SUPPRESSION OF WALL TURBULENCE USING A COMPLIANT SURFACE, BASED ON STABILITY AND TURBULENCE ANALYSIS

By

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To my wife and my teachers

CERTIFICATE

This is to certify that the thesis entitled **"Suppression of Wall Turbulence, by Stability and Turbulence Analysis, using a Compliant Surface"** being submitted by **Mr. P. S. Josan** for the award of the degree of Doctor of Philosophy, to the **Indian Institute of Technology, Delhi** is a record of bonafide work carried out by him under our guidance and supervision. The material embodied in this thesis, unless acknowledged otherwise, has not been submitted in part or in full for any other Diploma or Degree of any University.

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ABSTRACT

The present work discusses the problem of wall turbulence, based on the Sen-Veeravalli model, and its possible suppression by using compliant surfaces. Two types of wall models, based on Carpenter and Garrad (1985, 1986) and Sen and Arora (1988) are used. In the Sen-Arora model, a kinematic postulation of the wall boundary conditions is made. This model is used in the present work more in a generic sense that is from the standpoint of physical realisability of modes. The inverse method, as Sen and Arora method is also called, is used both for selecting the parameters for the stabilisation of the flow, and also for investigating physical realisability of the predicted modes. Based on the results using the kinematic postulation of Sen and Arora, the realisable generic material properties of the compliant layer are calculated. Thereafter, the actual material properties are back calculated using the Carpenter and Garrad model.

The outer boundary conditions, as mentioned in Sen and Veeravalli, are modified in the present work to make the calculations more efficient. The outer boundary conditions are applied at a non-dimensional $y/\delta = 0.3$, using a local solution of the Rayleigh equation. The instability analysis in turbulent flow with a compliant wall was carried out both in channel-flow and boundary layer flow mainly for inner modes, and also for some outer modes; though, in the context of the present problem, the effect of outer modes is not pronounced.

The results show that there are two important inner 'mode classes present in the flow': the Tollmien-Schlichting (TS) mode class and the Static Divergence (SD) or Kelvin Helmholtz (KH) mode class. It is the TS mode class, which is believed to be the so-called "root cause mechanism of turbulence", and, suppression of this mode class is desirable if turbulence is to be suppressed. Extensive investigations have been carried out for both the modes. It is observed that for a compliant surface with kinematic compliance $|\bar{\phi}_w| > 70\%$, and with carefully selected material properties, the TS mode class ceases to exist, and bifurcates into a high-speed highly damped (HSHD) stable mode class. Further, for such a surface, the SD modes also do not appear. A sample example to translate the above properties for the selection of an actual compliant wall is also discussed.

An example of a flat plate is considered, whose material properties were calculated using the predictions of the present work. It is believed that with proper selection of material properties, like high equivalent spring constant, damping coefficient and mass, the unstable TS modes will cease to exist and will bifurcate into the high-speed highly damped (HSHD) stable mode class.

Qualitative equivalences are established with respect to the experimental results of Gad-el-Hak et al. (1984) and the theoretical analysis of Yeo, Zhag and Khoo, (2001) with the plate spring model employed in the present work. Good correlation is obtained with the results of Gad-el-Hak et al. (1984), and also with Yeo et al. (2001).

Experiments by Sen and Veeravalli (2000) and Veeravalli and Sen (2004 unpublished) confirm the existence of the theoretically predicted TS wall modes. The plots for u_{rms} are in very good agreement with the experiments.

It is discussed in the first chapter, later herein, that, two-dimensional unstable TS disturbances are the so-called "root cause mechanism of turbulence". It is likely that this statement is true for the Sen-Veeravalli model, but more in a generic sense. In consequence, the following questions, against such a simplistic basis for turbulence, naturally arise: i) If we control two-dimensional disturbances, what happens to three-dimensional disturbances? ii) How are two-dimensional disturbances related to three-dimensional structures? iii) How does the formation of streaks take place? iv) How does transient growth occur? Reviews by Panton (1997) and Schoppa & Hussain (2002) suggest that successive evolution and regeneration processes are going on "in the near wall coherent structure". They also note that transient growth could be responsible for sustaining the regenerating process in the near wall region. All the above views may be reconciled to some extent, as discussed below.

It may be noted that a large class of three-dimensional modes, based on small perturbation theories, are extended forms of the two-dimensional modes with the span-wise periodicity included. As is well known, oblique Orr-Sommerfeld modes are similar to the two-dimensional modes, as may be shown from the existence of Squire, or Squire—like, transformations. In other words three-dimensional modes can also be obtained from extended forms of the Orr-Sommerfeld equation. *Hence, control of so-called two-dimensional TS mode would also result in the control of three-dimensional modes; because, these modes also belong to the TS mode class defined by us.* Moreover, a current theory of Sen and his co-workers under finalisation, seems to suggest that the *confluence of three-dimensional standing-wave span-wise periodic structures could be responsible for transient growth of the span-wise periodic modes*, even if the modes are slightly damped according to linear theory. The paper of Schoppa and Hussain (2002) is also relevant in this context. Thus, if the TS modes are suppressed, transients are also likely to be suppressed.

The study presented herein suggests that eliminating TS modes all together, by bifurcation into the so-called "high-speed highly damped (HSHD) stable mode class", would succeed in the elimination of TS-like 3-D modes as well. This in turn will also succeed in controlling the transient growth processes as well. This would result in suppression of the regeneration processes in the near wall region. It would also result in substantial control of wall turbulence.

The present work does not however look at the longitudinal coherent structures called Klebanoff modes.

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