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Discussion

Small Silicon Pressure Transducers for Space-Time Correlation Measurements in a Flat Plate Boundary Layer[1]

P. R. Bandyopadhyay.[2] The authors are to be congratulated for introducing a new technology to turbulence diagnostics and control. Historically, resolution in wall-pressure measurements has not been as great as in velocity-based measurements. Consequently, fruitful relationships between wall-pressure and turbulence are generally lacking. Perhaps this technology will make an impact in this area. It should now be possible to cluster various kinds of wall-sensors and miniaturize them to the viscous sublayer thickness.

There is a need to uncover any systematic behavior that might be lying hidden in the seemingly scattered data sets in Fig. 4. This discusser is interested in offering an explanation. The data in Fig. 4 seem to suggest a trend shown schematically in Fig. 12. It is slightly obscure, but there is a systematic trend in the data, viz., that they come from a family of d^+ $(= dU_\tau/\nu)$ values. In a recent review of Reynolds number effects,[3] it was concluded that meaningful trends in the inner layer can be extracted only when the sensors are of the order of viscous sublayer thickness. In Fig. 4 also, at all Reynolds numbers, the asymptotic rms values are reached by sensors approaching the size $d^+ = 5$. Furthermore, the slopes of the family of d^+ lines drop as d^+ values are increased (decreasing sensitivity of sensors to Reynolds number effects).

The data in Fig. 4 come from various sources with varying degrees of background noise, differences in signal processing, corrections applied and different inherent errors in the sensors and instrumentation. In other words, the uncertainties in each data set are different and probably not known accurately. There are also gaps in the data. Thus, it would be an useful contribution if the authors in future could systematically vary the sensor dimension (d^+) and the Reynolds number of the flow, and regenerate Fig. 12.

There are two issues regarding the experiment carried out by the authors which need further clarification. In Fig. 9, the authors report a convection velocity that is lower than ever reported: $0.4 < U_c/U_0 < 0.5$. They write that the low values result from the smallness of the sensors. However, in Fig. 10, they have spatial correlations agreeing with those measured using larger transducers. In any case, the low values of the convection velocity is intriguing and need further scrutiny. Finally, could the authors also provide more information on venting? Where is the transducer array vented? How many vents are there and are the vents near the transducer?

[1] By L. Lofdahl, E. Kalvesten, and G. Stemme published in the JOURNAL OF FLUIDS ENGINEERING, Vol. 118, Sept. 1996, pp 457–463.

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[3] Gad-el-Hak, M. and Bandyopadhyay, P. R. 1994, "Reynolds Number Effects in Wall-Bounded Turbulent Flows," Vol. 45, No. 8, pp. 307–366.

R. L. Panton.[4] The measurement of pressure fluctuations under a turbulent boundary layer is a very difficult task. This paper describes tests at a Reynolds number that is high enough for reasonable statistics, but still maintains very good transducer spatial resolution. Another unusual feature is that the spacing between microphones is small; a characteristic that is hard to produce with condenser microphones. I hope that the comments and questions that follow will clarify some issues and be useful in future work from the authors.

First with regard to some details. It would be of interest to know the von Karman constant, additive constant and wake constant for the velocity profiles. Likewise, how was the noise level on Fig. 5 determined?

It is always a problem to identify and account for acoustic noise and free stream oscillations in any facility. The 13 Hz filter seems low compared to the work of others. Is there any more information about these extraneous sources of pressure? The glider work of Panton et al. (1980) and wind tunnel work of Farabee show a rising spectrum at low frequencies. Theoretically one expects such trends if only turbulent pressure sources exist. The current measurements show a flat spectrum.

The verification of the ω^{-1} region of the spectrum is a most important result. This agrees with unpublished work of Wark et al. (1994) and is consistent with the overlap region found in wavenumber-phase velocity space in the recent paper of Panton and Robert (1994). It is not surprising that the extent of the region is small. With data from Panton and Robert (1994) and an assumption that the beginning of the viscous region is $k^+ = 0.1$, one can estimate that the Reynolds number must be $\mathrm{Re}_\tau = u_\tau\delta/\nu = 2400$ for a half of a decade of ω^{-1} to exist.

I am in disagreement with the form of the outer scaling (attributed to Keith et al. (1992)) used in Fig. 6. The ω^{-1} region is an overlap region between inner and outer scaling laws of very specific forms. Consider the inner or viscous dominated portion of the frequency spectrum at the high end. In inner variables the overlap region is

$$\frac{\phi(\omega)}{\rho^2 u_\tau^2 \nu} = C\,\frac{u_\tau^2}{\omega\nu}$$

where C is a constant. There is not any controversy about these variables. Obviously neither ν nor δ are important in this equation and $(\phi(\omega)/\rho^2 u^{*4}/\omega) = C$. If one transform the equation to proper outer variables (Panton and Linebarger (1974), Fig 15) the same form must arise

$$\frac{\phi(\omega)}{\rho^2 u_\tau^3 \delta} = C\,\frac{u_\tau}{\omega\delta}$$

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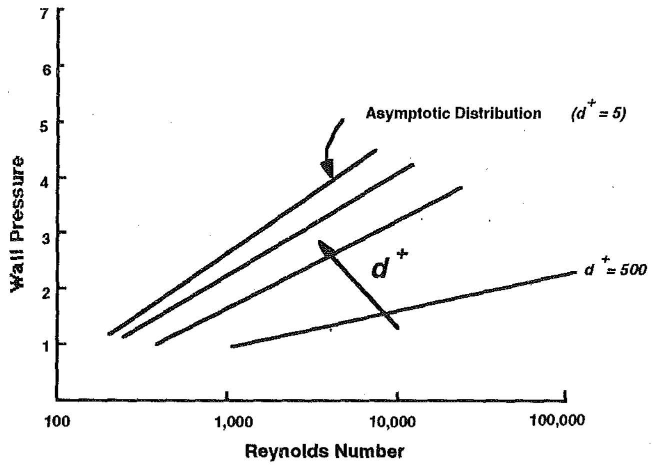

Figure 12 Schematic interpretation of Fig. 4.

The outer length scale is arbitrary; it could be δ^*, or Θ, but u_τ is required. However, if one uses the variables of Fig. 6

$$\frac{\phi(\omega)}{\rho^2 U_\infty^3 \delta^*} = C\left(\frac{u_\tau}{U_\infty}\right)^4 \frac{U_\infty}{\omega\delta^*}$$

Now the new "constant" is a function of Reynolds number; in conflict with the philosophy of the overlap derivation. The physical reason that u^* appears as the important parameter is that the intensity of turbulent fluctuations, which are responsible for the pressure, scale with u^* and not with U_∞. The dynamic pressure $\frac{1}{2}\rho U_\infty^2$ is not important in turbulent boundary layer theory but is associated with the shape of a body or wind tunnel.

If the wavenumber-phase velocity approach of Panton and Robert (1994) yields a correlation relatively independent of Reynolds number, then the frequency spectra will always show a Re dependence in the low frequencies but will still have the ω^{-1} overlap region. These facts were given in unpublished results of Panton (1994).

Comparing convection velocities to U_∞ is only a first approximation and one should expect a Reynolds number effect. The velocities in a boundary layer scale as a defect law $(u - U_\infty)/u_\tau$ in the outer region and u/u_τ in the inner region. In both cases u^* is the proper scale and U_∞ is only a reference in the outer layer.

One result of the paper which is surprising is Fig. 8 for the correlation coefficient as a function of time delay. Previous work of Bull (1967), Willmarth (1962), and Panton et al. (1980) show a far region where R_{pp} is negative. Figure 8 indicates only positive values. Is there an explanation for this?

I surmise from the article that the authors regard the use of pinhole microphones as an open question. Side by side tests of both magnitude and phase response of both pinhole and flush microphones would be of interest to settle this question.

Our knowledge of the viscous dominated region of wavenumber-phase velocity space is very poor. Perhaps an array of transducers such as used in the subject article will provide such information in the future.

Additional References

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C. Wark, S. Gravante, A. Naguib, and H. Nagib (1994) "Inverse-Power Law in Wall-Pressure Spectra Beneath a Turbulent Boundary Layer," *Bulletin of the Am. Phy. Soc.,* Vol. 39, no. 9, p. 1867.

W. L. Keith.[5] The authors have presented a thorough experimental investigation and supporting discussion of turbulent wall pressure fluctuations measured with small silicon pressure transducers. The measurements and analysis presented are very encouraging with regard to the general effectiveness of these new sensors. A significant result is that sensors of $d^+ = 7.2$ produce higher spectral levels than sensors of $d^+ = 21.6$, at the higher frequencies. This result re-opens the question as to the smallest sensor required to adequately resolve the smallest scale pressure producing turbulent structures. The authors compare the contributions to the rms from different portions of the boundary layer with the results of Farabee and Casarella (1991, Phys. Fluids A), in Table 3. Although one would expect a greater contribution from the high frequency region for this investigation, such was not the case. Rather, significantly greater contributions come from the mid and overlap regions, with a smaller contribution from the high frequency region. The spectra compared in Figure 7 show the levels of the present investigation at high frequencies are lower than those of Schewe (1983, JFM) and Farabee and Casarella, which is somewhat unexpected. It is suggested that these differences may reflect the response of the various sensors to the high wavenumbers. Although acoustic calibrations are the most commonly used method, a wavenumber-frequency calibration is actually required. The technology for such a calibration is not available at the present time. An inherent uncertainty therefore exists in all wall pressure measurements due to this effect. Perhaps modeling the response of the small silicon sensors to high wavenumbers and frequencies would be useful. However, such modeling should also be pursued for the sensors of Farabee and Casarella and Schewe, for completeness in the comparison. In conclusion, the authors are to be congratulated on their work, which will undoubtedly lead to further efforts in this area.

T. M. Farabee[6] and M. J. Casarella.[7] The authors are to be commended for providing an interesting and timely study of the application of micromachined pressure sensors for turbulent wall pressure measurements. It is quite encouraging that the authors were able to examine wall pressure fluctuations with such small sensors without suffering from electrical noise floor limitations at higher frequencies. Further studies using these sensors may provide data otherwise unobtainable with current techniques.

There are, however, two issues that should be carefully considered for any future studies. The first issue deals with the characteristics of the flow field. Both background noise and overall flow quality must be well understood for wall pressure measurements. Although the authors mention these subjects no detailed information is provided. Of particular concern is the fact that the measured wall pressures, as displayed in Fig. 6 for example, exhibit the highest low frequency levels for any of the spectra that are shown and there is no observable peak in the mid-frequency range. Such trends are often the result of background noise contamination, or the characteristics of a non-equilibrium flow. The second issue is related to the interpretation of the results presented in Fig. 7. It is reported that the high frequency data, when non-dimensionalized using inner variables, are lower than those of (for example) Farabee and

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