Structure of the Compressible Turbulent Shear Layer

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Abstract

THE large-scale structure of the turbulent compressible shear layer is investigated in a two-stream supersonic wind tunnel. Double-exposure schlieren photography reveals that the two convective Mach numbers, corresponding to each side of the shear layer, are very different: one is sonic or supersonic and the other is low subsonic. This contradicts the current isentropic large-scale-structure model, which predicts the convective Mach numbers to be equal or very close. It is speculated that effects of shock waves are responsible for these asymmetries.

Contents

It is a widely accepted premise that shear-layer entrainment and mixing are governed by the instability of the turbulent large-scale structure. The visualization of such structures in the compressible case led Bogdanoff[1] and later Papamoschou and Roshko[2] to characterize compressibility in the reference frame of the large-scale structure. For the flow conditions depicted in Fig. 1a, the convective Mach numbers were defined as follows:

$$M_{c_1} = \frac{U_1 - U_c}{a_1}, \qquad M_{c_2} = \frac{U_c - U_2}{a_2} \tag{1}$$

where U_c is the convective velocity of the structure.

In Refs. 1 and 2, the relation between M_{c_1} and M_{c_2} was obtained by requiring equality of the total pressures of the two streams in the convective frame. This stems from a well-known argument, used primarily with subsonic flows, that the stagnation point between two structures must be pressure balanced (Fig. 1b). No total-pressure losses due to shock waves were considered. This isentropic model gives $M_{c_1} = \sqrt{\gamma_1/\gamma_2}\, M_{c_2}$, were γ is the ratio of specific heats.

Although the convective Mach number correlates growth-rate data fairly well,[2] questions remained as to the accuracy of the isentropic model when shocks form on the structure. To test the model, direct measurements of convective Mach numbers were conducted in the Guggenheim Aeronautical Laboratory, California Institute of Technology (GALCIT) 25- × 57- × 200-mm supersonic shear-layer facility. Typical flow static pressures were 0.1 atm, with the resulting unit Reynolds numbers on the order of 10^4 per mm. In the region of the measurements, x/θ_1 exceeded 1000, where θ_1 is the trailing-edge momentum thickness for the high-speed stream.

Convective velocity measurements were obtained by means of a two-spark variant of the schlieren method, developed by the author. The operating principle is illustrated in Fig. 2, and details of the method appear in a different publication.[3] The elements of a conventional schlieren are retained, with the difference that two adjacent beams, produced by two distinct spark gaps, form a sequence of two exposures on the same piece of film. The exposure time of each image was 20 ns, short enough to capture details of the flow. The time interval between spark firings (and hence between images), Δt was controllable and ranged typically from 5 to 20 μs. Features of turbulent structures were identified in the schlieren photos and were seen to move a distance Δx in the time interval Δt. Their convective velocity was $U_c = \Delta x/\Delta t$. The convective Mach numbers were then inferred from Eq. (1).

On the average, seven photographs showing identifiable features were used to arrive at a value of U_c for each test case. For each case, all identifiable features, picked up on both edges of the shear layer, moved with the same velocity U_c, within the experimental accuracy. Consequently, U_c was found to be independent of streamwise position. The measurement error for U_c is roughly ±5%, based on the uncertainty in locating the precise position of a given feature from one exposure to the next. Different knife edge orientations produced no noticeable difference on the U_c measurements. Figure 3 shows a representative two-spark photo, spanning a distance from 50 to 140 mm from the trailing edge. Arrows indicate the structure features on which the measurements are based.

Table 1 summarizes the experimental conditions and convective Mach number measurements. Ten cases of different Mach number gas combinations are listed. For brevity, each case is assigned a name consisting of the gases and Mach numbers. Letters represent the gases: A for argon, H for helium, N for nitrogen, and S for sulfur hexafluoride (SF_6, $\gamma = 1.09$). Numbers represent the Mach numbers times 10. For example, A32S03 is the case with argon at $M_1 = 3.2$ and SF_6 at $M_2 = 0.3$. The faster stream is placed first in the name. The velocity ratio U_2/U_1 and density ratio ρ_2/ρ_1 are listed on the table. The last column contains the number of datum points N reflected in each measurement.

The experiments show that, at high compressibility (case H17N28 and below), U_c closely approaches U_1 or U_2, depending on the test case. This is a large deviation from isentropic-model prediction and produces the surprising convective Mach

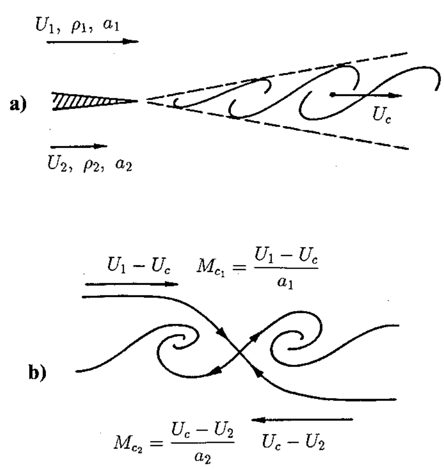

Fig. 1 Shear layer with sketches of streamlines according to Coles[4]: a) stationary frame of reference; b) convective frame of reference.

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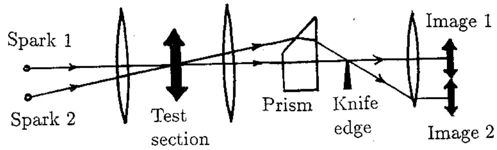

Fig. 2 Operating principle of two-spark schlieren system.

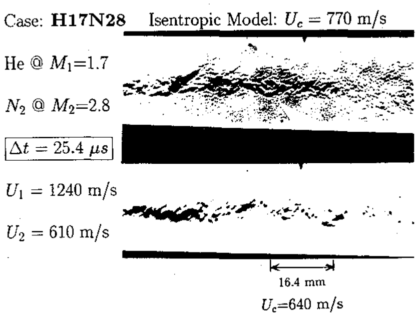

Fig. 3 Representative two-spark schlieren photo and associated measurement of U_c.

number trends seen in the table. One gets a better view of that discrepancy when the experimental M_{c_1} and M_{c_2} are plotted vs each other. This is done in Fig. 4, where the theoretical values according to Eqs. (1) are also included. Dashed lines connect the theoretical and experimental data for each case. At high compressibility, the difference between theory and experiment is striking: instead of being equal or close, M_{c_1} and M_{c_2} are very different, one low subsonic and the other sonic or supersonic.

Notable is the fact that the side of the shear layer with the higher M_c varies, depending on the test case. In some flows, M_{c_1} is higher, whereas in others, M_{c_2} is higher. There is no consistency of these trends based on quantities that are frame-of-reference independent, namely, ρ_2/ρ_1 and γ_2/γ_1. However, there is an apparent consistency based on the freestream Mach numbers: in supersonic-supersonic combinations, M_{c_1} is always highest, whereas in supersonic-subsonic combinations, M_{c_2} is always highest.

The measurements indicate that the isentropic model for the turbulent large-scale structure fails when the flow becomes highly compressible. An obvious suspect for the asymmetric behavior is the effect of shock waves on the pressure recovery leading to the stagnation point between two structures. It could also be, however, that the structure is highly three-dimensional, in which case two-dimensional theories and hypotheses loses their validity. These are issues to be determined by future studies in this area.

Table 1 Experimental conditions and convective Mach number measurements

Case	U_2/U_1	ρ_2/ρ_1	M_{c_1}	M_{c_2}	N
A32N16	0.94	0.24	0.07	0.07	5
N31N17	0.75	0.54	0.29	0.36	6
N28A26	0.75	1.8	0.48	0.26	8
H17N28	0.50	9.2	0.83	0.10	10
A32A02	0.13	0.23	0.39	1.14	8
S27S03	0.13	0.67	0.42	1.61	4
H26N28	0.42	5.5	1.47	0.10	16
H31N16	0.30	2.5	2.00	0.32	4
A32S03	0.08	0.83	0.13	3.15	2
N30S03	0.06	1.87	0.44	3.67	7

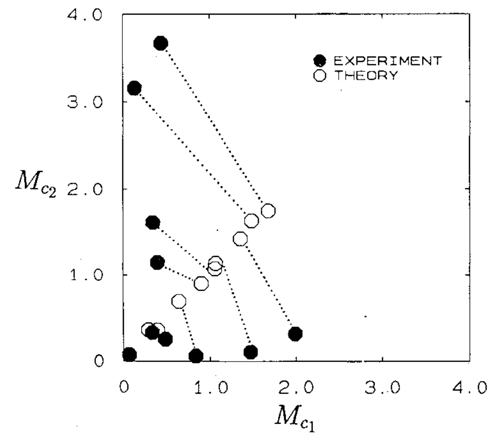

Fig. 4 Experimental and theoretical M_{c_1} vs M_{c_2} plot.

Acknowledgments

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References

[1]Bogdanoff, D. W., "Compressibility Effects in Turbulent Shear Layers," *AIAA Journal*, Vol. 21, No. 6, 1983, pp. 926–927.

[2]Papamoschou, D., and Roshko, A., "The Compressible Turbulent Shear Layer: An Experimental Study," *Journal of Fluid Mechanics*, Vol. 197, Dec. 1988, pp. 453–477.

[3]Papamoschou, D., "A Two-Spark Schlieren System for Very-High Velocity Measurement," *Experiments in Fluids*, Vol. 7, April 1989, pp. 354–356.

[4]Coles, D., "Prospects for Useful Research on Coherent Structure in the Turbulent Shear Flow," *Proceedings of the Indian Academy of Sciences*, Vol. 4, No. 2, 1981, pp. 111–127.