Engineering Notes

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New Smoke Generator for Flow Visualization in Low Speed Wind Tunnels

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Introduction

IN addition to quantitative tests on models in wind tunnels it is often desirable to obtain qualitative data on the nature of flow around a body under test. To make this possible, some system of seeding the air must be used to make the flow visible. Ever since low-speed wind tunnels were first built, engineers have been devising smoke systems to do this.

While several of the systems currently available produce excellent smoke for visualization and photography, they all suffer at least one major drawback; i.e., they are either: toxic, unpleasant to breathe or work with, persistent, not at ambient temperature, or not at ambient density.

For several years, one such system utilizing oil smoke has been used in the Texas A&M University 7′ × 10′ Low Speed Wind Tunnel. The biggest drawback has been its persistence. After approximately ten minutes of running, the tunnel becomes sufficiently full of smoke to make detailed photography difficult, and, at this point, tests have to be stopped and the tunnel run for at least another 10 min to purge it. Also, while not toxic, this smoke does create an unpleasant work atmosphere.

Although annoying the disadvantages of the system had not become critical until a study of the flow over delta wings was initiated. It was obvious that this program would require extensive flow visualization and that the oil smoke would be inadequate. It was therefore decided to design a system to overcome the disadvantages.

Description of System

The initial idea for a new method came from unpublished proceedings of the 1974 meeting of the Subsonic Aerodynamic Testing Association and in particular from discussions with W. Bettes of Caltech who had been using liquid nitrogen (LN_2) to simulate and visualize the flow from smoke stacks in environmental studies. Early tests with LN_2 at Texas A&M proved that on its own it was inadequate. On dry days, the smoke density was insufficient for photography; however, on humid days a dense white smoke could be obtained. The mechanism for this seems to be that the LN_2 causes the water vapor in the air to condense rapidly so that large droplets do not have time to form but rather myriads of minute droplets form that appear as a dense, white, highly reflective smoke. This discovery led to the conclusion that to obtain good smoke the LN_2 would have to be artifically supplied with water vapor. Work was started on a probe that would mix LN_2 and superheated steam.

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A schematic of the prototype currently in use is shown in Fig. 1. The LN_2 is contained in a 50-liter dewar pressurized by dry nitrogen. The pressure forces the LN_2 through a flexible tube into a tube inside a streamlined strut. Superheated steam is produced in a simple boiler and forced through a flexible tube into another tube inside the streamlined strut. To reduce heat transfer inside the strut, the two tubes are separated by ceramic beads, and the whole streamlined strut is sealed and evacuated. At the base of the streamlined section the two tubes are bent and joined together to allow free jet mixing of the LN_2 and steam (Fig. 2).

Operation is quite simple. For the prototype it has been found that steam pressure of 50 psi and nitrogen pressure of 18 psi produce an excellent smoke that is close to ambient temperature and density, is very easy to photograph, and extends 15-20 ft downstream (depending on airspeed) before vanishing completely. A typical picture obtained during the delta wing tests is shown in Fig. 3. The delta wing tests were conducted at low speeds (50 fps), but the system has been tested up to 100 fps. There is no reason why it should not be used at wind speeds considerably above this.

To date, the maximum continuous time producing smoke in the A&M tunnel has been 2.5 hr after which time there has been no deterioration in smoke density, contrast, or working conditions in the test section. There is no danger of "nitrogen poisoning" (i.e., nitrogen replacing oxygen in the atmosphere and causing drowsiness) as a fifty-liter dewer of nitrogen normally lasts 4 days with about 10 hr of running; the quantity of excess nitrogen produced in the atmosphere is therefore negligible.

Recommendations for Development

While the current system works well, it was designed as a prototype and is not the optimum configuration. Im-

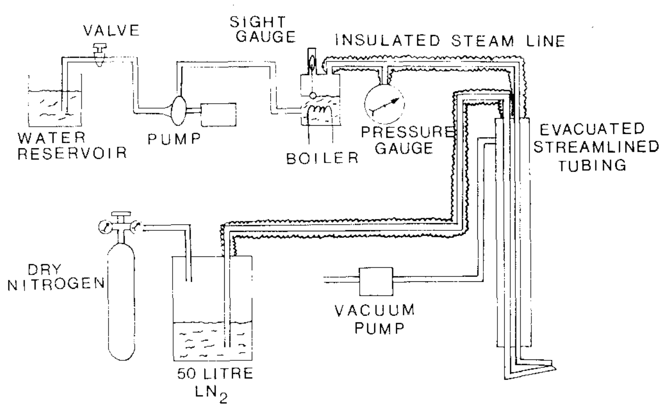

Fig. 1 Schematic of LN_2/steam smoke generator.

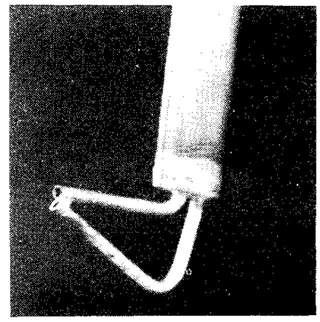

Fig. 2 Details of probe tip.

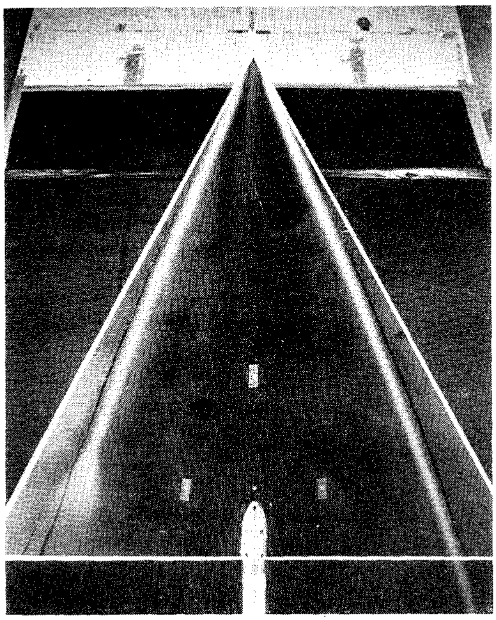

Fig. 3 Vortex flow pattern over a delta wing.

provements that would make the most difference in case of operation would be replacement of the current steam boiler with an off-the-shelf fully automatic boiler. A 1.5 boiler horse power (about the smallest available) would provide more than enough steam at adequate pressures (most units will operate up to at least 120 psi) while still being semiportable. Operation would only require setting the steam pressure and switching on.

On the nitrogen side, more pressure would be desirable, particularly for higher wind speeds. This is not possible with the current dewar, but high-pressure dewars capable of withstanding several hundred psi are available. Also the flexible tubing used for the nitrogen is not a cyrogenic part and stiffens at the reduced temperatures. Lines that remain flexible at the cyrogenic temperatures are available and will be used in future models. Another improvement is the tip for steam and nitrogen mixing. A new nozzle using peripheral injection of nitrogen around a central jet of steam is being tested, but higher nitrogen pressure than currently available is required for proper operation.

A new system constructed with these improvements should be easy to use and versatile. It is anticipated that hardware costs for the modified unit will be approximately $3000. In conclusion, the LN_2-steam system is a considerable improvement over existing methods of smoke production for flow visualization purposes.

Calculation of Initial Vortex Roll-Up in Aircraft Wakes

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Introduction

YATES,[1] in an interesting paper has recently given in closed form, the initial roll-up process of the vortex wake behind a lifting wing in symmetric flight. The intention of this Note is to rederive his results by using a Fourier sine series for the lift distribution instead of the Chebyshev polynomials he has used, and to complete the analysis by also considering nonsymmetric flight conditions. The results of Yates[1] and of this Note, therefore, form a quantitative step forward to Donaldson's basic hypothesis[2] that the initial vorticity shed between the local minima of the curve $|dF/dy|$ vs y will roll-up into a discrete vortex, by providing information on the inplane acceleration of the fluid particles in the wake. These results may be used, as pointed out by Yates as the first step in the use of the extended Betz theory for roll-up calculations.

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Analysis and Discussion

Following Yates, at time zero we have the following relations:

$$W(y) = (1/\pi) -\!\!\!\!\!\!\int_{-1}^{1} \frac{F'(\eta)\,d\eta}{\eta - y} \tag{1}$$

$$V(y) = 0 \tag{2}$$

$$A(y) = \dot{V}(y) = -(1/\pi) -\!\!\!\!\!\!\int_{-1}^{1} \left[\frac{W(y) - W(\eta)}{y - \eta} \right] \times \frac{F'(\eta)}{\eta - y}\,d\eta \tag{3}$$

where V, W are the velocity of the vortex filament (Y, Z) along the y and z axes (see Fig. 2, Ref. 1), $A(y)$ the initial inplane acceleration of the shed vorticity, $F(y)$ the normalized section lift or bound vortex strength, and the slash indicates the integrals to be of Cauchy principal value type. Also a prime denotes differentiation with respect to the function argument, and a dot differentiation with respect to time.

We expand the given $F(\eta)$ in a Fourier sine series with the following change of variables

$$\cos\theta = \eta \tag{4a}$$

$$\cos\phi = y \tag{4b}$$

so that

$$F(\theta) = \sum_{n=1}^{N} a_n \sin n\theta \tag{5}$$

and from Eq. (1)

$$W(\phi) = -(1/\pi) -\!\!\!\!\!\!\int_{0}^{\pi} \sum_{n=1}^{N} n\,a_n \cos n\theta / (\cos\theta - \cos\phi)\,d\theta$$

$$= -\sum_{n=1}^{N} n\,a_n \sin n\phi / \sin\phi \tag{6}$$

The a_n can be calculated from

$$a_n = (2/\pi) \int_0^{\pi} F(\theta) \sin n\theta\,d\theta \tag{7}$$

by any standard numerical method.[4]

On substituting for F and W in Eq. (3) we find that

$$A(\phi) = (1/\pi) \sum_{m=1}^{N} m\,a_m \frac{\sin m\phi}{\sin\phi} \times -\!\!\!\!\!\!\int_0^{\pi} \frac{\sum_{n=1}^{N} n\,a_n \cos n\theta}{(\cos\theta - \cos\phi)^2}\,d\theta$$