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A New Method of Acquiring a Permanent Full-scale Oil Flow Pattern in Hypersonic Pulse Tunnel

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***Abstract*:** This paper presents a new method of acquiring a permanent full-scale oil flow pattern using a sheet of wax paper and its application to the study of swept shock and boundary layer interaction in the hypersonic pulse tunnel. It is gratifying to notice that the technique is easy to apply to a model and offers a clear authentic full-scale visible flow pattern that is investigated by visual inspection without photographic processing. The present study indicates that the oil dot wax paper visualization is trustworthy and particularly suited to short duration facility.

***Keywords*:** surface flow visualization, oil dot wax paper technique, hypersonic pulse tunnel, interaction of swept shock and boundary layer.

1. Introduction

It is known that the surface flow visualization is a useful means to reveal the nature of the complex flow near the surface, and it is also a powerful method to diagnose whether flow is normal or not and discover all kinds of abnormal phenomena. The technique has been applied to research on many complex flows because of its simple operation, visual result and leading to more physical understanding than a large set of costly and tedious point measurements.

During the past over 30 years, scholars of many countries have researched on the basic principle of oil flow visualization and the analytic theory of flow pattern, while they have developed the surface streak methods which are suited to different experimental equipment and test conditions. Merzkirch (1974) has presented a review of the widely used methods for oil flow visualization. Frankly, the application of oil flow visualization is straightforward in blowdown facilities. However, the long streaks obtained in the oil flow visualization technique do not form in a hypersonic pulse tunnel due to the short run times. Without visible streaks, the oil flow technique would be of limited utility. In the last few years, alternate surface streak methods have been used to avoid the problem (Pace, 1991 and Tang, 1993). The oil carrier fluid has been replaced by a silicone oil with low viscosity and low vapor pressure that were needed. Small oil-dots to sense the direction of surface shear stress were used instead of oil-film on the model surface. The clear streak pattern was obtained. It was deemed that oil-dot visualization brings about new vitality for short flow duration wind tunnel applications. However, this technique still suffers from a serious defect. It is main problem that the streak pattern is wet at the end of a run in hypersonic pulse tunnel. If the pattern on the surface is lifted off and preserved using ordinary transparent adhesive tape, there was a possibility of ruining it. If the pattern is recorded on a camera film, it introduces optical distortion and resolution less in the streak pattern. In order to avoid these problems, we alter the traditional method mentioned above. It is first to stick tightly a thin sheet of strong plastic paper, which is waxed and polished, onto the surface of model. Then to apply discrete dots of the mixture of silicone oil, titanium dioxide and oleic acid onto the paper surface using a pen. After a run, the paper reserving streak pattern is lifted off. It yields immediate results without photographic processing. This method eliminates camera parallax and provides full-scale visible flow pattern that is investigated by visual inspection. This paper states the achievement in scientific research and its application briefly.

2. Method of Wax Paper for Reserving Pattern

The basic principle of oil flow visualization with the wax paper and the analytic method of streak pattern are the same as the traditional technique. However, there exist still many differences in the process of carrying this technique into execution because of using the new means to record the streak pattern. The working operation is as follows:

2.1 Manufacturing of Wax Paper and Sticking It on the Test Surface

The paper used for the present experiment was treated with wax specially. The select paper should satisfy the following conditions: (a) The paper is so thin that its effect on flowfield is negligible. (b) The tensile strength of paper is high and not easy to crease, roll up and tear. (c) The surface of paper is waxed easily. (d) There is high-contrast between the colors of paper and pigment in paint. The paper was waxed then polished it. The wax layer should be smooth and tough. The layer has two functions in the oil flow visualization: (a) Decrease the force of friction between the paint and paper when the air stream causes the paint to flow along the paper surface. (b) The oil in wet streak pattern obtained at the end of a run can penetrate slowly through many pores in the wax layer into the paper after the experiment, forming a full-scale dry pattern. Thus it can be seen that the manufacture of wax paper is a prerequisite for the application of this technique.

Sticking wax paper on test surface is another key to the technique. In order to obtain a clear intact trustworthy streak pattern, the wax paper should be sticked tightly onto the surface of model. The select adhesive should ensure that the paper would not be separated from the surface of model during the run and would be lifted off from the model without causing any damage after the shutdown.

2.2 The Preparation of a Paint

It is known that an ideal paint should follow air stream to flow quickly along the model surface during tunnel run, leaving a clearly defined pattern of streaks, and the surface pattern should not be affected by tunnel shutdown. For this purpose, the paint should have the correct combination of viscosity and surface tension. In the present investigation, silicone oil with low viscosity and low vapor pressure is chosen as carrier fluid such that the requirements of vacuum and short duration for hypersonic pulse tunnel are satisfied. A white titanium dioxide powder is used pigment for mixing the paint to form a distinct pattern with sharp contrast on a black wax paper. It is the art of the experimenter to find a paint of suitable consistency by mixing an oil and a pigment with a certain ratio according to experimental condition. In principle, the paint should be thick in the place of high surface shear stress. Otherwise, the paint should be thin. A few drops of oleic acid can be putted into the paint to control the size of coagulation of the pigment.

2.3 The Arrangement of Oil-dots and the Preservation of Streak Pattern

To apply discrete dots of the mixture of silicone oil, titanium dioxide and oleic acid onto the surface of wax paper with a pen before the run. The size of oil-dot and the spacing between the adjacent oil-dots depend on the flow features in the observed region. The size of oil-dot should be smaller and the distributions of oil-dots should be denser in the place of high surface shear stress. Otherwise, the size of oil-dot should be bigger and the distribution of oil-dots should be sparser.

It is important that the tunnel should start immediately after applying discrete dots of the paint onto the surface of wax paper. Since too long time some of oil penetrates through the wax layer into the paper, the mixture is thickening so that no ideal streak pattern is formed. After a run, the wax paper of recording streak pattern is lifted off from the model surface carefully and is laid aside. When the oil penetrates into the paper entirely and the streak pattern on wax layer dries, a sheet of clear cellophane is pressed over the pattern forming a permanent full-scale record of the surface streak lines.

3. Application of the Wax Paper Technique

The application of wax paper technique was a great success in the JF_{4B} hypersonic free piston gun tunnel at the Institute of Mechanics, Academia Sinica. The nominal freestream Mach number was 7.8. The stagnation pressure and stagnation temperature were 17.2MPa and 770K respectively. The corresponding unit Reynolds number was 3.5×10^7/m. About 20ms of quasi-steady uniform flow condition was provided. The test model consisted of a unswept sharp fin mounted perpendicularly on a 300mm wide by 550mm long flat plate. Figure 1 shows schematically the test model and includes other details to be discussed later. An example of surface flow pattern of the 30° sharp fin interaction on the flat plate is shown in Fig. 2. It can be seen that the surface streamwise streaks are the same orientation as incoming flow in the incoming turbulent layer region. These streaks turn outward at the beginning of the interaction. Immediately thereafter streaks coalesce. It indicates flow separation. In all the cases studied, separation occurs almost immediately following interaction onset. The separation line "S" and reattachment line "A" are represented by converging streaklines and diverging streaklines respectively. Inspection of the oil-dots traces indicates that the surface flow is quasi-conical. That is, except near the fin leading edge, streaklines can be traced back upstream to a common point, enabling the flow features to be quantified in angular terms. In addition, we can see clearly two pairs of converging and diverging lines in Fig. 2. This means there exists a secondary separated vortex beneath the primary separated vortex in the strong interaction. We can interpret the problem that secondary separation is usually not observed in the company of secondary attachment from the pattern now. This topologically impossible situation is due to a negligible angle between secondary separation and reattachment, such that they appear as a single feature. To sum up, the pattern obtained helps to reveal the nature of the flowfield and can lead to more physical understanding of the flow features.

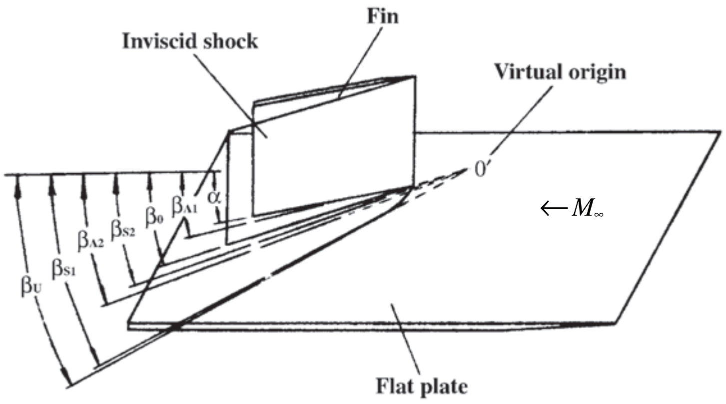

Fig. 1. Sketch of test model.

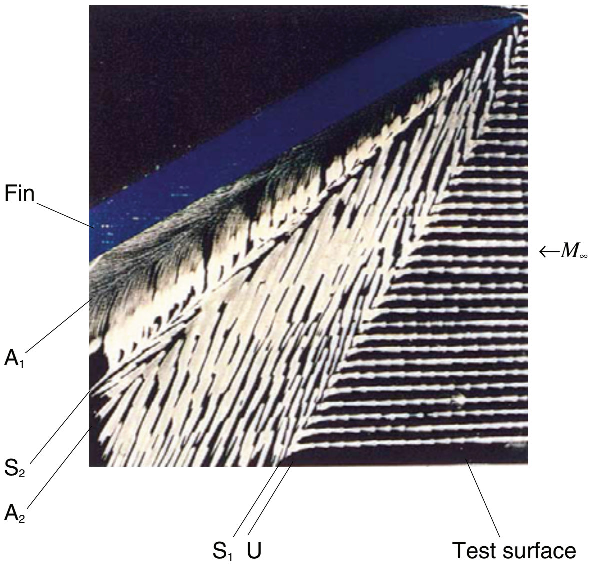

Fig. 2. Surface flow visualization.

There are two questions clarified for this technique: (a) Is the pattern of oil-dot wax paper visualization disturbed by the tunnel shutdown? (b) Is it validity that the pattern provides information on mean-flow features? In order to answer these questions, we took photographs of the streak pattern through the tunnel window at 20ms from starting the tunnel and after shutdown respectively. The result shows two patterns are the same. It can be seen that the streak pattern is not disturbed by the tunnel shutdown. To determine the validity of the oil-dot wax paper visualization, locations of the separation and reattachment were compared with those determined from thermogram, distributions of surface pressure and heat transfer in the interaction region (Wang et al., 1993). Liquid crystals thermogram of the 30° sharp fin interaction on the flat plate is shown in Fig. 3. We also photographed through the tunnel window at 20ms from starting the tunnel. The liquid crystals used here (Type TCS 522, manufactured by BDH Ltd. UK) changes color from colorless, to red, to green, to blue and again to colorless gradually as their temperature is increased. The red start temperature is 24.5°C and the bandwidth (red-start to blue-start) is 4.8°C. When the surface temperature is below 24.5°C or above 42°C, the liquid crystals become transparent and the black painted model surface can be seen underneath. It can be seen clearly from the thermogram that the extent of the interaction region and the flow features within it. The result indicates that surface flowfield structure in fin interaction region is quasi-conical, which is the same as the streak pattern. A distinct boundary between the green liquid crystals in the recirculating flow and the black region adjoining it in the undisturbed flow appears at the location of primary separation line in oil flow pattern. The heat transfer rises sharply in the reattachment region near by fin, increasing the surface temperature with time. Because exposed long enough, the liquid crystals are heated to above 42°C so that the color near by fin in the thermogram photograph displays again the black painted model surface. The narrow black band between two of blues is a low surface temperature region. Its location corresponds with the location of secondary separation line in oil flow pattern. We have measured the surface pressures and heat transfers using fast response platinum film resistance thermometers and high frequency pressure transducers beneath the footprint of 30° sharp fin interaction. The distributions of normalized mean surface pressures and heat transfers in conical coordinate are shown in Fig. 4. The peak pressure and heat transfer, just ahead of the fin, appear at the location of reattachment line A_1 in surface flow pattern. The characteristic dip in the distributions of pressure and heat transfer is seen in the Figure. The local minimum appears at the same place as secondary separation line. The upstream influence locations determined from the distributions and oil flow pattern show excellent agreement. Further oil dot wax paper visualization in the hypersonic pulse tunnel has been performed on the turbulent separated flows induced by blunt fin with good results (Wang et al., 1998). Hence, it is deemed that oil-dot wax paper visualization is a viable technique for hypersonic pulse tunnel applications.

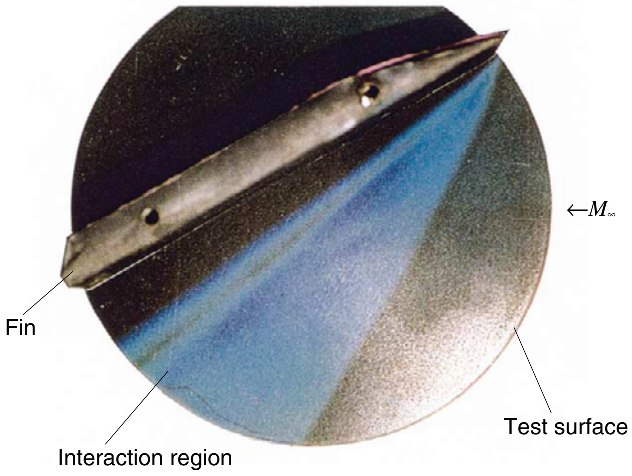

Fig. 3. Liquid crystals surface thermogram.

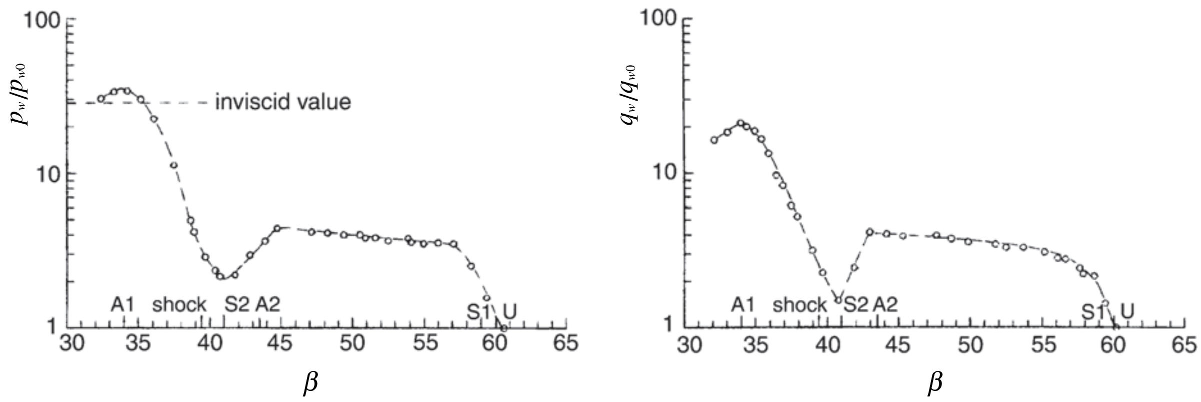

Fig. 4. Distributions of normalized mean surface pressure and heat transfer in conical coordinate.

Using obtained full-scale highly detailed traces of the surface flow features, direct measurements of separation distances and reattachment distances can be made from such traces to develop the scaling law on fin-induced shock turbulent boundary layer interaction. The results (Wang and Wang, 1994) shown in Fig. 5 reveal that the Mach number effect on the far-field primary separation and reattachment lines can be simply accounted for by inviscid shock angle β_0 and fin angle α. They indicate that variations of the interaction response with Mach number are almost entirely due to the inviscid flow conditions and compressibility effects on the turbulent boundary layer are of secondary important over the Mach number range considered (M_∞ = 2 - 8.2).

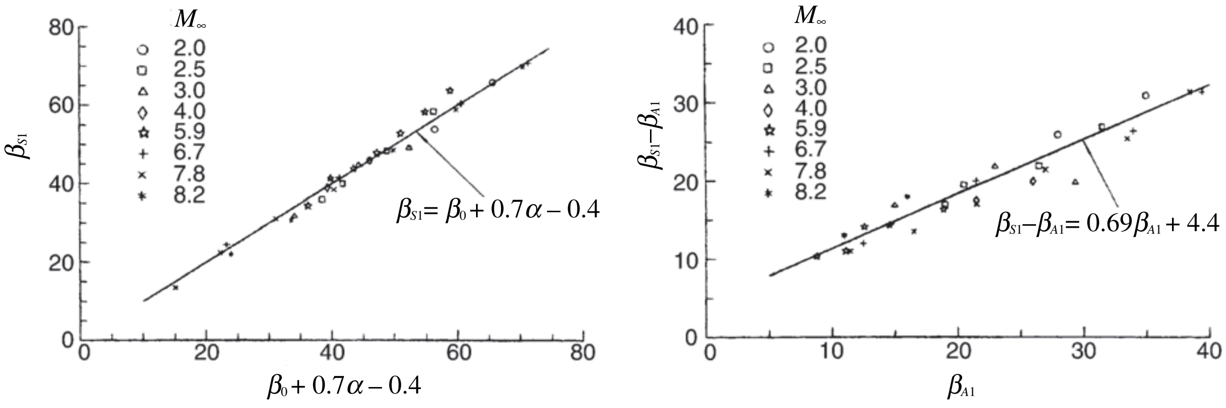

Fig. 5. The scaling law of primary separation and reattachment for unswept sharp fin interaction.

4. Conclusions

The oil-dot wax paper visualization is a viable technique for hypersonic pulse tunnel applications. It yields immediate results without photographic processing and provides undistorted full-scale, highly detailed traces of the surface flow feature. The method has many advantages, for example, simple operation, clear authentic pattern and visual result etc. The pattern obtained helps to reveal the nature of the flowfield and leads to more physical understanding of the flow features.

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Authors' Profiles

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