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*Ithaca, New York*

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# Experimental Investigation of Several Neutrally-Buoyant Bubble Generators for Aerodynamic Flow Visualization


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Experimental aerodynamicists and others concerned with understanding air motion have long sought practical methods for actually *seeing* air movement. For decades now they have had to rely almost exclusively on smoke for this purpose. But, less and less, smoke is able to do the job. Most air flow patterns of current interest are very complex, usually turbulent and frequently unsteady. Subject to these conditions, smoke mixes and dissipates too rapidly. In addition, it is often difficult and noxious to use, especially in the large closed-circuit wind tunnels that are employed.

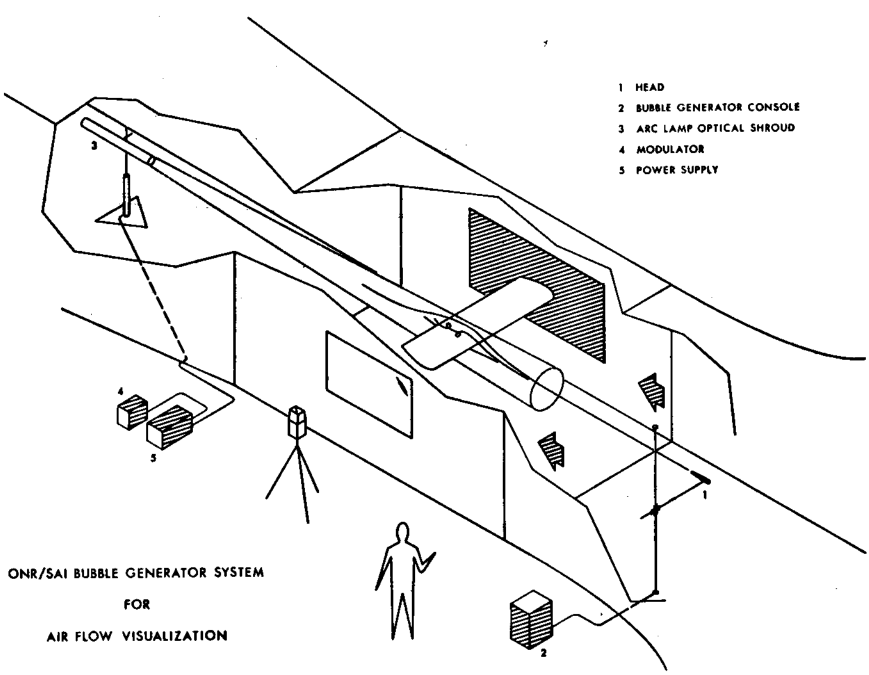


*Figure 1 — ONR/SAI bubble generator system for air flow visualization*

Recently, a new technique for flow visualization has emerged. Under Office of Naval Research sponsorship, Sage Action, Inc. of Ithaca, N.Y. devised a practical way of implanting small bubbles, about 1/8 inch in diameter, in an air flow and photographing their motion. The key features of this development are the unique generation scheme and neutral buoyancy of the bubbles. They are generated extremely rapidly, on the order of 15,000 per minute. Their neutral buoyancy is achieved by filling them with helium gas. This allows the bubbles to follow any air motion faithfully over an entire range of flow velocities from near 0 to more than 200 feet per second. So far, an upper limit has not been determined; it is anticipated that more advanced versions of the device will produce bubbles capable of remaining intact in transonic air flows.

To apply the technique, the necessary equipment can be set up easily in a few hours. A typical arrangement in a wind tunnel is shown in Figure 1. The "head" that generates the bubbles is a small, pencil-shaped device, approximately 4-1/2 inches long and 5/8 in diameter (Figure 2). The bubbles are first formed inside the head and then injected into the surrounding freestream. They accelerate quickly and reach the freestream velocity after traveling a short distance. The head is installed upstream of the flow pattern to be visualized, far enough to avoid any disturbing influence. A compact, high-intensity lamp to illuminate the bubbles is installed downstream of the region to be studied. The lamp has a narrow beam which is directed upstream along the bubble trajectories. This minimizes reflections and stray light.

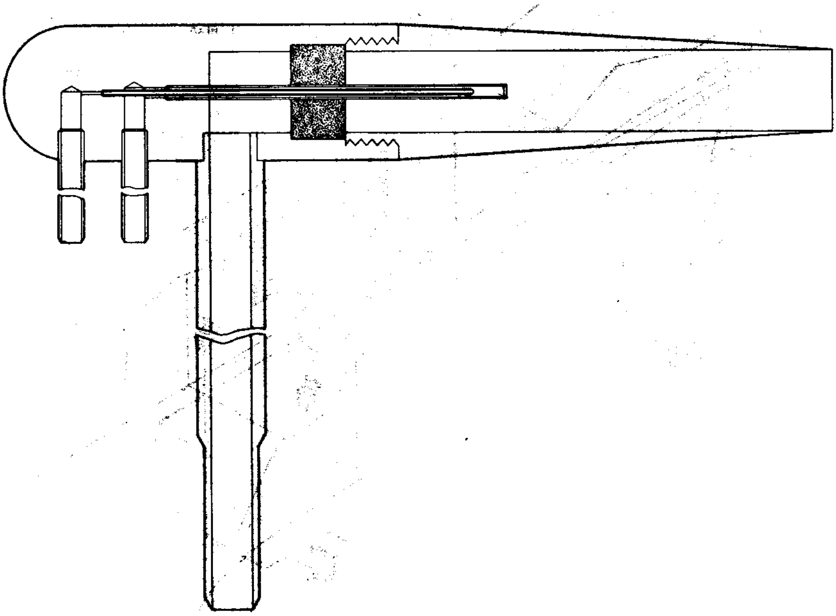

*Figure 2 — Cross-section schematic of the high speed bubble generator head*

The motion of the bubbles, and therefore the air, is generally viewed and photographed from the side or above. With a camera, the shutter speed is set so that a number of bubbles pass through the field of view during the exposure. Each bubble in turn leaves an image of its path, or a streak, on the film and this streak becomes a record of the air movement within this time frame. The record of a number of streaks on a single photograph then produces a remarkable history of the air motion, revealing the flow in graphic detail!

Another dimension has been provided by modulation of the lamp that illuminates the bubbles. That is, the lamp is effectively turned off and on very rapidly, from 250 to 1,000 times each second. With this modulated light, the streaks appear "dashed" or broken at precise intervals in time, whenever the lamp is turned off. From the measured length between breaks in the streak and the known time interval, the actual bubble velocity is found. This affords an instantaneous velocity map of the complete flowfield where point-by-point measurements with a conventional probe are tedious or impractical.

An integrated system of the bubble generator head, the lamp and the modulator, together with the somewhat specialized photography which is required, attained maturity in tests carried out at NSRDC in November 1970. These tests were performed in the 8 × 10 foot Subsonic North Wind Tunnel. They were piggybacked to another test program aimed at the problem of the "tip vortex" from an aircraft wing or helicopter rotor blade. This is a particularly interesting flow phenomenon to investigate. It is so common and yet, at the same time, so poorly understood. Currently, there is a great deal of interest in this problem because of the appreciable and sometimes dangerous wake turbulence behind the new jumbo jet aircraft and the rotor bang or blade slap noise of helicopters, both due to trailing vortices.

An overall view of the vortex pattern is portrayed by the bubble streaks in Figure 3. The upper surface of the blade, or wing tip, is seen in Figure 3. This blade has a 15 percent thick, symmetrical airfoil section with a constant 8 inch chord set at 10 degree angle of attack to the tunnel flow. The flow is from left to right. The core of the vortex appears as a brilliant, solid tube downstream of the blade and passes roughly through the middle of the streak pattern. Within this core, the motion is predominantly in the downstream or axial direction. Outside the core, on the other hand, there is a strong rotational motion superimposed on the axial motion. Facing downstream, the rotational motion is in the clockwise direction. It becomes larger moving radially away from the core, rises to a peak value and then decays. The rotational motion, combined with the axial motion and a small radial motion, results in helical bubble trajectories with changing pitch and radius. This creates the beautiful "basketweave" pattern that is observed.

The flow pattern depicted in Figure 5 is established downstream twelve chord lengths or so. The streaks inboard of the core end abruptly because they pass out of the light beam. The same overall features as above reappear, but there does seem to be a difference between the helical trajectories that are inboard and outboard of the core. Inboard of the core the pitch increases, indicating that the axial velocity profile is less and not axisymmetric about the core. This must be a manifestation of the viscous wake behind the wing that arises from the boundary layer.

To understand the flow better, the same picture was shot with lamp modulation and is presented in Figure 6. The lamp was modulated at 250 cycles per second. At this frequency, a bubble moving with the free-stream velocity at 50 fps would go 0.2 foot or 2.4 inches between breaks

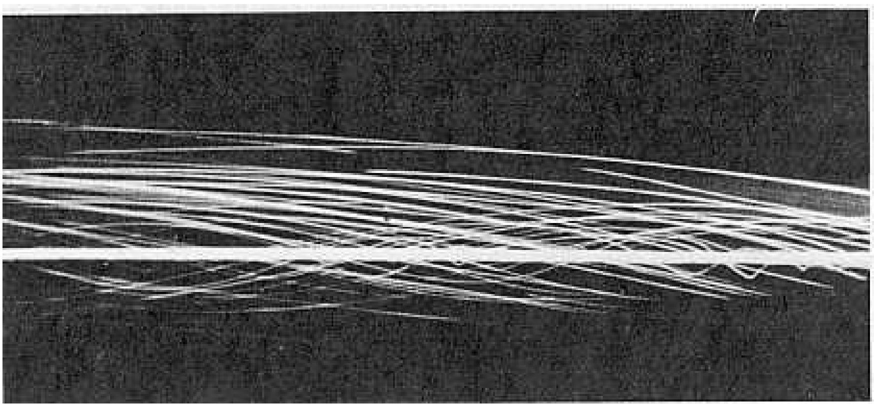

*Figure 5 – The flow pattern depicted here was established about 12 cord lengths downstream*

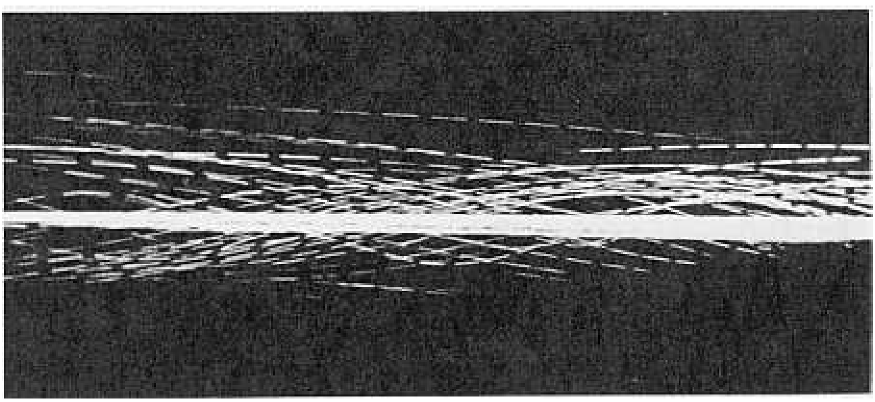

*Figure 6 – Here the lamp was modulated at 250 cycles per second*

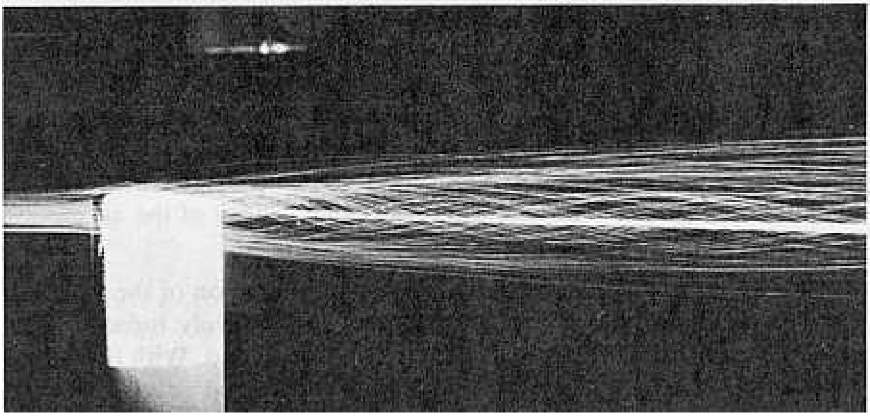

*Figure 3 — An overall view of the vortex pattern is portrayed in the first bubble streak photograph. The upper surface of the blade or wing tip is seen in the photograph.*

Figure 4 shows a closer view of the flow in the vicinity of the blade taken with a shorter exposure. In certain cases, a shorter exposure has a beneficial effect because fewer bubble streaks are recorded. Here it brings out several intricacies, for example, the motion over the edge of the tip and the manner in which the bubbles spiral around and into the core. The radial velocity is also clearly evident. This velocity plays a pivotal role, sustaining the vortex strength by convection of angular momentum inwards. Since the pattern is so strongly three-dimensional, it would be almost impossible to obtain such a wealth of information in any other reasonable fashion.

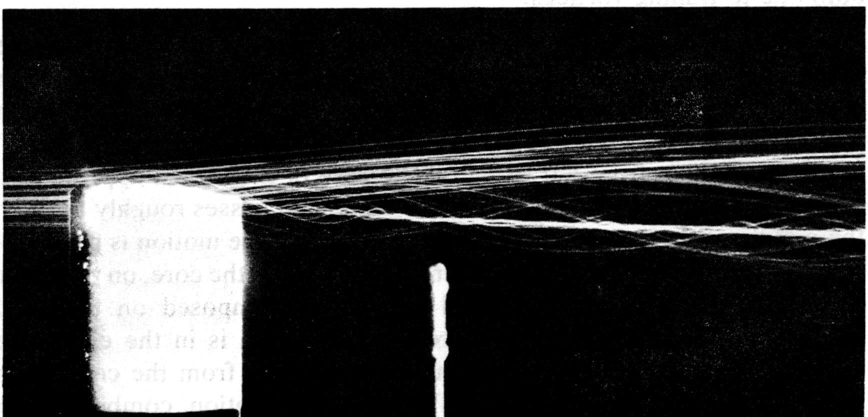

*Figure 4 — A closer view of the flow near the blade taken with a shorter exposure*

in its streak. A great deal of quantitative data can be gathered from this photograph. The calculated axial velocity outboard of the core is essentially the freestream velocity, while the axial velocity inboard is appreciably lower, as suspected. Roughly, it is two-thirds of the free-stream value. Rotational and radial velocities were computed as well. The rotational velocity is on the order of 15 fps and the radial velocity 2 fps at a radius of 1.3 inch. The core itself, as defined by the solid tube of bubbles, is about 1 inch in diameter and grows slowly in the down-stream direction.

These representative photographs constitute, perhaps, the best description of a tip vortex in existence and illustrate what a powerful tool flow visualization is. Relatively speaking, complicated flow patterns are deduced in an instant, which before would have to be ferreted out by means of an extensive set of measurements. In fact, once the pattern is visualized, any measurements themselves can be made much more efficiently. The cost savings and the insight gained are hard to over-estimate.

The new technique advanced has successfully demonstrated its simplicity, reliability, accuracy and adaptability. Currently, efforts are underway at Sage Action to try to develop an even better picture of the tip vortex phenomenon and to increase the speed capability of this technique to high subsonic or transonic velocity. We may expect in the not too distant future, that many wind tunnels will offer flow visualization with bubbles as part of their overall testing equipment.