Structure of a Reattaching Supersonic Shear Layer

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Abstract

A MACH 1.83 fully developed turbulent boundry layer was separated at a backward step and formed a free-shear layer, which went through a reattachment process. The objective was to explore the existence, frequency content, and coherency of large-scale structures in the shear layer. The results show that large scale and relatively organized structures are formed in the free-shear layer. While passing through the recompression and reattachment processes and interacting with the reattachement shock, the structures do not seem to break up; however, they seem to lose their organization. The structures regain their coherency right after the reattachment.

Content

The level of activities in the area of supersonic shear layers has increased substantially in the past few years because of the renewed interest in airbreathing hypersonic vehicles with supersonic combustion. A better understanding of compressible mixing and the ability to manipulate the mixing process will play an important role in the success of supersonic combustion technology. From experimental research using a simple two-stream configuration, it is known that as the compressibility is increased the gross mixing rate and turbulence fluctuations level are decreased. Also, it is known that there are large-scale structures in the shear layer that are not as organized as their subsonic counterparts and do not seem to go through rolling and pairing processes. Topology, frequency content, and three-dimensionality of these structures have not been investigated and need to be explored. Computational and theoretical work also show the decrease in the shear layer and the instability waves growth rates as the compressibility level is increased.

So far, enhancement techniques have been proven to be ineffective.[1] The objective of this research was twofold: First, to explore the existence and the frequency content of structures in the reattaching shear flow shown schematically in Fig. 1a. Second, if the frequency content was within the reach of the available acoustic drivers, then to explore the possibility of acoustic excitation of the structures. The flowfield we are investigating is more complex than the simple plane shear layer used by many[1]; however, its major advantage is that the incoming turbulent boundary layer becomes laminar in passing through the expansion fan at the step and the formed shear layer is initially laminar and becomes turbulent within a fraction of the step height. It is well known that this type of shear layer is more receptive to excitation than those with an initial turbulent boundary layer. This paper presents the first phase of the effort.

The experiments were conducted in the blowdown supersonic wind-tunnel facility at the Ohio State University Aeronautical and Astronautical Research Laboratory. The tunnel test section measured 76.2 mm high and 152.4 mm wide right before the 25.4-mm high step. The reattachment floor was equipped with a moving centerpiece in which a circular plug containing two fast-response pressure transducers was inserted. The incoming flow was a Mach 1.83 fully developed turbulent boundary layer with the boundary layer and momentum thicknesses of 8 mm and 0.5 mm and the Reynolds number based on the momentum thickness of 2.6×10^4.

A standard schlieren system with 0.5-μs flash duration was used for flow visualizations. Two miniature Kulite pressure transducers with an active diameter of 0.79 mm and frequency response up to approximately 60 kHz were used. A two-component coincident laser Doppler velocimeter system was used for velocity measurements.

Figure 1b shows a schileren photograph of the flowfield. The average reattachment line is located approximately 2.4 step heights from the step. Large-scale structures can be seen from approximately one-half step heights all the way through the reattached shear layer. Right after the average reattachment location, the structures are more pronounced than those in the free-shear layer and do not seem to extend to the wall. However, further downstream the structures extend all the way to the wall and form a 40-45 deg angle with the mean flow direction.

Figure 2 presents the coherence function between two transducers aligned in the streamwise direction with about 9.5 mm separation distance. The x is the distance, in step heights, between the center of the upstream transducer and the step. The coherence was smoothed using averaging over 50 blocks of data. At $x = 1.0$, the coherence peak becomes much sharper and shifts to lower frequency in comparison with a wider peak at $x = 0.5$. This is because of the growth of large-scale structures which results in dropping the frequency and providing a better signature. At $x = 1.5$, where the downstream transducer is in the recompression region, the coherence level drops slightly, and the frequency range becomes wider. At $x = 2.5$, the coherence level has almost diminished. One could say that the passage frequency of large-scale structures becomes increasingly random while they encounter recompression, reattachment, interaction with the reattachment shock wave, and the reorientation process. After reattachment, the coherence

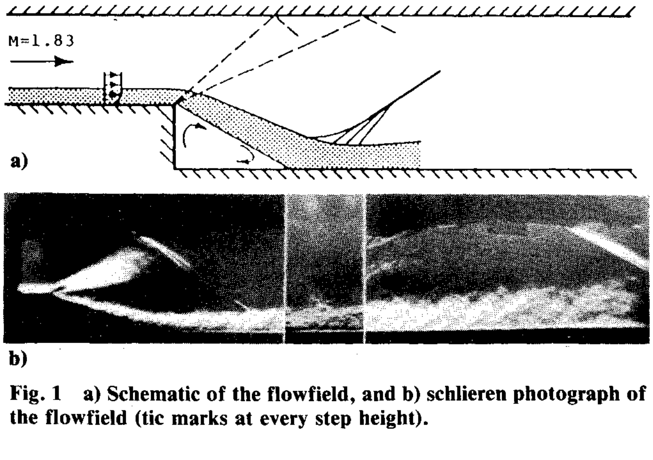

Fig. 1 a) Schematic of the flowfield, and b) schlieren photograph of the flowfield (tic marks at every step height).

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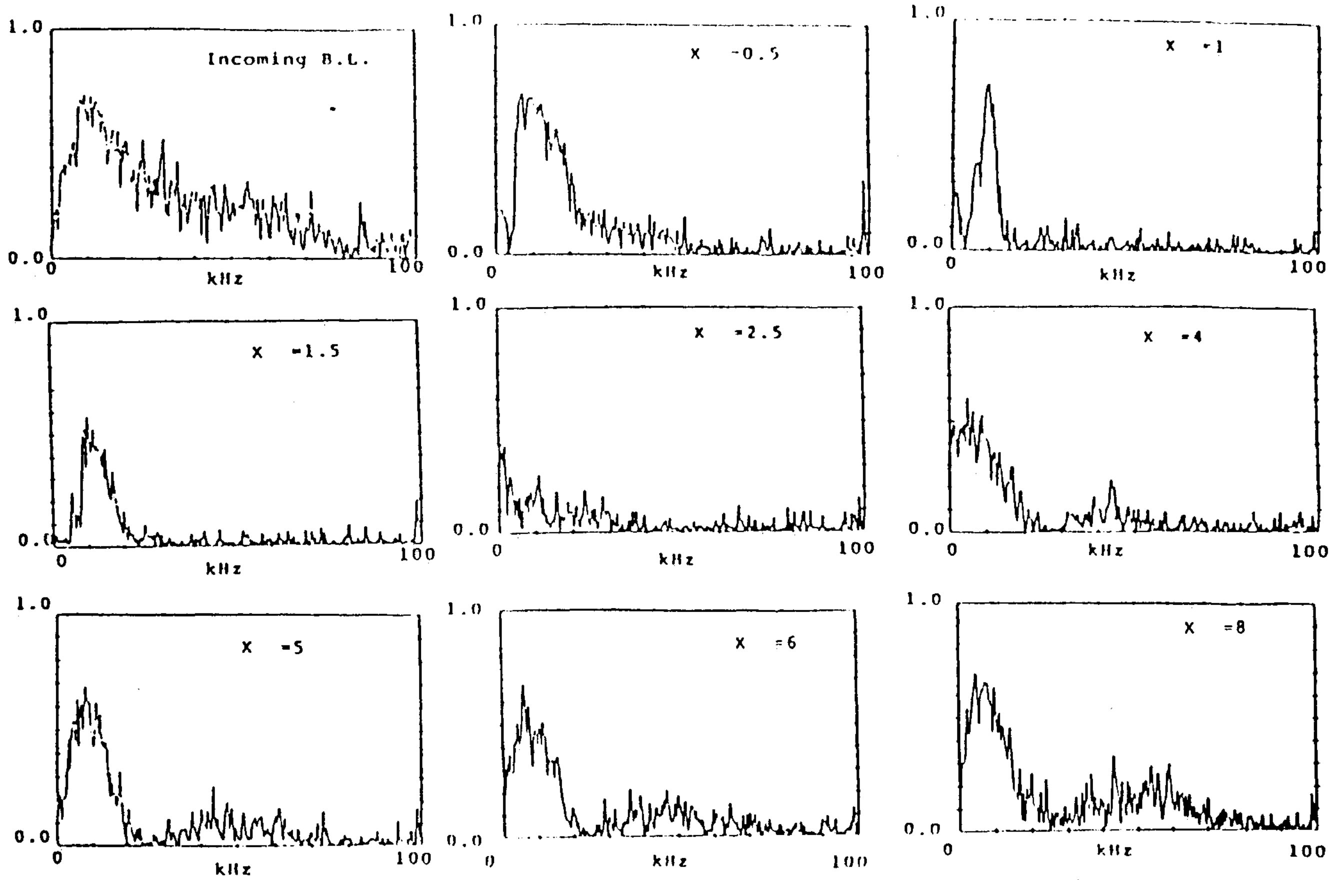

Fig. 2 Coherence function with the transducers aligned in the stream-wise direction.

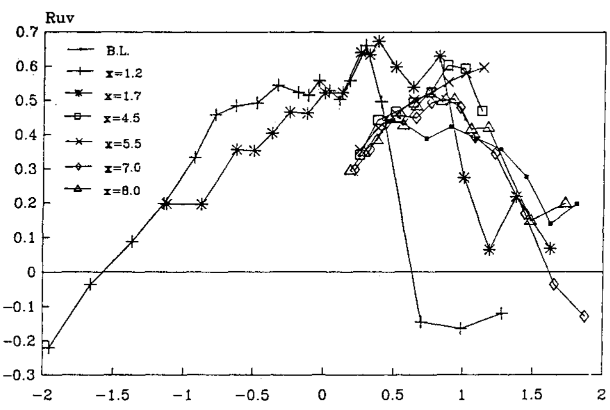

Fig. 3 Velocity correlation coefficient profiles.

level increases rapidly and at $x = 4.0$ peaks at a frequency similar to that in the free-shear layer which suggests that these structures are the same structures as in the free-shear layer. This finding is in accord with what the schlieren photographs in Fig. 1b show. The maximum coherence level is almost constant between $x = 5.0$ and 8.0 with another peak, however much smaller, appearing at higher frequency because of the viscous dissipation. When the transducers were aligned in the spanwise direction, the coherence showed a similar trend to those shown in Fig. 2, however, with a lower coherence level. This suggests that the structures have either a limited spanwise extend or are skewed in the spanwise direction.

Figure 3 shows the correlation coefficient R_{uv} between the streamwise and the transverse velocity fluctuations. The Y^* is the transverse location from the tunnel floor nondimensionalized by the boundary-layer or shear-layer thickness. For the shear layer, $Y^* = 0$ corresponds to one-half freestream velocity location. At $x = 1.7$, the range of Y^* at which R_{uv} is above 0.3 is approximately 20% greater than that at $x = 1.2$, even though the change in Y^* partially takes into consideration the physical growth of the developing shear layer. This is consistent with the shift of peak coherence to lower frequency in Fig. 2. The maximum R_{uv} value remains almost constant between $x = 1.7$ and 4.5, which further supports that idea that the large-scale structures formed in the shear layer do not break up as they pass through recompression and reattachment. There is a gradual decrease in R_{uv} level between $x = 4.5$ and 7.0, but no appreciable change between $x = 7.0$ and 8.0. There is a significant reduction in the turbulence level, Reynolds stress, and transverse transport of kinetic energy between $x = 4.5$ and 7.0. However, all of these parameters show very little change between $x = 7.0$ and 8.0. This shows that the interaction of large-scale structures with the recompression shock wave and the process of their reorientation generate a rapid mixing. However, this enhanced mixing continues for a short distance and is followed by a very slow development. At $x = 8.0$, turbulence fluctuations and R_{uv} levels are higher than those of the incoming boundary layer which suggest that the redeveloping boundary layer is far from becoming fully developed. A similar behavior has also been observed in subsonic redeveloping boundary layers.[2]

Acknowledgments

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