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Mark V. Morkovin

ILLINOIS INSTITUTE OF TECHNOLOGY
Chicago, Illinois 60616

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Langley Research Center
Hampton, Virginia 23665

OBSERVATIONS ON STREAMWISE VORTICES IN LAMINAR AND TURBULENT BOUNDARY LAYERS

By Mark V. Morkovin
Mechanics, Mechanical and Aerospace Engineering
Illinois Institute of Technology

SUMMARY

Attention is called to the frequent but often unsuspected presence of streamwise vortices in nominally two-dimensional laminar and turbulent boundary layers and some of their consequences are mentioned. Since there is no body of systematic information on streamwise vortices imbedded in boundary layers a number of issues concerning their genesis and behavior are discussed in the form of a set of succinct observations. Recommendations are made on desirable experimental and numerical research to remedy the current lack of knowledge.

INTRODUCTION

The present set of observations on the occurence and behavior of steady or quasi-steady streamwise vortices in boundary layers distills lessons learned by the author from a study of much boundary-layer literature. Often these vortices were not the intended target of the papers and their appearance interfered with the original objectives. As such their study has been seldom sufficiently systematic to yield a body of knowledge that could be called definite. Very few generic or positive statements could be gleaned from these studies. Therefore, instead of citing the individual papers with comments on their deficiencies, these observations, after brief descriptions, focus on what could be done to remove much of the uncertainty.

OBSERVATIONS

1. When nominally two-dimensional laminar or turbulent boundary layers at higher Reynolds numbers are probed in the spanwise direction z, invariably variations of their properties at fixed normal distance y_o from the wall are found. Thus the mean streamwise velocity $U(x_o, y_o, z)$ and the boundary-layer thickness $\delta(x_o, z)$ often exhibit irregular plus-minus variations in excess of 20% which are indicative of mean streamwise vorticity (ω_x) structures with spanwise scales on the order of 2δ to 3δ. In zero and adverse pressure gradients these structures can apparently maintain themselves over distances of 50-100 or more boundary layer thicknesses.

2. For laminar shear layers the major practical consequence is an earlier transition to turbulence. In turbulent layers the practical impact may be of special importance where heat and mass transfer is present (reentry heating, erosion, etc.). Not insignificant is the possiblity that in any given test the information from the customary traverses at a single z location may be misleading.

3. In view of (2) and the absence of awareness of the phenomena in texts and class rooms, it is suggested that at least limited spanwise traversing be generally encouraged especially under research contracts. Furthermore, it is recommended that a premium be placed on further development of techniques for reliable measurement of v and w velocity components and of streamwise vorticity <u>inside</u> boundary layers (high spatial resolution, minimum flow interference).

4. Whatever the cause of the vorticity (see (9)), its observed persistence in x over distances of 100δ and more in turbulent boundary layers goes counter engineering concepts of high turbulent diffusivity and randomness. Also, these concepts would allow for randomized streamwise vorticity but <u>not</u> for its <u>preferential spanwise locations</u> persistent in time. Recent ideas of the large-scale structures in turbulent boundary layers may be more readily reconcilable with the observations, especially if we understood the role and the probability distributions in x and z of the "bursts". (Can these probabilities be conditioned in z by upstream conditions?)

5. Thus far the studies of turbulent layers with streamwise vorticity (in absence of concave curvature) have been more or less accidental and the generated information is not of the quality that would permit general or unifying conceptual observations other than that the behavior described under (1) is probably very common and generally undetected. It is therefore recommended that careful and detailed research of the behavior of the turbulent structures be undertaken for a number of cases of "controlled"

streamwise vorticity. Specifically desirable are "modern" studies of (a) developments downstream of a symmetric protuberance and an asymmetric small vortex generator placed within a turbulent layer and (b) developments within two turbulent wedges generated early in a laminar layer with special attention to conditions all along the lines through the apices of the wedges and the line half way between the apices. The latter experiment generalizes studies of interactions between turbulent spots and also tests some aspects of the possible long-distance dependence of the phenomena on the nonuniform character of the transition region. Here, tools described under (3) would be helpful.

6. A sobering negative conclusion concerning our theoretical capabilities for describing realistically vortical fields within laminar boundary layers was reached in conjunction with the studies of Drs. Ray Sedney and C. W. Kitchens of Aberdeen Proving Grounds. Their attempts to compute numerically the observed evolution of the mid- and far-wake of a small protuberance in a laminar layer, together with various other considerations, lead one to believe that the phenomenon is not reachable within even second-order boundary-layer formulation. An adequate formulation apparently must involve the normal pressure gradient, $\partial p/\partial y$. Presumably the same will be true for turbulent boundary layers. Without theoretical underpinning, interpretation of experiments is a risky proposition, see first statement under (5) and (4).

7. It is recommended therefore that systematic numerical studies be undertaken for laminar boundary layers first to substantiate or disprove the tentative conclusions in (6). A concerted effort to establish an adequate theoretical-numerical basis for the description of streamwise vortical behavior in boundary layers would then be the next important step. Since understanding of laminar boundary layers often aids in interpretation of turbulent layers, the availability of reliable numerical solutions for several classes of problems with streamwise vorticity would be of general utility. (Coupling with a thermal field for heat-transfer research could well be considered at the outset.)

8. The reliable experimental data-base for checking of such numerical studies is meager, consisting primarily of the study by Tani, Komoda, Komatsu and Iuchi (pages 133-13 of Rept. No. 375, Nov. 1962, Aeron. Res. Inst. Univ. Tokyo). It is therefore recommended that careful experiments of type (a) in Section (5) be undertaken for laminar boundary layers in a neutral and a favorable pressure gradient. The flow in the immediate vicinity of the protuberances is too complex to serve as a touchstone for numerical studies. It is rather the less disturbed more generic conditions 20k to 200-400k downstream (where k is the protuberance height) which are of interest. The extra detailed measurements of y, z distributions of all velocity components (and their possible regular time variations) would serve as initial conditions for the numerical studies.

9. When one considers the genesis of mean streamwise vorticity in turbulent boundary layers without protuberances it is clear from the scattered experimental evidence that one has to look first upstream to spanwise inhomogeneity of the transition region, to three-dimensional aspects of the secondary instability and breakdown, and to the causes of mean three-dimensionality in the parent laminar layer. The irregular plus-minus spanwise variations in streamwise vorticity in the upstream laminar layers can come from: (a) vorticity in the oncoming stream, distorted and transformed by the straining field near the leading edge of the body and (b) the local pressure gradients, $\partial p/\partial z$, associated with small spanwise unevenness of geometry especially at leading edges with sharp curvature and high $\partial p/\partial x$. (Source strength per unit area of streamwise ω_x vorticity production at the wall is shown to be proportional to $\partial p/\partial z$ when no-slip boundary conditions are applied to the z-momentum equation in the Navier-Stokes formulation.) The vorticity in the oncoming stream depends on the upstream history of shear layers which can move into the stream from the walls through secondary flows or are formed at solid boundaries of inserts (coolers, fan blades, central hub, honeycombs, screens, etc.). Unless an insert (grid or screen) is located just upstream of the leading edge, the vorticity will be that associated with the later, decaying stages of quasi-homogeneous turbulence, which tends to return to initial larger-scale anisotropy and is also characterized by intermittent smaller scale activity. Obviously, there is an enormous variety of possible three-dimensional spectra of the oncoming flow. Furthermore, one can infer from some experiments that freestream vorticity components can be convected above the boundary layer and still induce ω_x contributions within the boundary layer.

10. One of the shortcomings of the published studies lies in insufficient or completely absent characterization of the causative conditions described under (9), especially the free-stream conditions and the three-dimensional transition characteristics. Since there is evidence of sensitivity of the magnitude of the subject streamwise vorticity to the nature of the last screen or grid (including seems in the screen which appear innocuous) little progress will be made unless: (a) this very difficult characterization is undertaken, preferably through two-probe space-time correlations, in basic experiments or (b) one minimizes and overrides the upstream influences through the type of controlled experiments described under (5). It should be clear that one thereby shifts the attention from the extremely complex interactions of poorly detectable, relatively small disturbances (which are evidently enhanced by elusive instability mechanisms) to the more controllable direct study of basic turbulent boundary-layer properties in presence of streamwise vorticity.

11. In an attempt to clarify some aspects of the generation of streamwise vorticity in proximity of a circular leading edge

through local distortion and probably algebraic amplification of oncoming vorticity, a critical survey of theory and experiment for geometries with symmetric stagnation regions was undertaken. This study by M. V. Morkovin, "On the Question of Instability of Vorticity Fields Near Cylindrical Stagnation Lines" constitutes a self-contained companion NASA report. It illustrates indeed how complex the interactions appear to be even for this simplified local geometry and how inadequate is our modeling of the phenomena. There is evidence that a related enhancement of streamwise vorticity takes place for both laminar and turbulent boundary layers near the reattachment lines (stagnation lines) after local subsonic or supersonic separation. This enhancement may be stronger due to the curvature of the separated layers as under (12) below.

12. Two mechanisms of streamwise vorticity generation probably depend to a lesser extent on the upstream conditions than that of Section (11) because they involve genuine instabilities with initially exponential amplification of miniscule preexistant streamwise vorticity within boundary layers. In case of concave curvature of mean streamlines in the boundary layer, patterns of the preexistant streamwise vorticity are filtered and amplified in the x direction into so-called Görtler vortices with spanwise wavelenths roughly proportional to the layer thickness in both laminar and turbulent layers. A critical survey of our theoretical and experimental knowledge of the onset of laminar Görtler vortices and of associated secondary instabilities which ultimately lead to turbulence will be found in Morkovin's forthcoming monograph on laminar-turbulent transition. A discussion of the unsettled theoretical points for laminar layers with latest numerical results will be presented by J. M. Floryan and W. S. Saric at the AIAA 12th Fluid and Plasma Dynamics Conference in July 1979.

In boundary layers which are turbulent upstream of the start of the concave curvature, a yet unanswered question, similar to that in (4), arises: should there be a persistent spanwise location of the mean streamwise vorticity or should one expect the random features of the turbulence to average out the vorticity and render it z - independent in the time-mean?. P. Bradshaw's 1973 AGARDograph No. 169: "Effects of Streamline Curvature on Turbulent Flows" provides us with unsurpassed theoretical and experimental information in depth and breadth on the consequences of enhanced (or diminished) streamwise vorticity in presence of concave (or convex) curvature.

13. Another instability mechanism causing growth of essentially streamwise vortices within laminar boundary layers has been observed on swept back wings and rotating disks. In contrast to the previous cases where the vorticity in the basic unperturbed boundary layer was perpendicular to the streamlines the base flow here is intrinsically three-dimensional. Consequently the perturbed vorticity interaction is exceedingly complex and is not yet satisfactorily characterized even in its linearized formulation*.

* For latest progress see A. H. Nayfeh: Stability .. Three-Dimensional Boundary layers, AIAA Paper NO79-0262.

Evidence from a number of flow visualizations (buttressed by computations based on a simplified theory due to Stuart) suggests that essentially streamwise vortices grow at first exponentially and reach a nonlinear stage with subsequent slow growth over considerable distances. The vortex patterns then undergo transition to turbulence rather rapidly due to some secondary instability.

This so-called cross-flow instability leads to vortices predominantly of one sign, whereas the streamwise vortices arising in nominally two-dimensional boundary layers alternate in sign. It is not clear whether such one sided vortices are found in fully turbulent layers, as Görtler vortices in turbulent boundary layers on concave walls are found.

14. Visualization techniques reveal only perturbations of sufficiently large amplitudes. Since fluctuation amplitudes in excess of 2% of the driving reference velocity invariably cease to follow the linearized equations, the visual evidence generally describes only the nonlinear stages of the process. Generally then the growth characteristics of the visually observed patterns differ significantly from those indicated by linear theory (and most prediction techniques) whereas the frequencies or wave lengths appear to be nearly preserved in the nonlinear stage.

On rotating disks visualization suggests the existence of essentially helical vortices, stationary in space. It is possible that nonlinearity may fix vorticity patterns that linear theory might indicate should be slowly shifting in time. It seems that these laminar vortices or the subsequent large-scale coherent turbulent formations can excite resonant vibrations of industrial buzz saws as well as contribute to objectionable noise levels.

15. Observations (11) to (13) dealt with the instability subset of mechanisms which could lead to streamwise vorticity patterns in turbulent boundary layers. The experiments recommended in Section (5) and (8) on the nature and evolution of forced or driven streamwise vortices in boundary layers can be supplemented by experiments on these instabilities and subsequent transition to turbulence. Such experiments should document important details of the instability mechanisms and require adequate familiarity with the underlying theory. The rapid growth of accidental or deliberate perturbations associated with the nature of instability phenomena makes these experiments extra difficult and extra challenging.