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HYSTERESIS OF A SEPARATED VARIABLE-VELOCITY FLOW ABOUT A STRAIGHT-WING MODEL

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It is known that if the angle of attack of a wing increases and decreases sequentially, its aerodynamic characteristics, such as lift and drag [1], change, which leads to an ambiguous flow pattern within a certain range of the angles of attack [2, 3].

The author [4] and Lushin [5] have revealed that the hysteresis phenomena can be observed in the flow about a wing mounted at a constant angle of attack if the flow velocity first increases and then decreases. These papers dealt with a global separation (leading-edge stall) on a straight-wing model. The separation was shown in [4] to be eliminated by an increase in velocity, whereas it occurs again at a different (lower) velocity, i.e., the hysteresis is observed within a certain range of flow velocities. In this case, the angle of attack was not changed. It was also found [4] that the irreversible flow can reattach to the wing surface under the acoustic action on the flow in the hysteresis range of velocities, i.e., the separation is not restored when the sound is switched off. For flow velocities lower than the hysteresis ones, acoustic forcing leads to reversible reattachment — the separation is restored after the sound effect is eliminated.

With a global flow separation (stall) from the leading edge, a vast separation region is formed above the wing. This region extends over the entire wing surface from the separation line to the trailing edge. An important feature of global separation, which has been noted by many authors, is flow three-dimensionality in the separation region, which manifests itself in the emergence of a pair of large-scale vortices rotating in the wing plane (see, for example, [3, 5–8]).

A typical flow pattern on the upper wing surface for a global stall is shown in Fig. 1. The contribution of the three-dimensional vortex structure of the separated flow to the appearance of hysteresis has not yet been studied. The goal of the present paper is to obtain flow patterns on the wing surface in the hysteresis range of flow velocities and to determine which changes in the three-dimensional structure of the separated flow are caused by an increase and a sequential decrease of the flow velocity and how these changes are related to the hysteresis. In addition, the effect of acoustic forcing on the flow pattern has been studied.

The experiments were performed in a T-313 low-turbulence supersonic wind tunnel at the Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences. Use was made of the model with a rectangular wing in plan and with a symmetric profile whose relative thickness was 10%. The model span was 945 mm, and the chord length was 196 mm (aspect ratio 4.82). Top plates were installed at the model edges to avoid flow spillage. A 8° angle of attack was kept constant during the experiments. The results were obtained using the oil-film visualization technique.

With an increase in the flow velocity from 0 to 22 m/sec, stalling from the leading edge (global separation) occurred, which was confirmed by a hot-wire anemometer. Upon reaching a velocity of 22 m/sec (chord-based Reynolds number $2.9 \cdot 10^5$), flow reattachment occurred. The flow velocity was then decreased. The global flow separation on the model was observed again at a velocity of 16 m/sec (chord-based Reynolds number $2.1 \cdot 10^5$). Thus, the hysteresis exists within the range 16–22 m/sec. Visualization of the limiting streamlines using the oil-film technique allowed one to clarify the specific features of the flow pattern under hysteresis conditions. Figure 2 shows the flow patterns on the wing surface obtained by visualization as the free-stream velocity U_∞ increases. For $U_\infty = 15.4$ m/sec (under the hysteresis range), a global flow separation

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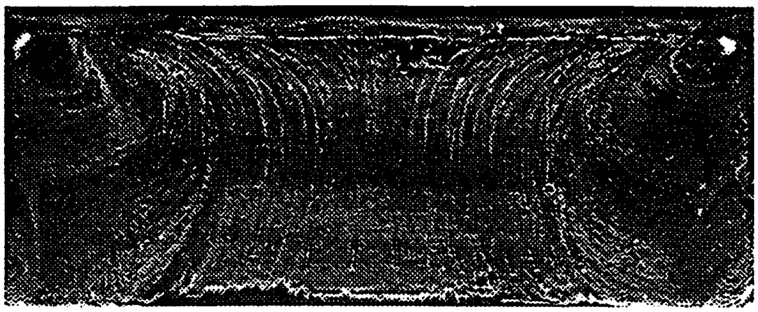

Fig. 1

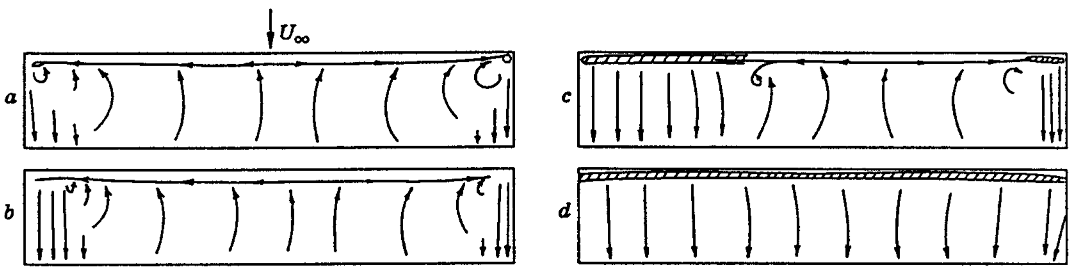

Fig. 2

(stall) from the leading edge was observed on the model (see Fig. 2a). The streamlines on the model surface support the existence of two counterrotating vortices in the wing plane, their foci being located at the model edges near the leading edge. The flow moved from the trailing edge toward the leading edge over most of the model surface. Near the leading edge, the flow moved along the divergence line toward the foci. The flow was attached at the model edges near the trailing edge, which is probably a consequence of the effect of the vortices issuing from the corners formed by the model surface and the top plates. The resultant pattern is typical of global flow separation on this model and was described in [5, 7]. An increase in velocity up to 17.6 m/sec (within the hysteresis range) led to flow reattachment at the model edges (see Fig. 2b). The global flow separation and vortex flow from the trailing to leading edge were preserved on the remaining part of the model. With a further increase in velocity up to 20.8 m/sec (see Fig. 2c), the attached-flow zones at the model edges extended appreciably. Laminar separation bubbles (dashed regions), parallel to the leading edge, were formed in both zones near the model nose. For $U_\infty = 23.2$ m/sec (over the hysteresis range), the flow was completely attached (see Fig. 2d). A laminar separation bubble, which covers the entire span of the model (the dashed region), was clearly seen near the leading edge.

When the flow velocity was further decreased from $U_\infty = 23.2$ m/sec (Fig. 3a) to $U_\infty = 17.6$ m/sec (Fig. 3b), the flow remained attached. The flow separated when the flow velocity was decreased to 16 m/sec. At $U_\infty = 15.4$ m/sec (see Fig. 3c), a separated flow was observed, as before the increase in velocity. Thus, the hysteresis in separated flow about the wing at constant incidence is caused by the fact that a gradual reattachment of flow occurs as the velocity increases, beginning from the model edges, whereas the flow remained completely attached as long as possible as the velocity was decreased, and then the flow separation occurred simultaneously on the entire wing surface. A similar phenomenon was previously observed [1–3] in studying the hysteresis arising in varying the angle of attack — instantaneous separation with an increase in the angle of attack and gradual reattachment with a decrease in the angle of attack.

The effect of external acoustic forcing on the flow pattern at stall was examined. For $U_\infty = 15.4$ m/sec, the reattachment occurred with acoustic forcing at frequencies from 2800 to 7100 Hz. The separation was observed again after switching the sound off, i.e., the reattachment is reversible. Figure 4 shows the changes in the flow pattern at $U_\infty = 15.4$ m/sec that were caused by acoustic forcing with a frequency of 4500 Hz.

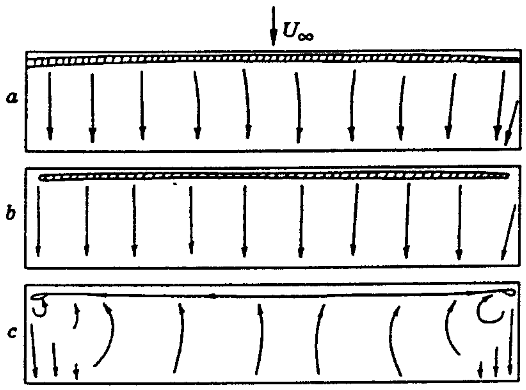

Fig. 3

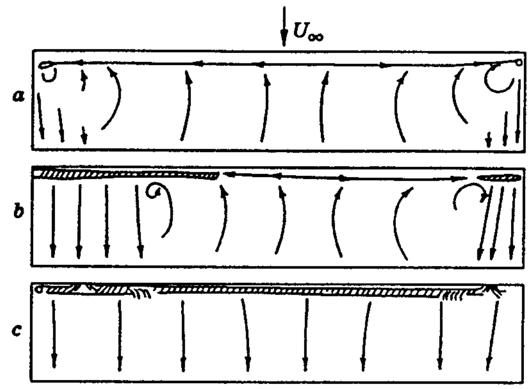

Fig. 4

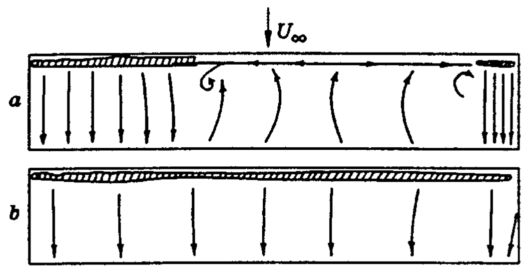

Fig. 5

Prior to forcing (see Fig. 4a), the model was flown about, with global flow separation from the leading edge. At a moderate level of acoustic forcing, the flow was reattached at the model edges (see Fig. 4b). A laminar bubble was formed near the leading edge in each reattached-flow region. A further increase in the sound level led to a complete reattachment of the flow to the model (Fig. 4c). The laminar bubbles merged into one bubble located near the leading edge. This laminar bubble had discontinuities, as shown in Fig. 4c, through which flow spillage probably occurred. The initial separation flow was restored after turning the sound off.

An irreversible reattachment flow was observed for $U_\infty = 17.6$ and 20.8 m/sec (within the hysteresis range). In this case, the flow remained attached after stoppage of the acoustic forcing. The sound frequency ranged from 3000 to 6000 Hz. The changes in the flow pattern at irreversible flow reattachment during acoustic forcing are illustrated in Fig. 5 ($U_\infty = 20.8$ m/sec). Prior to this forcing, the flow was attached at the model edges, and there was a separation region in the central part of the model (Fig. 5a). Having been affected by sound with a frequency of 5000 Hz, the flow was reattached over the entire model surface (Fig. 5b). After switching the sound off, the flow remained attached. Contrary to the case of reversible reattachment, the laminar bubble was continuous. Thus, we can conclude that an irreversible elimination of flow stall is possible if the flow is already attached at the model edges.

To estimate the edge effects on the flow structure, the flow was visualized for the case where the global separation occupied only its central part, rather than the entire model surface. Linear roughnesses (a wire 0.5 mm thick and 130 mm long) were glued to each model side near the leading edge. This changed the flow structure significantly. Three separation regions were formed on the model for $U_\infty = 15.4$ m/sec: one region in the central section of the model and two regions at the model edges behind the wires (see Fig. 6a). Each separation region had two vortices, with their foci at the edges of the separation region. The effect was studied of the flow velocity on the separation in the center of the model, which was limited now by other separation regions rather than by top plates. A separation flow was observed here until $U_\infty = 22.6$ m/sec. Upon reaching this velocity, the flow became reattached. With the velocity further decreased, the separation was restored at $U_\infty = 17.4$ m/sec. For a separation occupying the entire wing surface, as was shown above, the hysteresis

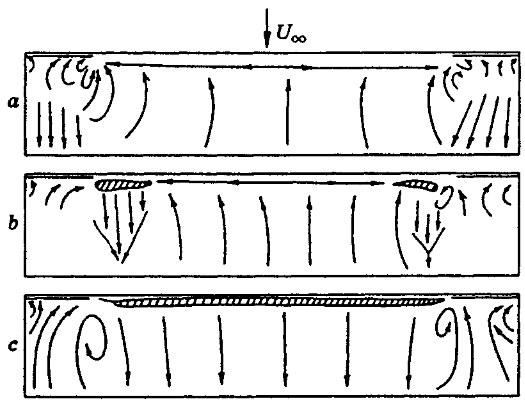

Fig. 6

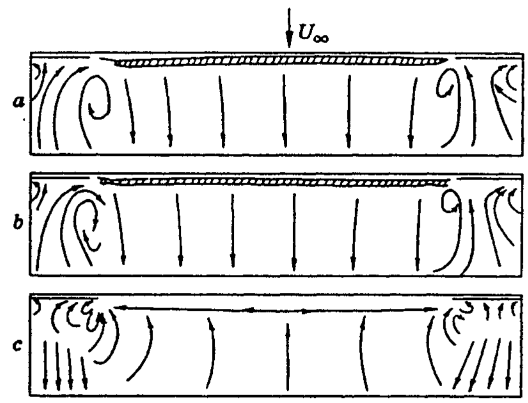

Fig. 7

was observed at U_∞ = 16–22 m/sec, i.e., the hysteresis range somewhat changed. An increase in velocity up to U_∞ = 20.2 m/sec led to a gradual reattachment of flow and to the formation of laminar bubbles near the leading edge at the edges of the central separation region (see Fig. 6b). This is similar to the case without roughnesses. For U_∞ = 22.9 m/sec, the flow was completely attached (Fig. 6c), and the laminar bubble near the leading edge covered the entire span of the central separation region between the humps. The separation was still observed behind the wires at the model edges. As the velocity was further decreased, the central flow remained completely attached down to the lower boundary of the hysteresis range. After that the global separation was restored (Fig. 7a–c for U_∞ = 22.9, 20.2, and 15.4 m/sec).

Thus, the three-dimensional flow structure over the surface of a wing mounted at constant incidence has been studied for the first time in the hysteresis range of flow velocities. The hysteresis phenomenon is caused by the fact that the flow reattachment occurs gradually as the flow velocity is increased, beginning from the model edges, while the flow remains completely attached as long as possible with decreasing velocity, and the flow separation is then restored immediately on the entire wing surface.

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