SELF-EXCITATION OF OSCILLATIONS IN SEPARATED SUPERSONIC FLOWS

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The self-excitation of acoustic oscillations has been studied in several papers [1-2]. We have conducted investigations in conventional closed-jet blowdown wind tunnels in the ranges of Mach numbers $M = 1.6–3.5$ and Reynolds numbers $Re = (0.13–40) \cdot 10^6$. Plane models were set up on the wall of the test section, filling its entire width between the windows. The ratio of the recess length L to its width W in the direction normal to the main flow was in the interval $L/W = 0.06–1.25$.

Supersonic flow over rectangular recesses with shoulders of equal height is considerably complicated, in connection with the inception of self-excited oscillations, by the generation of a system of discontinuities and wave disturbances. The common source of the latter is the recess itself, and a complex obstacle-flow spectrum results from the interference of a series of simpler wave systems. Instantaneous schlieren photographs and high-speed motion picture films make it possible to trace the salient features of the flow spectrum and analyze the mechanism of its formation. The latter possibility is afforded by the lack of any singular variations in the character of the spectrum when the geometry of the recess and flow parameters are varied.

We examine the general form of the spectrum in the special example of flow at $M = 1.8$ past a two-dimensional recess of length $L = 16$ mm and depth $h = 8$ mm. At the separation point the boundary layer is laminar and has a thickness $\delta = 0.12$ mm. The Reynolds number calculated from the freestream parameters and length between the edge of the model and the separation point is $Re = 2.4 \cdot 10^6$. The photograph in Fig. 1a was obtained with the blade in a horizontal position and exhibits all the prominent details of the flow spectrum. For a sharper presentation Fig. 1b gives a schematic drawing based on the photograph. The following elements are distinguished in the flow spectrum: 1) disturbance from separation shoulder; 2) sequence of waves forming a sonic beam; 3) system of sound waves originating near leading shoulder; 4) system of sound waves originating at the reattachment site; 5) system of waves formed by upper branches of wave system 4; 6) unattached boundary layer; 7) sequence of vortices forming rotational boundary layer; 8) freestream boundary layer; 9) separation zone.

We analyze the sources and causes of formation of these features.

1. The disturbance from the separation shoulder has a wavy profile and is generated by periodic oscillations and rotations about the shoulder of the unattached boundary layer; which forms a periodically varying concave angle with the freestream flow. This effect is clearly visible in Fig. 2, which gives a single frame of a high-speed motion picture film of flow at $M = 1.8$ over a rectangular recess with $L = 60$ mm and $h = 16$ mm. The average angle of the given disturbance is about 2.0-3.5° greater than the Mach angle, i.e., a finite, though weak disturbance is observed here. This angle corresponds to a shock of intensity $\xi \approx 1.1$.

2. The sequence of waves forming the sound beam is caused by interaction of the impinging supersonic flow with the oscillating unattached boundary layer.

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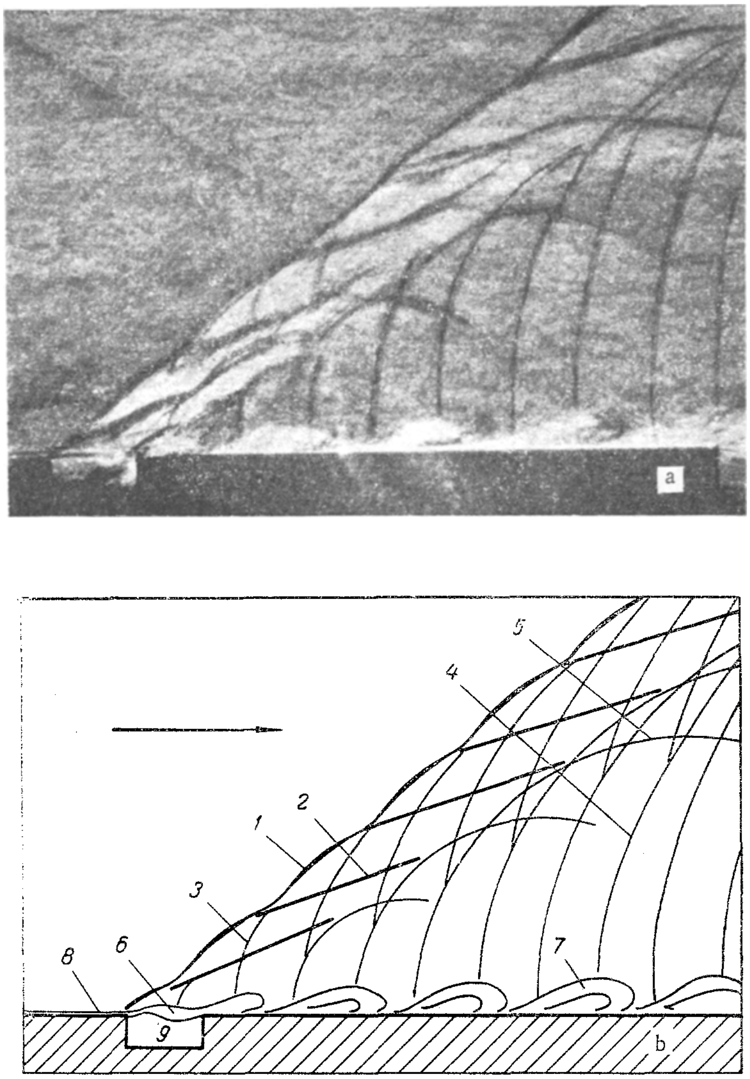

Fig. 1. Spectrum of flow over a two-dimensional recess. L = 16 mm; h = 8 mm; M = 1.8; a) schlieren photograph with horizontal blade; b) schematic representation of flow spectrum.

Fig. 2. Single high-speed frame of flow with M = 1.8 over a recess with L = 60 mm. Film speed: $2.5 \cdot 10^5$ frames/sec.

Film strips spliced from high-speed schlieren frames show that the boundary layer separated from the leading shoulder of the recess fluctuates like an undulating flag. The successive reconstruction of the disturbance fronts produced by these fluctuations at equal time intervals (Fig. 3a) illustrates the process of formation of the sound beam. The arrow k marks the particular wave front whose instant of formation is registered in the illustrated film frame of Fig. 3b. The wave is generated in the vicinity of the rear shoulder of the recess. The motion of the wave front is made up of its own normal motion and the displacement of the freestream flow. After a certain small time interval another wave is generated off of the primary wave at the upper part of the bend of the mixing zone due to the deflection of the impinging supersonic flow at that bend. The trailing part of the new wave joins with the leading part of the primary wave, which has already passed by overhead and behind. This coalescence of several primary waves forms a rippled oblique continuous wave extending over the entire recess. Its subsequent departure is accompanied by straightening (due to interference) of the wave front. The recurrence of these processes generates a sequence of approximately rectilinear waves, which form a sonic or ultrasonic beam.

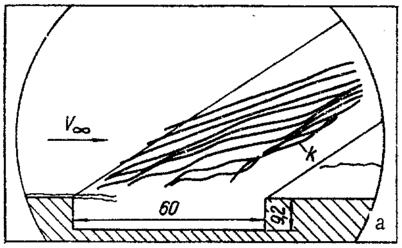

Fig. 3. Formation of an individual wave front of the sonic beam, reconstructed from frames registered at intervals τ = 16 μsec, M = 1.829 (a), and a single high-speed frame (b), corresponding to the wave front k in Fig. 3a.

3. The system of sound waves originating near the leading shoulder is formed by concussive, shock-like rotations of the flow at small distances from the boundary-layer separation point every time the leading part of the unattached boundary layer reaches its low point in the course of oscillation. The resulting concussion forms a compression wave, which is transported downstream by the flow. Two such waves are seen in Fig. 2, the forward wave having been recorded just after its inception.

4. The system of sound waves with source at the reattachment site is similar in the nature of its origin to the system 3. One significant difference is the fact that these waves are created by periodic impacts of the supersonic flow against the rigid boundary. The general form of this wave system is illustrated in Fig. 4.

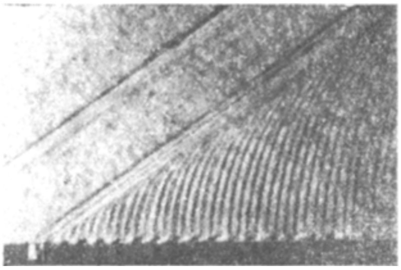

Fig. 4. Schlieren photograph of the system of sound waves originating at the boundary-layer reattachment site. Exposure time 0.5 μsec.

5. The system of waves formed by the upper branches of the wave system 4 is observed in Fig. 1a; the cause of its formation is clearly perceived in Fig. 1b.

6. The unattached boundary layer is formed as a result of the inertia of the boundary layer after its separation from the plate at the leading shoulder of the recess. Its flexural oscillations in the form of transverse waves traveling downstream constitute the central factor responsible for the complexity of the flow spectrum. The generation of the waves may be regarded as one manifestation of Helmholtz instability.

7. The sequence of vortices forming the rotational boundary layer [3, 4] is also induced by the oscillations of the unattached boundary layer. Those oscillations result in a periodic "lapping over" and eventual discontinuity, the surface of which swirls into discrete vortices, and the latter are transported with the flow over the surface of the body.

8. The boundary layer at the separation point in our experiments was both turbulent and, in some cases, laminar. In every case, however, its thickness was several times smaller than the vertical depth of the recess.

9. The instantaneous photographs and high-speed films show that the flow in the separation zone is also unsteady.

The flow spectrum appears more complex in the schlieren photographs than in Fig. 1. This apparent disparity is due not only to the definite influence of a variation of the geometrical and gasdynamical parameters on the flow pattern, but also to interference of the wave disturbances, which is an entirely natural effect under the given conditions. We now analyze the most characteristic highlights:

a. The wavy profile of the forward disturbance 1, viewed in the individual photographs, can be attributed to the successive addition of the waves 3. However, the independence of the sources of these wave systems is clearly witnessed in Fig. 2.

b. During propagation of the waves in the system 3 their upper branches interfere with the waves 2, while the lower branches interfere with the waves 4 after the former waves leave the recess.

c. Interference of the wave sequence 2 with the waves 5 also contributes to the formation of the overall flow pattern. The incipient stage of this process is seen in Fig. 1a.

d. The wave sequence 2 forming the sonic beam has a higher intensity than the waves of the systems 3 and 4.

The analyzed type of acoustic self-excitation is not limited to flow over two-dimensional plates. It also occurs in flow over rectangular notches in cylindrical and spherical surfaces.

NOTATION

Re is the Reynolds number; M is the Mach number; L is the length; h is the depth; W is the width of the recess; δ is the boundary-layer thickness; ξ is the shock intensity; τ is the time interval between high-speed frames.

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