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RESEARCH FOR THE VISUALIZATION OF TRANSITIONAL AND OTHER TURBULENT PHENOMENA IN A BOUNDARY LAYER

S. X. Li, Y. Shen, and Y. D. Shi,
Beijing Institute of Aerodynamics
Beijing, China

Abstract

In this experimental investigation we use models made of materials which may melt or sublime under test conditions. The surface response is used as an indication to visualize flow property near the wall in supersonic and hypersonic flows. Various surface patterns in different regimes of boundary layer are presented, such as streamwise grooves, turbulent wedges, cross-hatches etc. A physical model of flow is then proposed to explain some transitional and turbulent phenomena in supersonic flows and to clarify the relation between instability of the streamwise vortex and the underlying physical mechanism for the cross-hatch development.

I. Introduction

Flow visualization, as an experimental technique for discovering new flow structure and as aid to theoretical analysis in reducing complex flow pattern to simple pictures, is an important subject in current experimental research. It is especially useful in the study of viscous shear layers.

Since the famous Reynolds dye experiment the techniques have been developed to a wide extent, and many new techniques with stimulating ideas were recognized. Recent achievements in analyzing turbulent organized motion, bursting phenomena, transitional flows, turbulent spots and large scale eddies turbulent structure with these techniques are prominent. Cantwell[1] has summarized the pertinent results, primarily restricted to low speed flow field.

In supersonic or hypersonic flows, many tranditional techniques used in low speed flows are not applicable, consequently the research in transitional and turbulent flow in this speed range is more difficult and more complex than it is in low speed flow. New technique to visualize the complex flow structures bears an important significance. There are some characteristic features in supersonic flows, such as simultaneous occurrence of momentum and heat transfer, the small disturbance propagation being limited inside a Mach cone and the interaction between shock wave and viscous shear flow. How can these new features be employed to devise new visualization technique? This is an interesting problem.

Under laboratory conditions, various experimental tools are used in the study of flow in transitional and turbulent boundary layer. We noticed that if a model surface is made of a material which may melt or sublime, then some cross-hatch patterns appear on the post-test surface. The experimental conditions which lead to such surface patterns are as follows;[2,3,4]

1, flow speeds outside the boundary layer are supersonic,
2, the boundary layer is in the transitional or turbulent regime,
3, the materials on the model surface should have a proper response during the test process.

In the meantime the effect of Mach number at the boundary layer edge on the cross-hatch angle and pattern pair spanwise spacing and its relation to local pressure and temperature are studied. The visualized pictures thus obtained are quite different from those obtained with ordinery coating method, such as oil film or others.

Therefore a set of such visualization experiments are provided in this paper, and indeed new phenomena are observed. The surface response is then employed to interpret the flow structure inside a supersonic boundary layer for both laminar, transitional and turbulent regimes.

II. Description of model, test conditions and results

Model The test model is a flat plate with a sharp metallic leading edge and substructure shown in Fig. 1. Its upper surface is made of wax (melting material) or naphthalene and camphor (subliming material).

Test conditions

Free stream Mach number: $M_\infty = 5$

Stagnation pressure:

$P_o = 147.1 -- 441.3\ N/cm^2$

Stagnation temperature:

$T_o = 383.16 -- 523.16\ K$

Reynolds number per meter:

$R_e\ /\ m = 2.8 -- 7.5 \times 10^7$

The operating pressures and temperatures are chosen to ensure that the model material starts melting or subliming in a short time after the tunnel runs, and at the same time Reynolds number per meter can be varied.

Experimental results

The tests are carried out in a hypersonic wind tunnel at $M_\infty = 5$. After steady hypersonic flow is established, the model is projected in the test section, then the surface material of model begins to respond to hot air flow. In case of melting a thin liquid layer is formed on the surface. Since the thickness of the layer is very small and the viscosity of melting liquid is very large, the velocity of liquid flow is so low that its effect on the velocity distribution of boundary layer can be neglected. Thus the flow traces on the surface must be related to the flow pattern of the subsonic viscous sublayer of boundary layer. Various patterns on surface are observed in different regimes of boundary layer as the test continues.

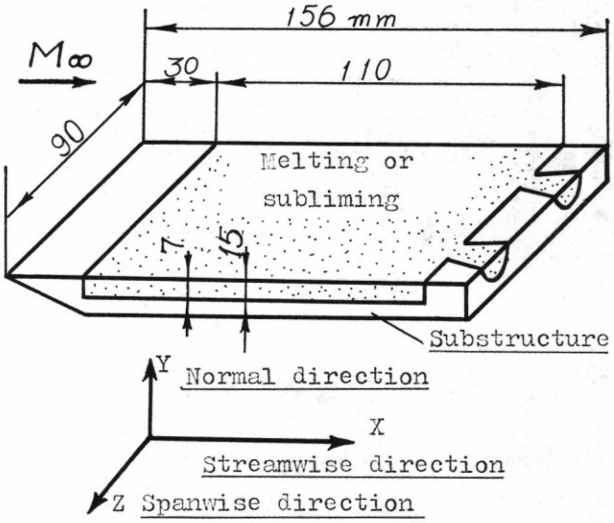

Figure 1. Sketch of the flat plate model

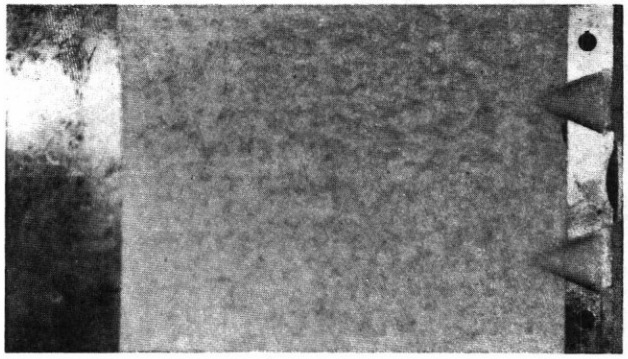

Photo. 1. A pre-test wax model

As an illustration, we show some of the photographs taken during the test. In these photographs the flow is from the left to the right.

In photograph 1. there is a pretest wax model.

Photo. 2. A post-test wax model
$Re/m = 4.7 \times 10^7$

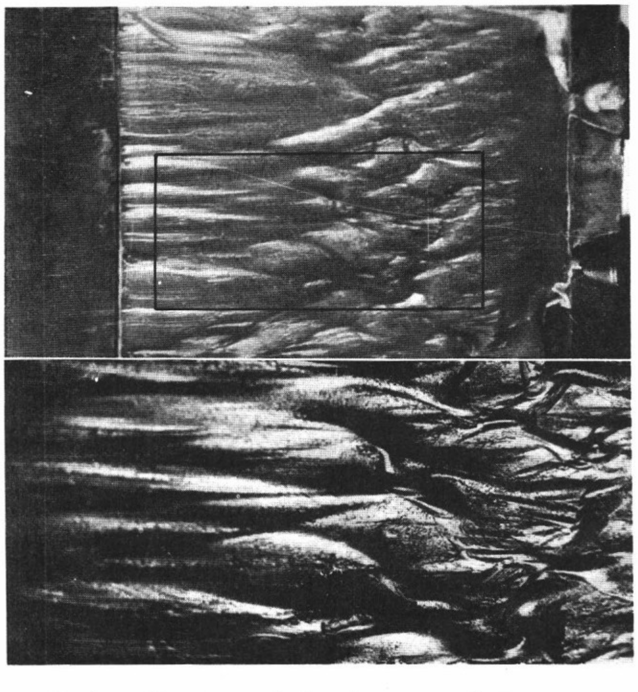

Photo. 3. A post-test wax model
$Re/m = 7.2 \times 10^7$

In photograph 2, 3, 4, there are post-test wax models, each of them corresponding to different stagnation conditions with different surface patterns. The complete model is shown in the upper part of the photograph and a local enlarged photograph is shown below.

In photograph 5. there is post-test model made of naphthalene.

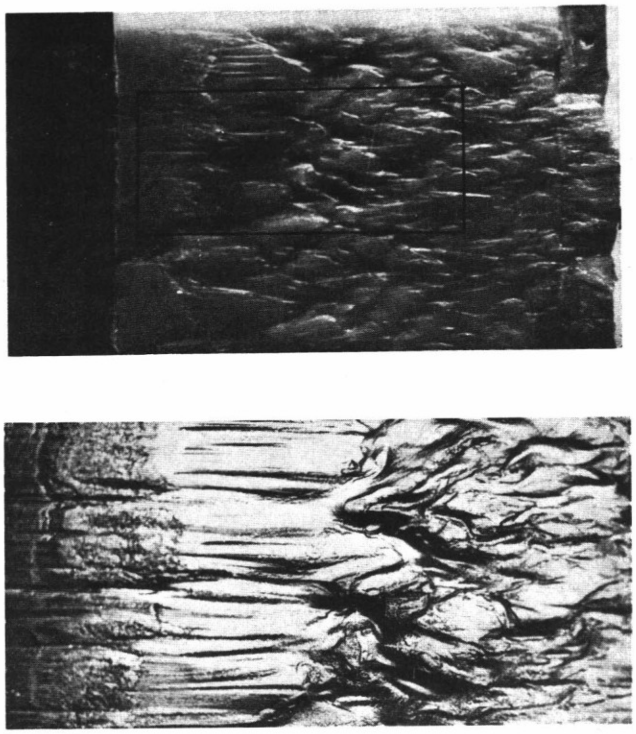

Photo. 4. A post-test wax model
$Re/m = 7.5 \times 10^7$

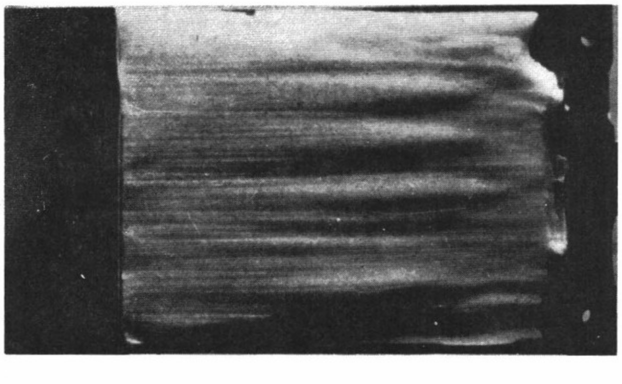

Photo. 5. A post-test model made of naphthalene, $Re/m = 5.6 \times 10^7$

We find that the patterns are usually of three different forms, which may be described as follows:

1, Streamwise grooves

If R_{ex} is less than 2×10^6, streamwise grooves on surface appear to be steady and the spanwise distance between neighboring grooves λ_1 essentially do not vary in the flow direction. As unit Reynolds number increases i. e. either stagnation pressure P_0 increases or stagnation temperature T_0 decreases, λ_1 decreases. We can see it in photographs 2 - 5 . It seems that these grooves are not part of turbulent streamwise structure. Its spacing λ_1 is about equal to a few times of the thickness of boundary layer and much larger than the corresponding spacing in turbulent flow. So in photograph 5, the steady patterns are believed to be a characteristic of laminar boundary layer.

2, Turbulent wedge

As $Rex \geqslant 2 \times 10^6$, the grooves become instable, a pair of grooves at an interval of about 8 - 10 streamwise grooves first begins to deviate from the original direction and then wedge grooves are formed. As $Rex \approx 2.8 - 4.0 \times 10^6$ a wedge groove led by a pair of streamwise grooves is shown in photo. 2, and the flow direction at the valley of wedge groove is apparently not in coincidence with that of the free stream. The depth of wedge grooves is larger than these of streamwise grooves. Photo. 5 shows some of the large grooves with wedge shaped grooves. In other photographs these flow features are also observed.

As unit Reynolds number increases, the initial points of wedge formation move upstream, and the patterns get crowded. With a calculated laminar boundary layer thickness δ , as a length scaling parameter. We have observed that at the position, where the wedge grooves are generated, the spanwise spacing λ_1 or λ_2 (as shown in Fig. 2) between neighbouring pair of streamwise grooves or wedge patterns roughly

$$\lambda_1 = 2 - 2.5\ \delta$$

$$\lambda_2 = 21 - 23\ \delta$$

The thickness δ of course depends on local Mach number, Reynolds number and the ratio of stagnation temperature to wall temperature.

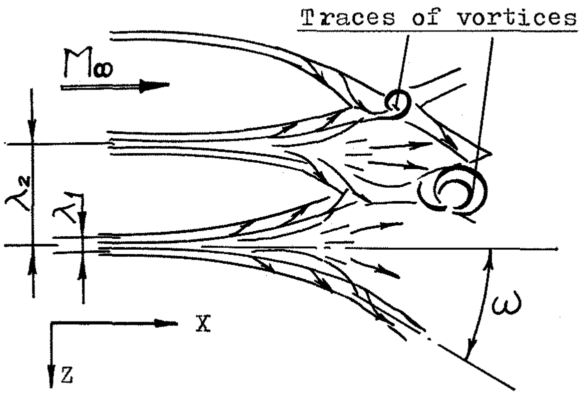

Fig. 2. Spanwise spacing between neighbouring pair of streamwise grooves and turbulent wedges

We may regard the first appearance of wedge grooves corresponds to the beginning of transition, so the first wedge grooves may also be called turbulent wedges (shown in Fig. 2, 3.) .

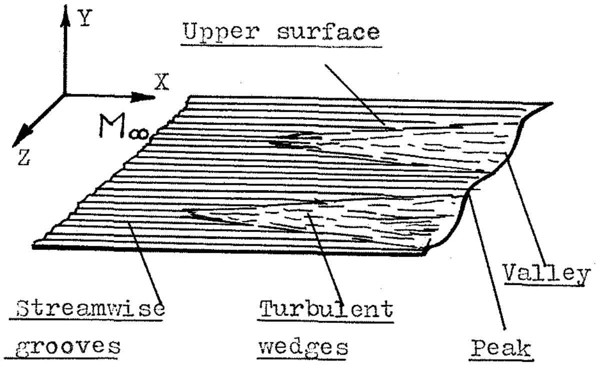

Fig. 3. The peak and valley of grooves on surface

3, Cross-hatches

The turbulent wedges will expand downstream until they intersect. Up to their intersection, the traces of vortices are remained on surface shown in Photo. 2, 3, 4, and in Fig. 2. Then it seems as if a vortex with a lean angle is going up from the surface to the boundary layer edge, new wedges stretch to downstream and subsequently the cross-hatches are developed. The groove depth at the first cross-hatches and intersection tends to a maximum (shown in Photos.). In supersonic flow shock waves are generated and interact with the boundary layer. The stem of shock waves is essentially along the cross-hatch edges. The initial wave angle ω of the cross-hatch is about the same as Mach angle μ. As more surface materials are lost during test, the disturbance become larger, and the wave angle is actually larger than the Mach angle. Present test result about the wave angle is in fair agreement with previously published works in References 2, 3, 4.

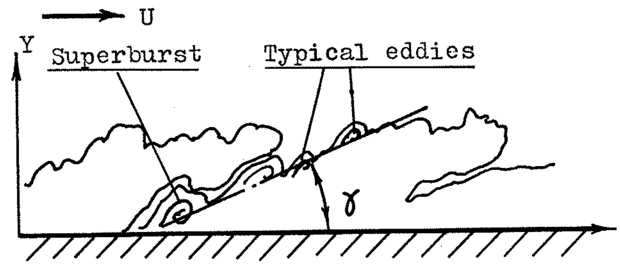

Fig. 4. Schematic of the superburst and ejective flow from the wall

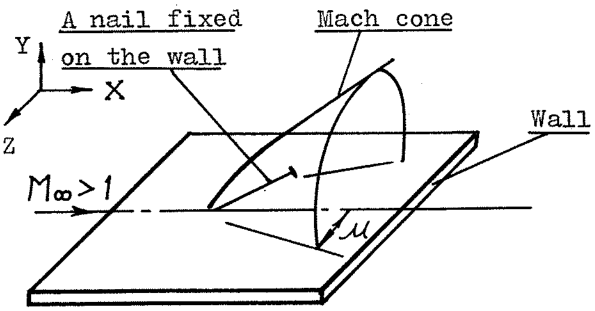

Fig. 5. The effect of a small disturbance on supersonic flow field

III. A tentative proposal for the flow structure

Based on the experimental results we should be able to explain how the patterns on surface are generated and how they are correlated with the boundary layer states. Simultaneously we try to build a physical flow model under present test conditions.

It is possible that the longitudinal grooves are formed by pairs of counter-rotating streamwise vortices. If $Re_x < 2 \times 10^6$, these vortices are hydrodynamically stable and regular, and so does the longitudinal grooves configuration shown in Photographs. The size of vortices is larger than that of streamwise vortex in the sublayer of turbulent flow.[1,5] So it is reasonable to consider that the streamwise vortices observed in the test lie in the laminar part of the boundary layer.

As we go downstream Re_x increases, and under the action of viscosity the vortices become thick and dynamically unstable. It is very interesting to note that a pair of vortices becomes unstable at an interval of 4 - 5 pairs of other vortices. The instability of vortices indicates that their interactions may lead to a burst producing an ejective element of fluid flow lifting up from the wall surface to the boundary layer edge with a characteristic lean angle γ of about 18°.[6,7] Other observed results suggested this angle varies from 8° - 40°[1] (shown in Fig. 4). The disturbance caused by burst or ejective flow propagates in supersonic stream, disturbance with the generated waves, similar to that waves from a nail fixed on the wall shown in Fig. 5.

At the position, where the probability of the burst phenomenon or ejective flow occurring is maximum, the disturbance is almost a continuous one. There appear some differences in surface responses upstream and downstream of the disturbance wave, because the pressure and temperature vary to some extent, hence the rates of melting (subliming) must not be the same and the surface material responses are not alike.

As test goes on, the surface mass loss increases, various patterns being formed , and the small disturbance waves developing into shock waves. These phenomena would not be observed on the wall, in case the surface materials do not respond under the test condition.

As mentioned above, the instability of vortex and bursting phenomena of fluid element are closely related to transition process (origin of turbulence). In the regions of interaction between shock wave and boundary layer, the flow velocity deviates from its original direction near the wall, shown in Fig. 6. Locally melting liquid on the surface move from downstream side of shock wave to upstream. The materials are piled up there, so that the wedge patterns have a nearly clearly cut picture. The wedge angle is usually larger than local Mach angle.

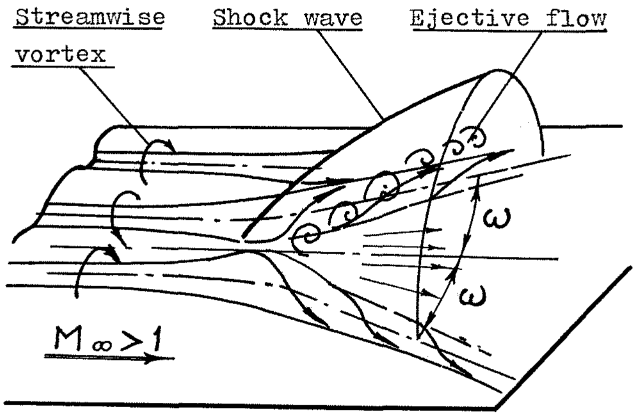

Fig. 6. Sketch of the flow structure about the instability of the streamwise vortices with the burst producing ejection flow and cross-hatch formed

Summarizing we have first streamwise grooves appeared in the laminar part of boundary layer then a pair of grooves become unstable (which indicates the beginning of transition) and develop into a turbulent wedge with the wedge angle approximately equal to local Mach angle, the boundary of wedge is very sharp and indeed it is the extension of these originally straight streamwise grooves, the grooves (actually the vortex filament) intersect and lift up at a lean angle with a trace left on the surface, the underneath streamwise vortex merges to it, then becomes unstable and new wedges are to be formed, an almost regular shock wave net is then formed shown in Fig. 7 (which is related to the cross-hatches) in the transition or turbulent part of boundary layer.

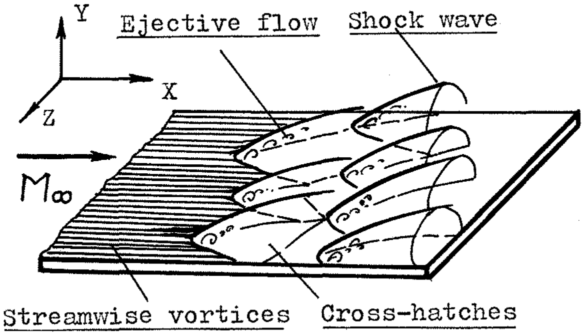

Fig. 7. Shock wave net related to the cross-hatches

IV. Conclusion

A new experimental method with the surface material response is to visualize flow field near a wall at supersonic and hypersonic speed. Three types of patterns on surface are observed namely streamwise grooves, turbulent wedges and cross-hatches. It is recognized that the cross-hatches can only occur under the conditions of transition or turbulent flow at supersonic flow.

Based on the test results a physical model is proposed to interpret some transitional and turbulent flow phenomena. The instability of streamwise vortices is responsible for the burst or ejective flow phenomena. We find that the position of the beginning of transition where the probability of bursting is maximum depends on local Mach number, unit Reynolds number and the thickness of boundary layer. The spanwise spacing of turbulent wedge is about 22 times local laminar boundary layer thickness, or about 8 - 10 times of spanwise spacing of streamwise grooves.

If the burst occurs at supersonic flow field, a shock wave is formed, and interacts with boundary layer. The turbulent wedge is then formed. The wedges will intersect and new shock waves and wedges are formed. It is these intersections that cause the formation of cross-hatches

As mentioned above, some features about burst phenomena in transition and turbulance, small disturbance propagation property in supersonic flow field, and interaction between shock wave and boundary layer, as well as material response of surface are employed to build up this flow model.

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