Interpretation of Separation Lines from Surface Tracers in a Shock-Induced Turbulent Flow

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Abstract

IN experimental studies of shock wave turbulent boundary-layer interactions, surface-tracer methods, which have essentially zero frequency response, are widely used to determine the locations of separation lines. However, recent research has shown that in many cases the separation shockwave structure undergoes large-scale motion, raising questions about the physical meaning of separation lines deduced from such techniques. In the present study at Mach 5, the separation induced by an unswept semi-infinite circular cylinder has been studied using platinum thin films. Conditional sampling analysis of the signals suggests that this line is the downstream boundary of a region of intermittent separation.

Contents

In experimental studies of shock wave turbulent boundary-layer interactions, surface tracer techniques are widely used to locate separation lines.[1] Such methods are easy to use and generate sharply defined, repeatable separation lines (S). Quantitative measurements of flow length scales and angles are made using these methods and are used for evaluating the predictive capabilities of numerical methods and turbulence models. It is, therefore, important to understand what these lines physically represent.

In many of these flows, dynamic wall-pressure measurements show that the separation shock is unsteady and moves from the upstream boundary of the flowfield, where the wall pressure begins to rise from the undisturbed value, to just upstream of S.[2,3] In the context of such unsteadiness, the physical meaning of separation lines obtained using techniques with effectively zero frequency response is brought into question. This is the subject of the present paper. To address this question, the separation induced by an unswept, semi-infinite circular cylinder in a Mach 5 airflow was studied using platinum thin films.[4]

Tests were performed in the University of Texas' Mach 5 blowdown tunnel. All tests were performed on a full-span flat plate, 45.7 cm long, mounted at zero angle of attack. Platinum thin films, fired on a Pyrex substrate and mounted in plexiglass, were installed flush with the upper surface of the plate, approximately 33 cm downstream of the leading edge. An unswept cylinder with a diameter D of 1.59 cm was mounted approximately 38 cm downstream of the leading edge. The cylinder height was 5.08 cm and its position was variable to allow examination of different stations in the disturbed flowfield. A complete description of the films, models, and facility is given in Ref. 4.

At the film location, the test section Mach number was 4.96. The stagnation pressure and temperature were 2.09×10^6 N/m^2 ± 1% and 327 K ± 1% respectively, providing approximately adiabatic wall conditions. The freestream Reynolds number was 55×10^6 m^{-1}. The incoming boundary layer developed naturally and was fully turbulent at the film location. The boundary layer thickness δ was 5.36×10^{-3}m; the displacement thickness δ^* was 2.18×10^{-3}m; the momentum deficit thickness θ was 1.81×10^{-4}m, and the skin friction coefficient C_f was 1.01×10^{-3}. The wakestrength parameter Π was 0.47.

The "mean separation line" location S was determined using a kerosene lampblack technique. Its centerline location was at $X/D = -2.40$, which agrees well with previous work.[2] A single film was connected to a TSI Model 1050 constant temperature anemometer bridge and was operated at an overheat ratio of 0.05. The frequency response of the system, determined using a square-wave test, was approximately 10 kHz. The output of the bridge was amplified and analog filtered at the Nyquist frequency prior to digitization. The signal was sampled at 20 kHz, with select cases sampled at 80 and 500 kHz.

Sample time histories of the film voltage at four stations upstream of S are shown in Fig. 1a. Each station is defined by a value of γ, where γ is the intermittency; γ is the ratio of time the flow is disturbed, to the total time for the data sample. Details of how γ is calculated are given in the complete paper. In the undisturbed turbulent boundary later ($\gamma \approx 0.0$), the probability density distribution of the fluctuation amplitudes is essentially Gaussian (Fig. 1b).

In the intermittent region, the rms of the voltage fluctuations, σ_v, increases rapidly (Fig. 2a). The maximum value occurs close to S and is about $8\sigma_{v_0}$ where σ_{v_0} is the standard deviation for the undisturbed boundary layer. The large-amplitude fluctuations caused by the irregular passage of the shock over the film, and the disturbed flow downstream of the shock, result in skewed probability density distributions (see Fig. 1b, where $\gamma = 0.26$ and 0.53). At S, and at stations further downstream, the signal is no longer intermittent and is again distributed normally (see Fig. 1b, where $\gamma = 1.0$). The power spectral densities have the same shape at these downstream stations, but are slightly displaced along the power axis due to the decreasing σ_v. The lack of intermittency, and the fact that the surface patterns show streaks moving upstream, is strong evidence that the flow downstream of S is separated at all times.

The signal in the intermittent region was analyzed using a conditional sampling algorithm. The algorithm was used for two purposes: first to calculate γ as a function of X/D, and second to examine the statistical properties of the signal upstream and downstream of the shock wave separately. The algorithm examined the signal and split it into two parts: a zone upstream of the shock, and a zone downstream of the shock. A detailed description is given in the complete paper.

The intermittency as a function of X/D is shown in Fig. 2b. The distance over which γ increases from 0 to 1 defines the length scale of the shock motion L_s, and is approximately $0.7D$. Both observations agree with earlier work using pressure tansducers in similar flows.[2]

At each station, the standard deviation in the upstream zone σ_u and in the downstream zone σ_d were calculated (Fig. 2c). For all γ, σ_u is within the range of the undisturbed turbulent boundary layer, and the data comprising the zone have a

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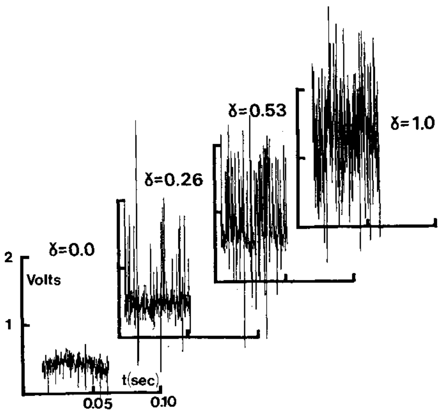

Fig. 1a Sample time histories of film voltage.

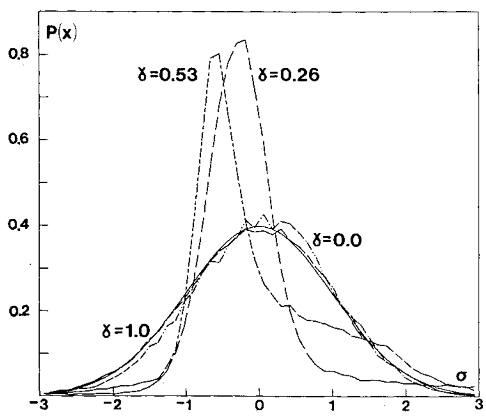

Fig. 1b. Corresponding probability density distributions.

Gaussian probability density distribution. Of greater interest is the observation that σ_d is typically a factor of 4 greater than σ_v, and is approximately constant. Further, σ_d has approximately the same magnitude as σ_v in the separated region downstream of S.

The power spectra of the upstream and downstream zones calculated using DFT algorithm are shown in Fig. 3 for several values of γ. The hatched and solid lines are the power spectra for the undisturbed boundary layer and for the flow downstream of S, respectively, and were calculated using an FFT algorithm on 50 records. For all values of γ, the power spectrum of the upstream zone corresponds closely to that of the undisturbed boundary layer. Similarly, the downstream zone power spectra correspond closely to those for flow downstream of S.

Since the fluctuations in the downstream zone are distributed normally and have the same σ_v and the same power spectrum as the separated flow, the indication is that the downstream zone is separated. Separation occurs across the shock wave and S, which is close to $\gamma = 1$, represents the downstream boundary of a region of intermittent separation.

A relatively simple explanation is available to explain why the surface-tracer material accumulates at this position. The mean wall shear stress, which the tracer responds to, is a time-average of the values of shear stress in the upstream and downstream zones. The upstream zone is supersonic, undisturbed boundary-layer flow, oriented downstream, and its value of wall shear stress is much larger than the downstream zone's value, which is oriented upstream. Hence, even at stations where the flow is separated a large fraction of the total time, the mean shear-stress vector is still oriented in the downstream direction. Thus, γ must be close to unity to generate zero mean wall shear stress, resulting in the formation of the separation line.

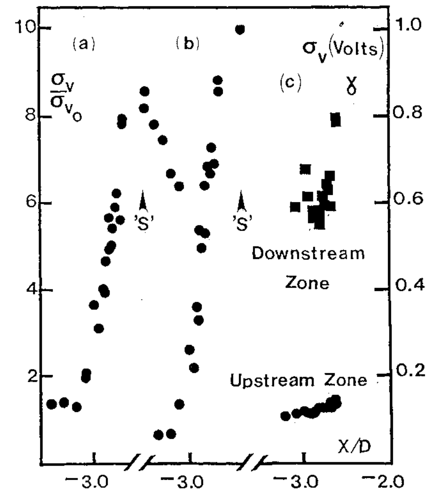

Fig. 2 a) Normalized standard deviation of film voltage in intermittent region; b) streamwise distribution of γ; c) standard deviation in upstream and downstream zones.

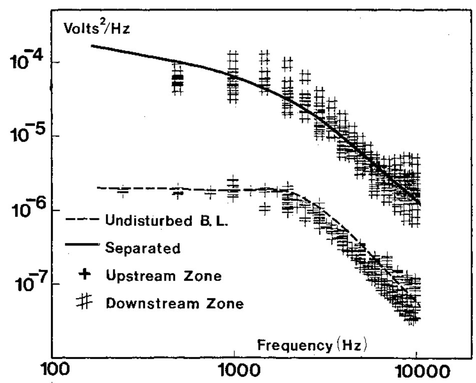

Fig. 3 Power spectra of upstream and downstream zones.

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