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FINAL REPORT

U. S. Office of Naval Research

Contract N00015-75-C-0335

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TURBULENT PRESSURE FLUCTUATIONS
IN BOUNDARY LAYERS*

Principal Investigator:

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FROM: Frank M. White
Principal Investigator
ONR Contract N00015-75-C-0335

Enclosed are copies of the final report on the subject contract. A complete bibliography of all relevant publications and reports is included.

I would like to take this opportunity to thank the Office of Naval Research for its support of these studies.

Sincerely,

Frank M. White

Frank M. White
Professor of Mechanical Engineering
and Ocean Engineering

FMW/cmw
Enclosures

FINAL REPORT

U. S. Office of Naval Research
Contract N00015-75-C-0335^{new}

"TURBULENT PRESSURE FLUCTUATIONS
IN BOUNDARY LAYERS"

Principal Investigator:

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March 1978

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FINAL REPORT

Contract N00015-75-C-0335

Throughout the duration of this contract the basic thrust has been to develop theoretical analyses for prediction of turbulent wall pressure fluctuations in the presence of various flow properties and system parameters. Whenever possible these analyses were supplemented by experimental investigations performed as M.S. theses and Ph.D. dissertations by students at the University of Rhode Island. Certain theses also pursued details of the theoretical investigations. The resulting 35 published articles and reports, listed at the end of this final report, have hopefully provided a comprehensive view of the analysis and interpretation of turbulent wall pressure fluctuations.

Early theoretical studies were made by the principal investigator in work sponsored by the U.S. Navy Underwater Systems Center in New London, Connecticut (Refs. 1-3). These reports laid the groundwork for relating the rather complex statistics of pressure fluctuations to flow properties more amenable to analysis, such as mean external velocity and pressure, boundary layer displacement and momentum thickness, and normal velocity fluctuations near the wall. By making assumptions about the equilibrium range of turbulent fluctuations, a quantitative theory could be developed which predicted not only the mean wall pressure fluctuations but also

their power spectra, autocorrelations, cross correlations, and convection speeds. Reference 1 laid the groundwork with pipe and flat plate correlations, while Ref. 2 investigated compliant boundary effects and Ref. 3 studied high polymer additives.

The first widely distributed publication from the project was Ref. 4, on the friction resistance of flow in the presence of high polymer additives. It was shown that the Toms effect of polymer friction reduction, while substantial over a wide range of Reynolds numbers and concentrations, was in fact limited to a certain range of body sizes and speeds. This article developed the first tentative analyses of skin friction on moving bodies immersed in polymer solutions. The theory was improved and generalized and subsequently published in Ref. 9. Even at the present, work in the field on polymer additives continues to be of intense interest.

It was realized early that wall pressure fluctuations were strong functions of hydrodynamic flow parameters such as body shape, pressure gradient, wall roughness, and free-stream temperature. Thus a comprehensive study was begun of the analysis of turbulent boundary layers under widely varying flow conditions. Early results on the empirical content of turbulent theories, such as the law-of-the-wall and the eddy viscosity, were given in Refs. 5 and 8. Subsequently a general review of turbulent analyses was given in Ref. 13.

The first experimental effort related to the project was the Ph.D. dissertation of McNally (Ref. 6), which studied the

effect of polymer solutions on wall heat transfer. It was found that the Reynolds analogy for newtonian fluids, in which the wall heat flux is proportional to wall shear, had to be modified. The reduction in wall heat flux due to the polymer solution was not nearly so large as the reduction in wall shear. This result was also verified analytically by combining an eddy conductivity assumption with the known thickening of the viscous sublayer due to the additive. Extensions and improvements to these results were subsequently published as Ref. 10.

An analysis of the effect of a polymer solution on wall pressure fluctuations was given in Ref. 7. It was shown that the polymer reduces the high frequency content of wall pressure but increases the low frequency part of the spectrum. This is especially true very near the wall in the velocity fluctuations. The net effect is that no significant noise reduction is achieved even though the wall shear drops greatly, because there is a substantial increase in the ratio of wall pressure to wall shear. Further extensions and improvements to this theory were given in Ref. 14.

A generalized theory of flow noise in a turbulent boundary layer was published as Ref. 14, which presented the first analysis of pressure gradient effects. It had been conjectured that a region of adverse pressure gradient, where the wall shear is low, might result in decreased flow noise. But the analysis showed that the strong increases in boundary layer thickness and normal velocity fluctuations associated with adverse gradients more than offset the wall shear reductions.

In a similar manner no especially beneficial effects were found in regions of favorable pressure gradient. The sole mitigating circumstance is that favorable gradients delay transition to turbulence, so that noise reduction is possible on the windward side of a moving body, as was well known previously. Otherwise the theory, and limited experimental results at NUSC, seemed to rule out pressure gradient as an effective noise reducer.

The generalized study of empirical turbulence theory led to an entirely new method for analysis of the turbulent boundary layer with arbitrary pressure gradient, published as Ref. 11. Further details and additional examples of this analysis were given in an M.S. thesis by Randall (Ref. 12). It turned out that this theory was extremely controversial, since it virtually ignored almost all of the traditional approaches to boundary layer analysis. Yet the method was unusually simple in application and could even be utilized by students in class exercises, previously an impossible assignment with existing techniques. Consequently, in spite of peer pressure to reject this work, its acceptance by industry and working designers eventually led to a publication of an improved version of the theory in Ref. 15. It has since become a widely accepted, though definitely non-traditional, method of turbulent boundary layer analysis.

The advent of acoustic designs incorporating very long towed cylinders led to a study of the properties of axisymmetric turbulent flow past long bodies of revolution. Early

work on external long cylinder flow was published by NUSC (Ref. 16), and a subsequent extension and revision appeared as Ref. 17. This work utilized the generalized theory of Ref. 15 and was again controversial, but eventually accepted. An extension of the theory to extremely thick boundary layers on arbitrary bodies of revolution was given in Ref. 25. The method is now commonly used in preliminary design of bodies of revolution such as torpedoes and missiles, its chief attraction being reasonable accuracy combined with simplicity.

Renewed interest in the effect of heat transfer and wall temperature changes on the properties of turbulent boundary layers led to an M.S. thesis by Christoph (Ref. 18). This thesis was extended, improved, and generalized and published as Ref. 19, which presented the simplest and still the most accurate method of analysis of flows with arbitrary compressibility, wall temperature, and heat transfer. This paper was awarded the 1973 Lewis F. Moody Award of the American Society of Mechanical Engineers, for research in fluid mechanics.

A further article allowing one to compute turbulent heat transfer in the presence of arbitrary wall temperature conditions was published as Ref. 26.

One of the most difficult tasks of turbulent theory is to predict the effect of wall roughness on shear and pressure fluctuations. Consequently an experimental study was undertaken in an M.S. thesis by Kobayashi (Ref. 20). It was found that, for pipe flow at low turbulent Reynolds numbers of the order of 20,000-50,000, a substantial reduction in wall shear

was achieved by polymer solutions flowing past rough walls. However, as the Reynolds number increased beyond 100,000, the reduction lessened and was essentially negligible as Re increased beyond one million. The effect of roughness in all cases, with or without polymer solutions, was to greatly increase the wall pressure fluctuations.

A theoretical analysis of roughness and other effects was given in Ref. 21, using the methods of Ref. 15 as a basis. A new effect considered here was that of fluid suction or injection through a porous wall. The method allows for arbitrary distributions of wall suction or injection, in addition to arbitrary roughness.

An important parameter in turbulent wall pressure fluctuations is the response characteristic of the transducer material. This was investigated in a Ph.D. dissertation by Randall (Ref. 22), who developed a method of computing the actual measured statistical properties of flow noise for arbitrary transducer response characteristics. Extensions and improvements to this work were published as Ref. 24.

The success of the initial theories of the turbulent boundary layer led to a study of three-dimensional effects. The first result was an extremely simple yet effective theory for the three-dimensional flow on a rotating disk (Ref. 23). Similar results were reported as a portion of Ref. 21. All of these techniques developed up to that time were then reported in a book by the principal investigator (Ref. 27). The rotating disk theory was then extended into a generalized analysis of

three-dimensional shear flow in the Ph.D. dissertation of Christoph (Ref. 28). Severe algebraic complications which arose in that theory were later eliminated and a revised theory published as Ref. 30. The method of Ref. 30 is the simplest technique available for three-dimensional turbulent boundary layers, yet it is capable of predicting the entire three-dimensional separation zone on a bluff body.

The final version of the three-dimensional method of Ref. 30 was then tested against other techniques in a competition held in Trondheim, Norway and sponsored by NATO (Ref. 33). It was found again that the method is the simplest by far of all existing theories yet of comparable accuracy to any other method, for a wide variety of three-dimensional flows. The ability of the method to predict arbitrary separation zones exceeded the capability of most methods tested at Trondheim, which become numerically unstable as separation is approached. The present method has no known separation instability.

Experimental work on the vibration, flow noise, and wall shear of a three-dimensional cylinder rotating in polymer solutions was reported in the Ph.D. dissertation of Brady (ref. 29). The cylinder was rotated at surface speeds from 7.5 to 94 ft/s, in fresh water and in Polyhall 295 solutions at 5, 30, and 60 ppm. Significant degradation of the polymer solutions occurred at all concentration levels and especially at high speeds (high shear rates). The reduction of wall shear due to the polymer was found to be consistent with other drag

reduction measurements, being up to 60% for a fresh solution of 30 ppm. The wall pressure spectra increased 24 dB for each doubling of speed, and the polymer caused slight but significant noise reductions in the high frequency region above 5 kHz. The non-dimensional wall pressure spectra actually increased due to the polymer but the mean level decreased slightly due to the reduction in wall shear. The vibration levels of the cylindrical shell were essentially independent of frequency, a characteristic of wall pressure induced effects. A limited amount of internal microphone data indicated an increase in level of about 8 dB for each doubling of speed. Far field noise behaved in the same manner as wall pressure, 24 dB increase per speed doubling, and was significantly decreased by the presence of the polymer solution. In fact the primary effect of the polymer seems to be a reduction in far field radiated noise.

A second experimental study of the effect of polymer solutions on flow past axisymmetric bodies was performed in the Ph.D. dissertation of Sirmalis (Ref. 31). The model bodies were studied both in well mixed polymer solutions and with polymer injection through the body walls. Experiments in the well mixed solutions gave wall shear reduction of up to 70% for concentrations of 20 ppm of Polyox WSR-301 polymer. The polymer injection measurements utilized both a nose-screen orifice and injection near the point of minimum pressure. Boundary layer velocity and concentration samples were taken along the body, along with dye studies of the diffusion in

the shear layer and wake. It was found that best results occurred when the polymer was injected into a laminar layer upstream of transition. The diffusion and wall shear results were compared with an analysis for arbitrary injection developed from the previous work such as Ref. 25. The dye studies indicated that the polymer effectively eliminated the high-frequency or small-scale content of the boundary layer and wake structure, which is consistent with flow measurements.

The possibility of applying the present theories to a turbulent boundary layer such as salt water, which can be affected by weak electromagnetic effects, was studied in an M.S. thesis by Sayles (Ref. 32). The results showed substantial changes in wall shear and other boundary layer parameters due to magnetohydrodynamic forces, but the field power levels required are significant.

An experimental investigation of flow noise on a long, fluid-filled, towed cylinder was performed in the Ph.D. dissertation by Markowitz (Ref. 34). The cylinders were towed at speeds from 3 to 18 knots and surface and internal noise spectra were measured. The dominant noise mechanisms were found to be longitudinal waves travelling through the flexible cylinder structure. At frequencies below 150 Hz the dominant contribution was a bulge wave travelling at about 300 ft/s, while higher frequencies were dominated by two types of extensional waves travelling at about 2500 ft/s. The existence and cross-over frequency of these two types of waves was in excellent agreement with theory. The specific mechanism generating these

waves was found to be end shell vibration, especially at the aft end. The surface flow noise data indicated much greater noise at the aft end, where the turbulent boundary layer is suspected of sweeping off due to lateral cylinder motions. Measured wall accelerations correlated well with these wall pressure fluctuations. The correlation lengths of the wall pressure were short, less than the distance between sensors. From the data obtained, wall pressure p^2 was approximately proportional to frequency f^{-2} over a wide range of the spectrum.

Finally, an important missing link in the theory was recently supplied by Lessmann (Ref. 35), who developed a striking new method of analysis of the transition range between laminar and turbulent boundary layer flows. Lessmann's technique results in a differential equation for the turbulent intermittency function in the transition region, which increases from zero in laminar flow to unity in fully turbulent flow. The results are then correlated with intermittent boundary layer profiles to provide accurate estimates of flow parameters throughout the transition range. Agreement with experiment is excellent, so that the method provides a significant advance which patches together, in an easily applied method, the existing laminar and turbulent theories. Thus, for the first time, we are capable of describing a complete theory which treats all relevant regimes of boundary layer flow, including the relaminarization phenomenon by which a turbulent flow reverts to a non-turbulent or laminar flow.

In conclusion, the principal investigator would like to express sincere appreciation to the Office of Naval Research, whose financial support made these studies possible.

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