is larger than the safe 6 degrees. It would have been interesting to examine the velocity profiles and pressure recovery factors at different phases of the excitation. Did the pulsation induce transition in the boundary layer? Or, when the boundary layer was turbulent, did the pulsation affect the wall bursting processes?

Authors' Closure

The authors appreciate the interest of Professors Hussain and Miller in their work. Selection of the diffuser angle and the nature of the excitation were made with a view toward the simplest attainable case of an excited turbulent boundary layer experiencing an adverse pressure gradient. Choice of a six degree angle of divergence of the diffuser was based on a compromise between achieving a substantial streamwise pressure gradient and avoiding onset of diffuser stall during boundary layer excitation. Frequency and amplitude limitations were imposed by the nature of the oscillating valve. At very low frequencies, the unsteady flow component deviated from a purely sinusoidal wave. At high frequencies, mechanical components of the valve could not safely withstand the excitation.

This investigation was mainly limited to amplitudes of excitation in the linear range in order to avoid additional complications of nonlinear effects. Attempts have not yet been made to determine the maximum amplitude which can be attained with this type of valve. Variation of valve geometry and size should enable higher amplitudes to be reached. However, it appears that the classical shutter-type system is best suited for very high amplitude excitation. We did not encounter parasitic effects of substantial amplitudes at frequencies other than the valve frequency,[6] most probably because our excitation wavelengths were much longer than the test section length. We agree that very high amplitude excitation is indeed an important topic which deserves immediate attention.

The mean boundary layer at the diffuser inlet in absence of excitation was turbulent as verified by the time mean velocity distributions and a complete spectral distribution. However, details of the inner layer structure require further study. For example, excitation of the boundary layer at a frequency of the same order as the bursting frequency could lead to a better understanding of the bursting process which occurs in the absence of controlled external excitation.

The mean velocity profiles of wide angle diffuser flow fields, where stall exists in the absence of excitation, can be significantly altered with appropriate excitation.[7] Alteration of the mean profiles in an unstalled turbulent diffuser flow may indeed be possible if the excitation Strouhal number (based on boundary layer thickness) is of the order of unity. However, the wavelength will be so small that standing waves may be produced in the streamwise direction, thereby yielding a complex streamwise pressure gradient.

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