Journal of Fluorescence, Vol. 3, No. 3, 1993

The Relevance of Pressure-Sensitive Paint to Aerodynamic Research

J. W. Holmes[1]

Received October 18, 1993

Aerodynamic tests are designed to give information about the performance of a model when subjected to an airflow. The introduction of pressure sensitive paint provides a new method for obtaining the pressure distribution on the surface of wind-tunnel models. A paint, the luminescence of which is dependent on air pressure, is applied to the surface of the model and the pressure distribution is obtained from the image produced. This paper gives an explanation of this technique, a résumé of possible applications and some results from research performed at DRA Bedford.

KEY WORDS: Pressure-sensitive paint; aerodynamics; wind tunnel; instrumentation; oxygen quenching.

INTRODUCTION

Aerodynamic tests are designed to give information about the performance of a model when subjected to an airflow. Pressure measurements made on the surface of wind tunnel models play an important role in the development of new aircraft, the prediction of performance and maneuverability, and the identification and resolution of aerodynamic problems. Aspects of interest include structural loading, aerodynamic efficiency, boundary layer and transition effects, and the validation of computational fluid dynamic (CFD) codes.

AERODYNAMIC TESTING

Pressure measurements are usually made by drilling hundreds of orifices on the model and linking them with hypodermic tubing to transducers. Figure 1 shows a typical model transport aircraft with approximately 350 pressure measurements. Even with this number of measurements the data coverage on the model surface is very sparse. Aerodynamics uses a system of nondimensional units to describe the measured parameters. For pressure, the coefficient C_p is used,

$$C_p = \frac{(P - P_\infty)}{\frac{1}{2}\rho_\infty V_\infty^2} \quad (1)$$

where P_∞ is the pressure, ρ_∞ is the density, V_∞ is the velocity of the air flowing past, and P is the pressure on the surface of the model. It is possible to estimate the airflow over the surface of a model using an iterative solution of the Navier–Stokes equations at discrete points (CFD). Figure 2 shows the prediction of the pressure on the surface of a transport wing [1]. What has not been available, until recently, is a method to measure directly the pressure on the surface of a model to the spatial resolution of the CFD grid.

The introduction of pressure-sensitive paint (PSP) provides a solution. A paint, the luminescence of which is dependent on air pressure, is applied to the surface of a model and the pressure distribution is obtained from the image produced. Figure 3 compares spatial resolution and pressure measurement resolution for conventional transducers and PSP, to illustrate the niche that PSP occupies. Complex models as in Fig. 1 will not be

[1] Aerodynamics and Propulsion Department, Defence Research Agency, Bedford, England.

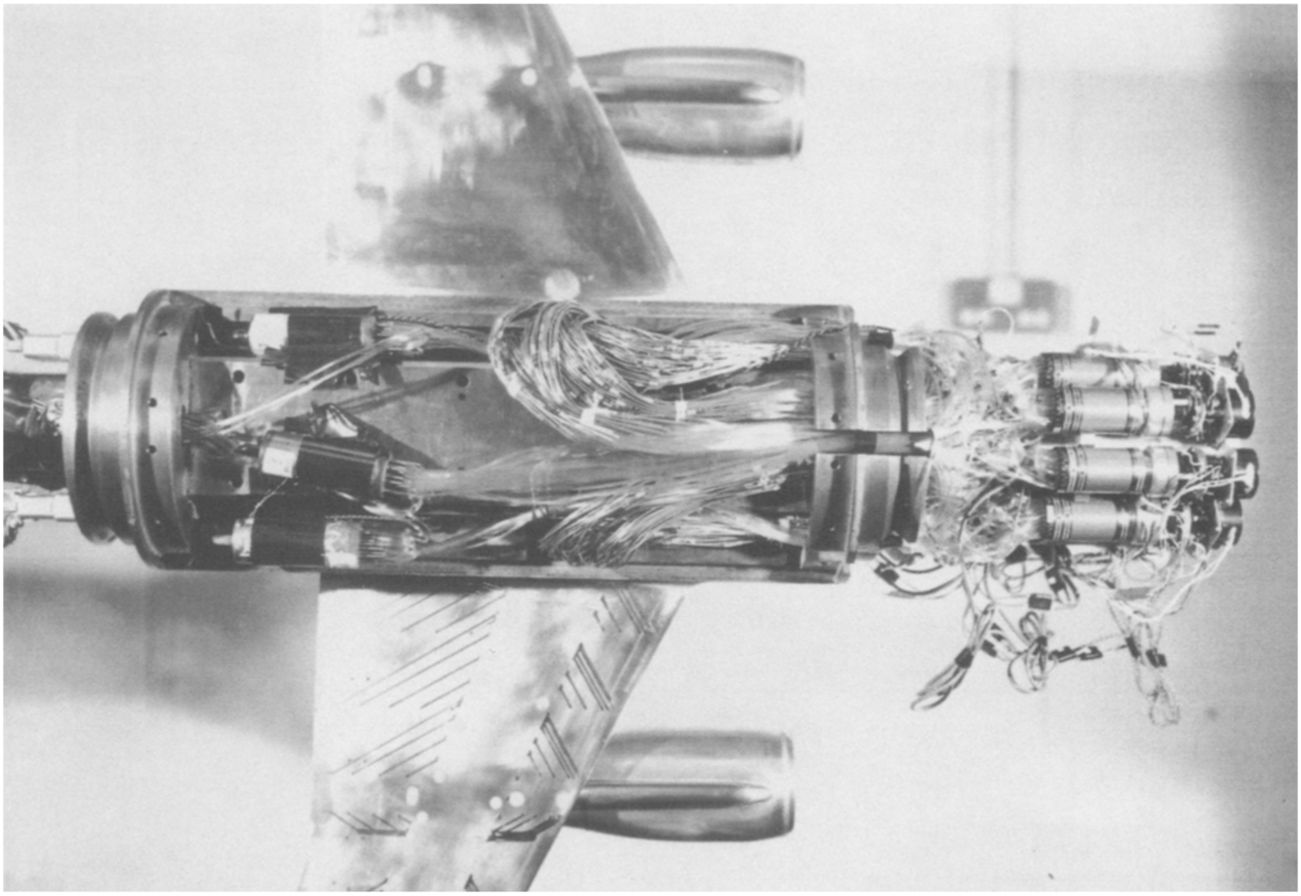

Fig. 1. Model with eight mechanical pressure scanners in nose.

required when using PSP. It will be sufficient to have only a limited number of discrete pressure measurements with PSP providing a global coverge, limited only by the spatial resolution of the imaging system.

HISTORY OF PSP

Certain materials are known to glow when subjected to ultraviolet light and are quenched in the presence of other compounds. In 1919 Stern and Volmer [2] published a paper describing the physics behind this phenomenon and a set of equations that model it. In 1978 Dickenson and Stedman [3] produced a paper describing how airflows could be visualized by injecting ozone into the flow. This work influenced Peterson and Fitzerald [4] to publish their paper in 1980 on the use of a pressure-sensitive dye to measure the flow over a surface.

Their paper was the first description of the technique and is the basis for more recent research. During the 1980s Ardasheva and his team [5] used a similar technique to measure pressure on the surface of wind tunnel models. This was the first time PSP was used as a tool for aerodynamic research. Recent advances in imaging technology, notably high-resolution, cooled CCD cameras interfaced directly to computers, have allowed the technique to be further refined [6,7].

PRINCIPLE OF OPERATION

The active dye, when made up into a paint that allows the diffusion of oxygen, may be sprayed over the surface of a wind-tunnel model. The model surface is illuminated and pressure changes acting on the model cause changes in the luminescent light intensity of the paint, due to variations of oxygen partial pressure in the airflow. Researchers [8–11] calculate the pressure by first recording a reference image (I_0) at a reference pressure (P_0) in still air. The light intensity, wind on, is then

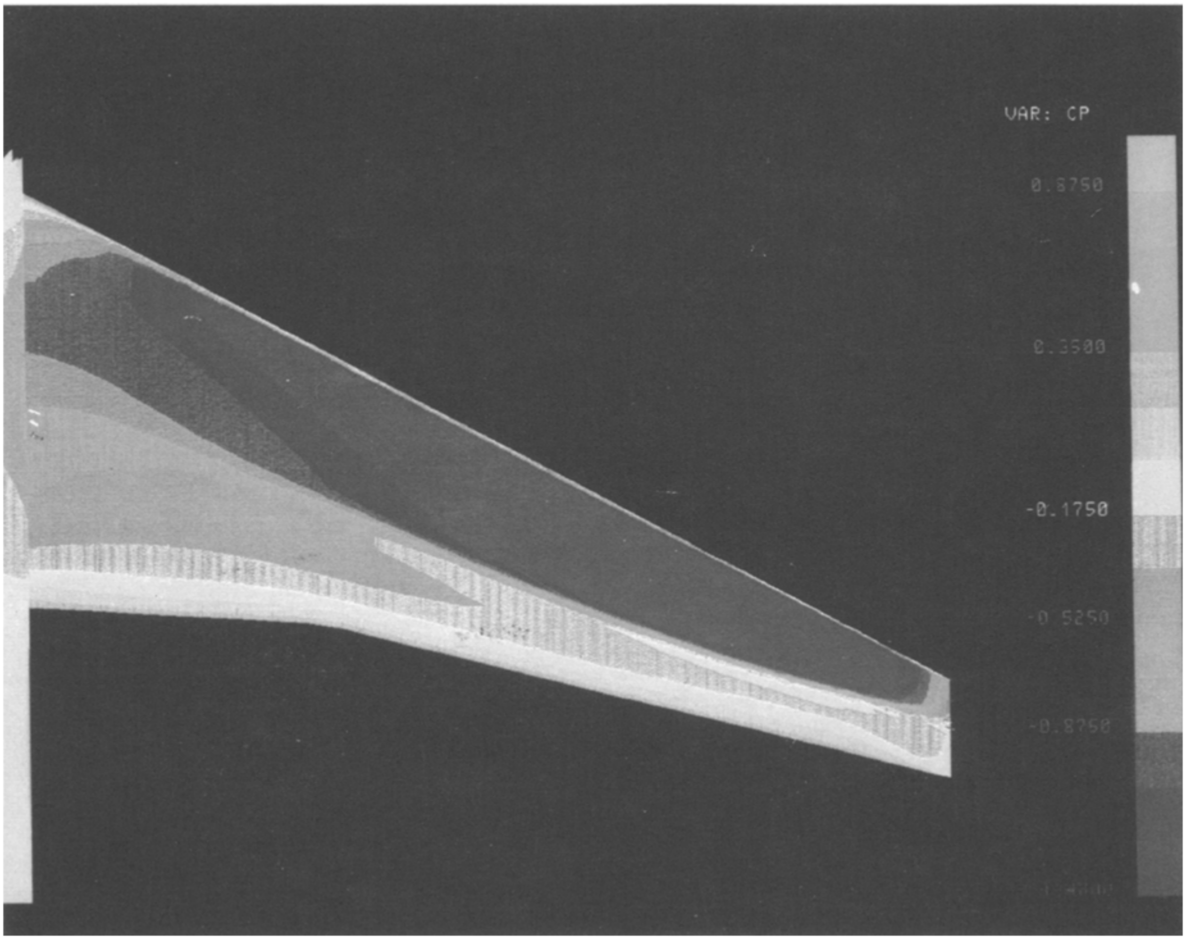

Fig. 2. CFD prediction of pressures on transport wing.

measured and compared with this reference case to produce the pressure map $P(\underline{r})$,

$$P(\underline{r}) = P_0 \, F\left(\frac{I_0(\underline{r})}{I(\underline{r})}\right) \qquad (2)$$

where I is the wind-on image, $\underline{r}$ is the pixel position vector, and F is a polynomial function determined by calibration assuming constant temperature and model geometry.

APPLICATIONS FOR PSP

The method can be applied to complex, curved surfaces, where either geometry or model thickness would limit the positioning of conventional pressure sensors, for example, on small models or in more complex areas such as wing, fuselage, and engine junctions. This allows more configuration changes to be made using simpler models. PSP has also been demonstrated on a full-scale aircraft to measure the aerodynamic loading on the glass in a side window.

At low speeds (civil engineering) the pressure changes are very small. Currently PSP is an absolute transducer with a laboratory [12] precision of 200 Pa and so is of little benefit. High-sensitivity and differential paints are being developed for low-speed work. At high speeds (rocket propelled) the pressure changes cover a wide dynamic range, favoring absolute transducers. This makes conventional measurements difficult but suits PSP, as the model pressures are at the most sensitive end of the pressure range. The problem to be overcome is to compensate for the large temperature change that occur over the model surface.

The trend in wind-tunnel tests, to achieve greater realism, is to use cryogenic temperatures. Conventional

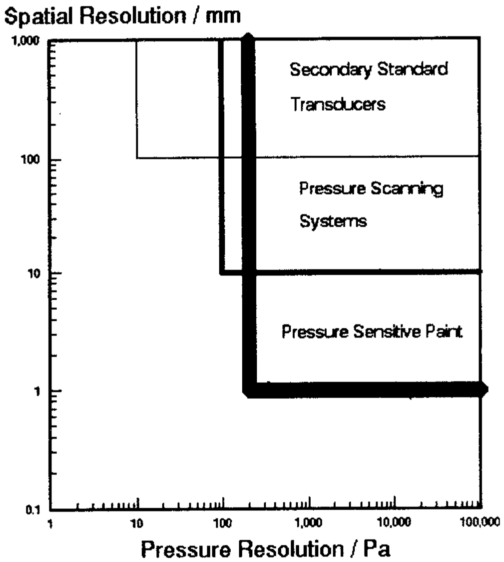

Fig. 3. Comparison of spatial and pressure resolution.

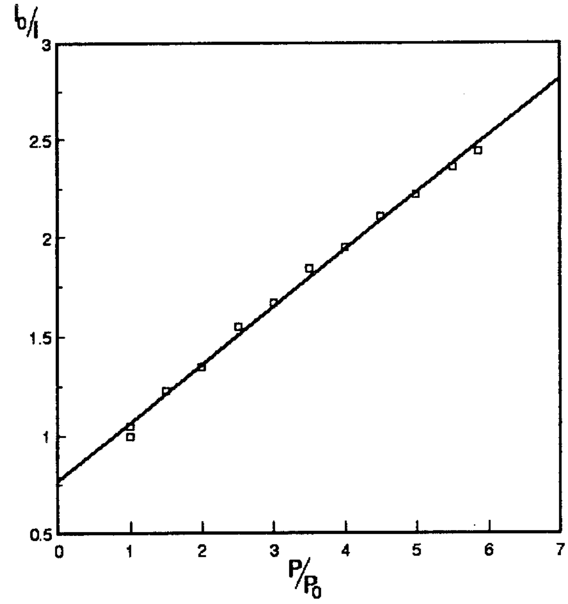

Fig. 4. Calibration curve of PSP.

measurement systems are not suited to this environment, but PSP could be exploited because the delicate measurement systems would be kept out of the cold.

RESEARCH AT DRA BEDFORD

DRA Bedford has a research program aimed at PSP optimized for wind-tunnel testing at all aircraft speeds. A paint must be produced that is robust enough to withstand supersonic speeds and workshop handling and hard enough not to deform. The paint must also be nonintrusive, thin enough not to change the shape of the aerofoil profile, and smooth enough not to alter the surface drag of the model. The paint must be easily removable and not damage the model structure underneath. Research at Bedford has produced a silicon-based paint with a thickness of 30 μm and a roughness average [13] of 0.2 ± 0.1 R_a.

Early laboratory research gave promising results (Fig. 4), with a precision of 10% of reading over a surface of 0.2 m^2. The problems identified were dyes suffering from photodegradation, unstable illumination sources, and imaging systems affected by a lack of resolution and smearing. Development has made the system more precise and repeatable, while new methods of calibration are being researched. The aim of the work is to produce a system that is capable of giving a pressure resolution of 1 mbar at atmospheric pressure.

Equation (2) assumed that there is a constant temperature and model geometry; in practice, this is not the case. As the air expands and contracts over the surface of the model, the temperature changes. Thermographic imaging currently uses this to spot areas of different flow characteristics. To PSP it poses a problem, as the dyes are sensitive to temperature as well as pressure. Methods are being investigated to compensate for temperature changes, including combining the pressure-sensitive and thermographic images. Movement, due to the aerodynamic forces imposed on the model, causes misalignment between the reference and the wind-on images. This seriously degrades the precision of the system. Techniques are being developed to compensate for this.

CONCLUSION

The technique offers a unique ability in being able to map the whole of an aerodynamic surface without disturbing the flow. PSP will become an economical alternative to existing pressure plotting techniques in aerodynamic testing as the technology advances. DRA Bedford is developing a system for use in wind tunnels.

ACKNOWLEDGEMENTS

This research is jointly funded by the Ministry of Defence and the Department of Trade and Industry. ©

REFERENCES

1. J. Fulker, DRA *unpublished research.*
2. O. Stern and M. Volmer (1919) *Physics* Z20, 183.
3. R. R. Dickenson and D. H. Stedman (1979) *Rev. Sci. Instrum.* **50,** 705–707.
4. J. I. Peterson and R. V. Fitzgerald (1980) *Rev. Sci. Instrum.* **51,** 670.
5. M. M. Ardasheva, L. B. Nevskii, and G. E. Pervushin (1985) *J. Appl. Mech. Tech. Phys.* **4.**
6. J. F. Donovan *et al.* (1993) *AIAA* 93-0176.
7. B. G. MacLachlan *et al.* (1993) *Exp. Fluids* **14,** 33–41.
8. M. J. Morris, *et al.* (1992) *AIAA* 92-0264.
9. A. Vollan and L. Alati (1991) *14th ICIASF Congress, Oct.*
10. J. Kavandi *et al.* (1990) *Rev. Sci. Inst.* **61,** No. 11.
11. A. P. Bakov *et al.* (1992) *Proc. Roy. Aero. Soc.,* pp. 14–17.
12. A. Sharma and O. Wolfbeis (1988) *Anal. Chim. Acta* **212,** 241–265.
13. *Exploring Surface Texture*, Rank Taylor Hobson.