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A new surface-streamline flow-visualization technique

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This paper describes a new surface-streamline flow-visualization technique that is suitable for use in low-speed wind tunnels or other low-speed gas flows. The technique provides a permanent record of ink traces that show surface-streamline direction and shape. The visualization of the endwall surface flow of the horseshoe-vortex system formed around the base of a cylinder by a separating turbulent boundary layer is used as an example. The results of the new technique are compared with those obtained from a conventional flow-visualization technique. Good agreement was found between the two, with the new technique appearing to give more-accurate surface streamlines.

1. Introduction

The ability to visualize the fluid flow near a solid surface is a valuable experimental technique. When properly interpreted, the flow visualization can provide an experimenter with a greal deal of information about the flow, fairly simply and in a relatively short period of time.

There are a number of techniques available, all with their particular advantages and limitations. One can use tufts, oil and dye mixtures painted on the surface, dye injected onto the surface, etc. to get surface-flow direction and surface-streamline patterns. The conventional techniques are discussed in more detail by Bradshaw (1970) and Chang (1976). The purpose here is to present a new surface-flow-visualization technique that is suited to the low-speed (up to a few hundred metres per second) flow of a gas, e.g. flow over surfaces in a low-speed wind tunnel.

The technique will be described by using as an example the endwall surface-flow visualization of the horseshoe-vortex system formed around the base of a cylinder by a separating turbulent boundary layer. The cylinder (0·304 m high and 0·16 m diameter) was mounted in a low-speed wind tunnel (0·304 × 1·83 m test section) along the tunnel centreline between the floor and ceiling (endwalls) of the test section. Following this description the accuracy and applicability of the technique will be discussed.

2. Description of the technique

Figure 1 (*a*) is a photograph of the mat side of a polyester drafting film (0·008 cm thick), on which the base of the cylinder has been traced. A matrix of ink dots is marked around the circles, to act as flow tracers. The dots are made with a felt-tipped pen (Staedtler Lumocolor 317) containing permanent (water-insoluble) blue ink. Depending on the type of flow to be visualized, a dot is made with one application of the felt-tipped pen, or several applications, with drying inbetween each application. In any event, the dots are not protuberances, but are smooth to the touch.

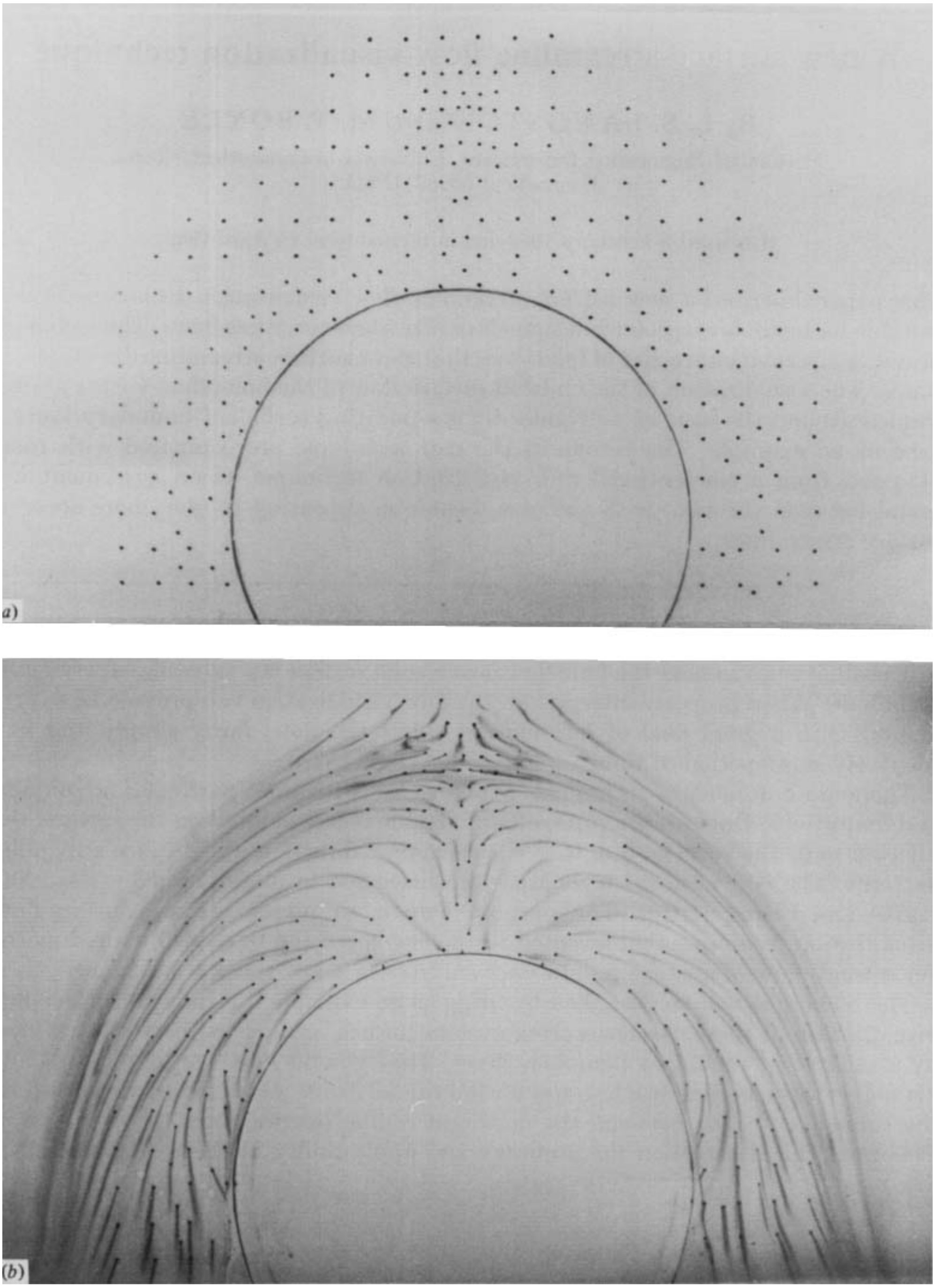

FIGURE 1. (*a*) Matrix of ink dots on drafting film before testing. (*b*) Resulting ink-dot streaklines in front of cylinder after testing.

The drafting film is then securely fastened to the lower horizontal endwall of the wind tunnel (the floor) using double-sided adhesive tape or rubber cement. The cylinder is mounted in place, on top of the drafting film with the ink dot matrix on the upstream side of the cylinder.

Just before the wind tunnel is turned on, the dotted area of the drafting film is

Cylinder Reynolds number	$2{\cdot}46 \times 10^5$
Freestream Velocity	24·3 m/s
Boundary-layer thickness δ	0·0541 m
Displacement thickness δ^*	0·0038 m
Shape factor	1·24

TABLE 1. Test conditions

sprayed with oil of wintergreen (synthetic methyl salicylate), so that the dotted area is completely covered with a thin but continuous liquid film. A small, handheld hardware-store aerosol sprayer (Preval, Precision Valve Corp.) was used, but an artist's air brush would also work. It is important that the dotted area be covered with a *continuous* film of oil, for a discontinuous film can give erroneous results.

After spraying, the matrix of dots becomes 'blurred' as the ink dots dissolve and diffuse into the film of oil of wintergreen. The wind tunnel is then turned on and quickly brought up to operating conditions. (The operating conditions for the test shown in figure 1 are given in table 1.) The turbulent boundary layer on the tunnel floor separates in front of the base of the cylinder to form the well-known horseshoe vortex system that has been studied by numerous investigators (e.g Baker 1978, 1980; East & Hoxey 1969; Ram 1963).

The oil of wintergreen film is then acted upon by wall shear forces and flows in response to them. The ink that has dissolved into the oil of wintergreen film now acts as a tracer, with each dot acting as a stationary source of ink, producing a streakline. In a few minutes the oil of wintergreen has evaporated or has been moved downstream, leaving a permanent picture of ink traces of the surface streaklines on the drafting film, as shown in figure 1 (*b*).

The streaklines in figure 1 (*b*) show clearly the primary saddle point of separation (a point of zero wall shear stress), the primary horseshoe vortex with one sense of rotation, and a smaller counter-vortex with an opposite sense of rotation at the cylinder–endwall junction. The flow-visualization picture is much clearer than those obtained by most conventional techniques such as the oil-flow method used by Baker, East & Hoxey and Ram.

In some downstream areas oil may accumulate from upstream areas, to such an extent that a ripple or wave motion is set up in the thickened film. This gives rise to misleading ink traces, and can be resolved by rerunning the test with ink dots and oil of wintergreen applied only in the area of question.

Since the oil of wintergreen is colourless, different coloured dots can be used in different areas to produce a picture that clearly shows where surface flows originated. This is particularly useful when several surfaces are being tested simultaneously.

If care is taken to spray a thin and continuous oil film, the technique can be made to work on vertical and downward-facing surfaces if the wind tunnel is quickly turned on after oil-film application. We were able to duplicate figure 1 (*b*) for the symmetrical upper endwall (the ceiling) of the tunnel. On vertical surfaces one tends to get a less-accurate picture at separation lines, where the oil accumulates and is acted upon by gravity, or in regions where the velocity and oil evaporation rate are low. Also, the experimenter can always use the 'piecemeal' approach, where small regions are dotted and sprayed at different times, to build up a larger composite flow-visualization picture.

Although a polyester drafting film was used in the above example, any impervious surface can be used if:

(i) It is of such a colour or texture that the ink traces will show up on it.

Specific gravity	1·18
Boiling point (1 atm)	222 °C
Kinematic viscosity (from Bannister 1982, private communication, Monsanto Co.)	$1{\cdot}97 \times 10^{-6}$ m^2/s

TABLE 2. Properties of methyl salicylate

(ii) Oil of wintergreen does not readily react with the surface (this can happen on some painted surfaces).

Some of the properties of oil of wintergreen are listed in table 2. We have tried other liquids and other kinds of ink, but no combination worked as well as that reported herein. For instance, when ethyl alcohol was tried as a solvent, it was found that (i) the ink dissolved too rapidly to produce a distinct streak line, and (ii) the alcohol evaporated too quickly in some areas. This was not an exhaustive study and more work could be done in this area.

3. Discussion

The ink traces shown in figure 1 (*b*) are wall streaklines, i.e. the locus of particles that have passed over a given point (the dot) during a time interval. If the flow is steady, then wall streaklines and wall streamlines are identical. To show that this was the case and that the wind-tunnel start-up did not measurably affect the steady-state flow-visualization picture, the ink-injection method used by Langston, Nice & Hooper (1977) was used as a check.

An ink-dot flow-visualization test was run on the endwall as described above. Then, with the tunnel running at the same steady-state condition, India ink was injected from a hypodermic syringe through a small-diameter hypotube onto the drafting film. The tube was quickly removed after injection, so that the flow drove the resulting India-ink droplet along the drafting film, painting out a streamline.

This was done at a number of locations on the drafting film and then the India-ink streamlines were compared with neighbouring ink-dot streaklines. There was close agreement between the two where shear forces were high and where streamline curvature was small (i.e. large radius of curvature). Where shear forces were low, the India-ink droplet did not move (such as in the region round the saddle point), even though adjacent ink dot traces indicated motion. Where streamline curvature was large, the ink-dot traces showed higher values of turning (more skew) than the India-ink traces. Langston (1980) presented data showing that, in regions of high turning, India-ink streamlines give values of turning that are too low.

A number of tests were run with various cylinder–endwall configurations in which the cylinder Reynolds number and endwall boundary-layer thickness were varied. Both flow-visualization techniques were used to determine the saddle-point position (as in figure 1 *b*). In all cases there was good agreement between the ink-dot technique and the India-ink method. The uncertainty in saddle-point position was much higher with the India-ink method, because the ink would not flow in the low-shear regions surrounding the saddle point.

Baker (1980) used the method of oil-flow visualization (the oil used was a paraffin with suspended titanium dioxide) in front of a cylinder mounted on an endwall in a low-speed wind tunnel. Baker's test conditions were similar to those listed in table 1. Baker interpreted his endwall flow-visualization results as showing two saddle points rather than one, consisting of a rather indistinct upstream primary saddle point and a more distinct secondary saddle point closer to the cylinder. He reasoned that there was a nodal point of attachment inbetween the two, but he could not distinguish it in the photograph of the oil-flow visualization. Based on these results, Baker inferred a multivortex system for the separation of the boundary layer from the endwall.

Using Baker's interpretation, we could also tentatively identify a primary and a secondary saddle point associated with the India-ink flow-visualization results discussed above. But this is based on the region where shear forces are low and the uncertainty of saddle-point position is high (the same would be true for the oil-flow method used by Baker). However, the streakline pattern provided by the ink-dot technique is quite distinct in this region (figure 1*b*). It clearly shows a single saddle point, indicative of a single horseshoe vortex, and not the more complex vortex system inferred by Baker. Flow-field measurements are needed to verify the single-horseshoe-vortex result.

Since the ink-dot–liquid-film technique has been perfected, other investigators have successfully used. it. E. M. Greitzer (1981 private communication) at MIT has used it to study the vortex formed between the ground and a jet engine inlet. It has also been used by R. E. Gaugler & L. M. Russell (1981 private communication) at NASA Lewis Research Center to visualize surface flows in a cascade of turbine inlet guide vanes. Figure 2 (plate 1) shows the ink-dot streamlines on the cascade endwall that were obtained by Gaugler & Russell. One can clearly see the complex nature of the endwall flow from the ink-dot streaklines. The endwall flow pattern shown in figure 2 agrees with that of Langston *et al.* (1977), where both flow visualization and detailed velocity and pressure measurements were made in a turbine cascade passage.

The basic technique described in this paper was discovered by one of the authors (M.T.B.) while using the China-clay method of flow visualization. The work was supported by NASA Grant no. NSG 3238 under the direction of L. J. Goldman of the NASA Lewis Research Center.

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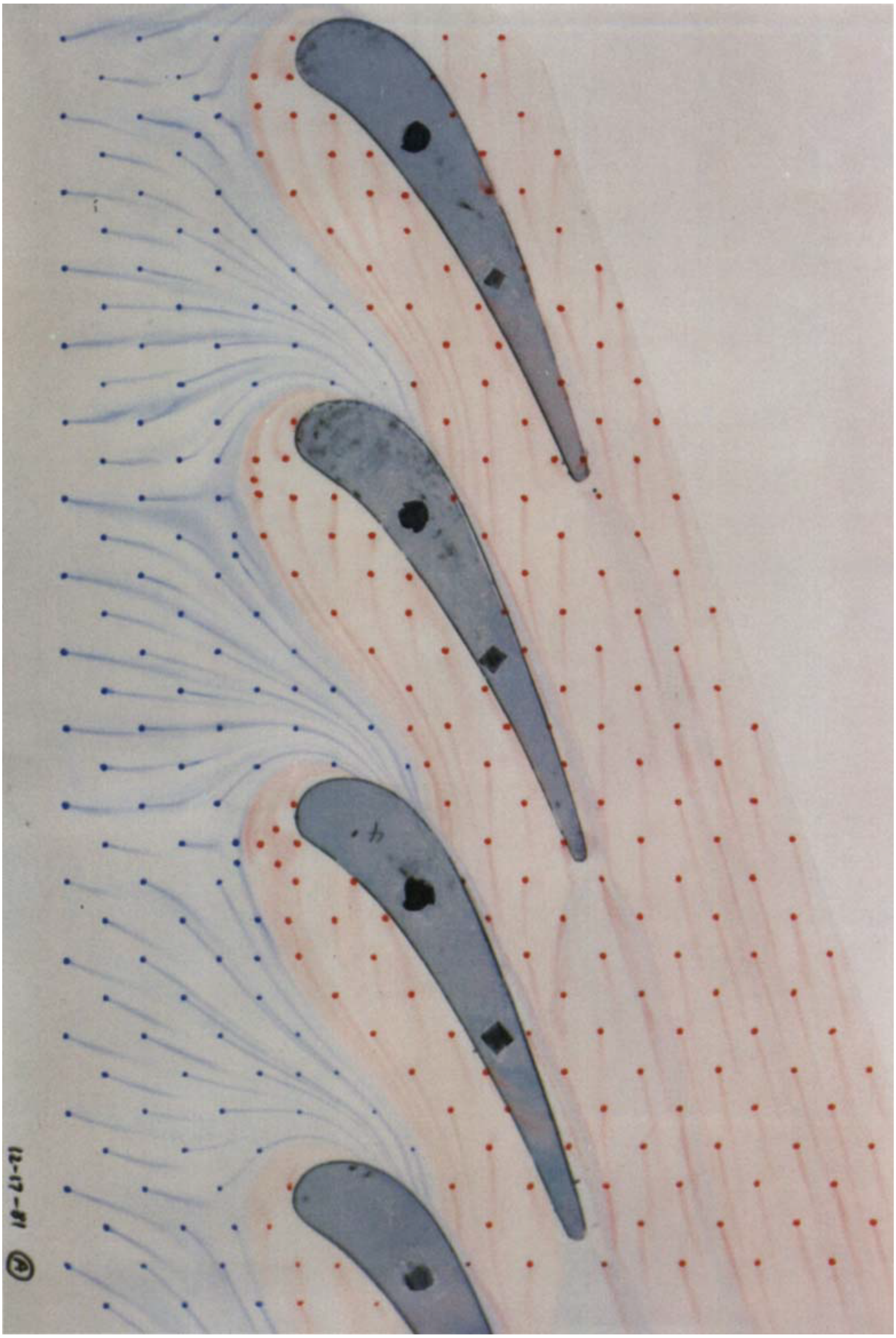

FIGURE 2. Ink-dot streakline pattern on the endwall of a turbine airfoil cascade obtained by Gaugler & Russell.