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Surface pressure measurements by using pressure-sensitive paints

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Abstract

Until recently, wind tunnel measurements were made solely by pressure taps. But now an optical measurement method has been introduced and is replacing the usual instrumentation, at least for transonic wind tunnels: Pressure-Sensitive Paint, or PSP, which is a method generating an image of the pressure on the surface. The enthusiasm for this technique is prompted by the considerable savings it offers in terms of model instrumentation cost and model construction time, while the wealth of information that can be extracted from the images makes it a preferential investigation tool for complex flows. This article presents the basics of PSP and the way it is used. It is relatively simple to use, in fact, but requires many precautions if a high level of accuracy is desired. The software aspects are important, especially for tests conducted in an industrial context. The various elements of a PSP system are illustrated here with an example of application in low-speed testing. Advanced topics as model deformation are also discussed.

Résumé

La mesure de la pression en soufflerie aérodynamique s'effectuait exclusivement à l'aide de prises de pression jusqu'à très récemment. Une nouvelle méthode de mesure optique a été introduite qui est en voie de supplanter l'équipement classique, au moins pour les souffleries transsoniques. L'acronyme de cette technique est PSP, pour Peintures Sensibles à la Pression. Il s'agit d'une méthode optique qui fournit une image en pression sur la surface de la maquette. L'engouement dont elle fait l'objet se justifie par les gains considérables en coûts et temps d'équipement des maquettes. La richesse d'information inhérente aux images en fait un outil d'investigation de choix pour les écoulements complexes. Les aspects fondamentaux de la PSP ainsi que les conditions d'utilisation sont présentés. La méthode est relativement simple à mettre en œuvre ; par contre elle nécessite beaucoup de précautions si une grande précision est recherchée. Les aspects logiciels sont importants pour cette méthode, en particulier si les essais sont réalisés dans un contexte industriel. Un exemple d'application en basse vitesse est fourni afin d'illustrer les différents éléments d'un système PSP. Enfin des points plus avancés sont présentés, tel que la prise en compte des déformations des maquettes.

Keywords: Pressure-sensitive paint; Wind tunnel testing; Image processing; Resection; Pressure; Low-speed testing; Aerodynamic

Mots-clés : Peinture sensible à la pression ; Essais en soufflerie ; Traitement d'image ; Recalage ; Rectification ; Pression ; Essais en basses vitesses ; Aérodynamique

1. Introduction

The very idea of wind tunnel testing is based on measurement. "Measurement" should be taken in its broad sense, because it includes fine measurements with complex apparatus as well as simple visual observations to determine the state of the flow. The range of measurements possible today is considerable, but surface pressure measurements on models is a constant: tests without pressure measurements are rare.

Pressure measurements are usually made with pressure taps, which have to be connected to transducers. This complicates the model design and increases its cost as well as manufacturing time. Measuring pressure by optical means was long considered to be a major, though utopian, objective. Real application possibilities have arisen only over the past

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ten years or so, with the emergence of Pressure-Sensitive Paint (PSP) [8,34,36]. PSP is based on the sensitivity of some molecules to oxygen, in that their luminescence is inhibited by the oxygen. The PSP principle is described in the second section of this paper.

There are many sources of error, as the temperature effect, and Section 3 describes the methods which have been developed to compensate for them. Section 4 gives a quick panorama of PSP development in the world. Section 5 briefly reports paints, hardware, and software used in PSP systems. The paint is of course the key to the PSP system, but this section will show that the software aspects are important. Section 6 is an example at low speed conditions chosen because it is quite close to applications that could take place in many research laboratories. It is fully described in order to highlight the main features of a real application.

PSP is now a well-established surface pressure measurement method for transonic wind tunnels. Developments are still needed, though, to increase the accuracy and extend the field of application, particularly to unsteady flows. These developments are briefly presented in Section 7. Two of them are discussed in detail: the so-called "*self-illumination*" effect in Section 8 and a method that accounts for model deformation due to aerodynamic loading in Section 9.

The main purpose of this paper is to present the basics of PSP, the state of the art, and its utilization conditions. This excludes a detailed analysis of all its aspects, and we have likewise limited the number of bibliographical references. For further information, the interested reader may refer to two excellent recent publications by J. Bell [5] and J. Sullivan [33] as well as less recent but very complete thesis by Y. Mébarki [24] and C. Klein [16] on the basics of PSP.

2. PSP principle

2.1. Pressure sensitivity of luminescence

Practically all existing materials are luminescent in that they emit light when they are excited at a certain wavelength. The emission wavelength is always greater than the excitation wavelength according to the Stoke's law. Emission may follow immediately upon excitation, in which case it is called fluorescence, or it may occur later, as in the phenomenon of phosphorescence. The emission intensity and spectrum depend on many parameters.

For the molecules used in PSPs, the oxygen captures a part of the decay energy as shown in Fig. 1. The molecules used belong to three broad families: porphyrins, ruthenium complexes, and pyrene derivatives. These molecules are excited in ultraviolet (pyrene) or in visible wavelengths (ruthenium). Some (porphyrins) can be excited over a large spectrum covering the ultraviolet and visible. Emission occurs in the visible portion of the spectrum.

The sensitivity to oxygen, more commonly called *oxygen quenching*, thus endows the molecule with a sensitivity to air pressure, because the oxygen concentration is constant in the air. So, it is not a matter of sensitivity to pressure in the mechanical sense. The physical and chemical phenomena are reviewed in detail in [24].

2.2. Composition of a PSP coating

The typical composition of a PSP coating is shown in Fig. 2. The model is first coated with a screen layer, which hides the luminescence of the model and increases the emission intensity by reflecting both the incident excitation radiation and the PSP emission.

A primer layer may be applied over the screen layer to fix the active part. The active layer consists of a porous binder mixed with the luminescent molecule. The binder must be porous because the PSP principle is based on transfers with oxygen molecules. Only if the binder is porous enough will the oxygen partial pressure in the paint be equal to that in the flow. The PSP response time depends on the paint porosity and thickness and is usually about one second. The thickness of the paint is in the range 30–50 µm.

PSP coatings are applied with a spray gun. The personnel has to be protected with adequate equipment (masks, gloves, coveralls) because PSP products and solvents are often toxic. The model is generally painted in a dedicated room, but it can also be done in the wind tunnel test section. However, the wind tunnel walls must be protected, as shown in Fig. 3. An air extractor system must also be used to remove vapors of solvent.

2.3. Stern–Volmer law

It can be shown that the sensitivity obeys the Stern–Volmer law over a large range. This law is:

$$\frac{I_{\mathrm{ref}}}{I} = A_{p_{\mathrm{ref}}} + B_{p_{\mathrm{ref}}} \frac{p}{p_{\mathrm{ref}}}. \tag{1}$$

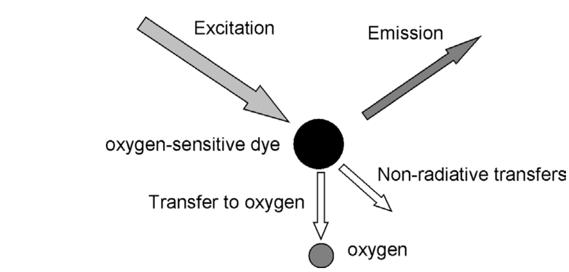

Fig. 1. Pressure sensitivity principle.

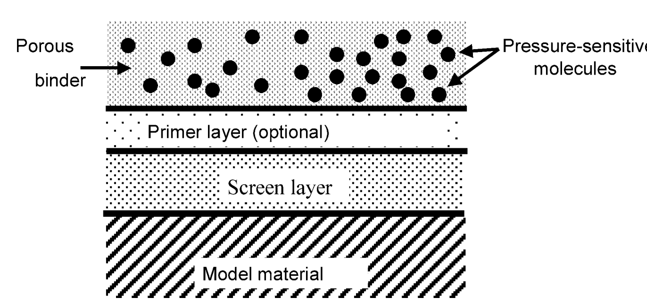

Fig. 2. PSP coating.