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INVESTIGATION OF UNIFIB-400 PRESSURE-SENSITIVE PAINT LOW SPEED PERFORMANCE

Henrique Fanini Leite
Instituto Tecnológico de Aeronáutica (ITA)
leite05@hotmail.com

Ana Cristina Avelar
Intituto de Aeronáutica e Espaço (IAE)
anacristina.avelar@gmail.com

Layra Mendonça Silva
Instituto de Aeronáutica e Espaço (IAE)
layramendonca@gmail.com

João Batista Pessoa Falcão Filho
Instituto de Aeronáutica e Espaço (IAE)
jb.falcao@ig.com.br

Roberto Gil Annes da Silva
Instituto Tecnológico de Aeronáutica (ITA)
roberto.gil.silva@gmail.com

Abstract. *Following the successful introduction of conventional pressure-sensitive paint measuring techniques at IAE, there has been an effort to expand its capabilities to low-speed and High-frequency measurements, to which new types of paint and equipment have been acquired. To properly evaluate the benefits of these new techniques, however, it is necessary to understand the limitations of the current PSP system. In view of that, a NACA-0012 airfoil was coated with UniFIB-400 paint and its pressure distribution was determined for two angles of attack and speeds as low as Mach 0,05. The results were compared to pressure tap data, and the minimum speeds at which UniFIB-400 was able to provide accurate results were determined*

Keywords: *Low-speed, Pressure-sensitive Paint, NACA-0012 airfoil, Pilot Transonic Tunnel*

1 INTRODUCTION

Pressure distribution is one of the most important data related to aerodynamic flows around any model. It is fundamentally important in the detection of shock waves, boundary layer separation and, when integrated over a surface, it provides the aerodynamic loadings on the model. Traditional pressure measurements are based in pressure taps, which provide discrete static pressure measurements over the model. Even though they provide highly accurate measurements, they are hard to build and aren't able to provide field measurements, sometimes failing to detect important phenomena, especially in small surfaces, such as corners.

Pressure Sensitive Paint is a relatively new technology that has become an important measurement technique in wind tunnels. Compared to pressure taps, PSP allows for lower costs, thanks to a simplified model construction, as well as more versatility, since it provides the pressure distribution over entire models. In addition, it is non-intrusive and has high spatial resolution (Mantel, 2005).

The PSP working principle is the sensitivity of some special dyes, called luminophores, to oxygen. These dyes are dispersed throughout a paint binder which is sprayed over the model. When excited by a light pulse, the luminophores absorb photons and jump to a higher energy state. To recover its original state, the molecules can either emit a photon back or transfer it's absorbed energy to an oxygen molecule, where it becomes vibrational energy. This is called oxygen quenching and is responsible for the dependence of luminecesnce to the partial oxygen pressure. The higher the concentration of oxygen, the lesser the photon emission (Fang, 2010).

A typical PSP setup includes a test model painted with PSP, an excitation source, which is usually a LED lamp or a laser, and a photodetector with a long-pass filter. The filter is required to avoid interference from other light sources. The paint is excited by the LED or the laser and its luminescence is captured through the photodetector, usually a CCD Camera.

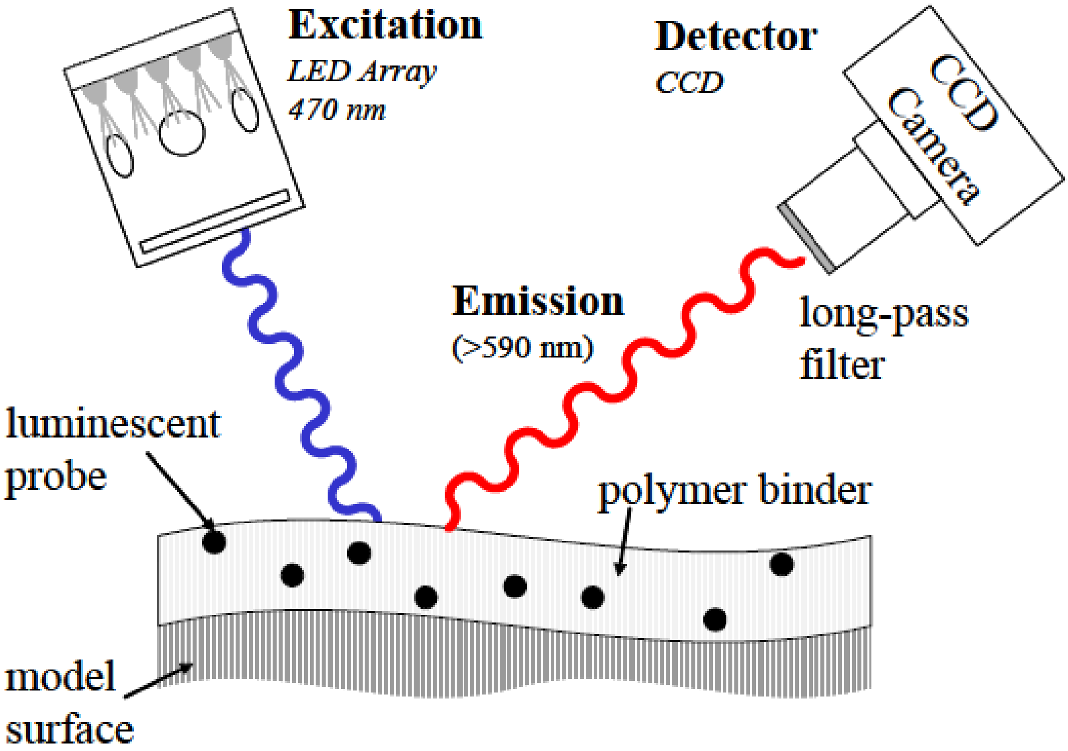

Figure 1. Basic Pressure Sensitive Paint system

1.1 Intensity Based Methods

There are many ways to relate the recorded data to pressure, which can be divided in intensity-based methods and lifetime-based methods. Intensity-based methods were the first to be developed and are still widely used. They derive the pressure by comparing the luminescence of an image taken at test conditions (wind on) to the luminescence of a reference picture (wind off). The luminescent intensity of the PSP is inversely related to the concentration of oxygen, and, therefore, pressure. It is described by the Stern-Volmer equation (Strojki, Majkut, Dykas, 2015):

$$\frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \quad (1)$$

One of the shortcomings of the intensity-based method is that it is very sensitive to motion between wind off and wind on images, which might happen due to the aerodynamic forces applied to the model at test conditions. Also, there might be differences in paint contamination, light stability, temperature and paint degeneration due to the time elapsed between capturing the wind-off and wind-on images, (Stich, 2009).

1.2 Lifetime Based Methods

Lifetime-based methods can be divided in frequency domain and time domain approaches. They are considered to be potentially superior to intensity-based methods because they are not affected by scattering or reflection, light instability, or by paint contamination and degradation. These methods are based in the relationship between luminescent lifetime decay and oxygen pressure, which can also be described through the Stern-Volmer equation (Yamashita, Nagai, Asai, 2007):

$$\frac{\tau_{ref}}{\tau} = \frac{I_{ref}}{I} = A + B\frac{p}{p_{ref}} \quad (2)$$

τ is the luminescent lifetime and τ_0 is the luminescent lifetime at a reference condition, where pressure is known. It is, however, hard to determine luminescent lifetime directly. To solve this problem, it is usual to infer τ by the ratio of luminosity intensities captured at two different time gates after a pulsated excitation source. The actual value of τ does not need to be determined, since pressure can be calculated through (Yamashita, Nagai, Asai, 2007):

$$\frac{R_{12}(p,T)}{R_{12}(p_{ref},T_{ref})} = A'(T) + B'(T)\frac{p}{p_0} \quad (3)$$

where $R_{12}(p,T)$ is the ratio of intensities captured at two different time gates after an excitation pulse and $R_{12}(p_{ref},T_{ref})$ is the same sort of ratio, but determined at known temperature T_{ref} and pressure p_{ref}.

Since this technique does not require direct comparison between wind-on and wind-off images, it is particularly well suited for experiments where model displacement, movement or deformation is an issue. The rationing of images eliminates most of the errors found in simple intensity-based measurements, such as scattering, reflection, paint thickness variations and changes on illumination. The technique described above is said to be in the time domain. An alternative are frequency domain measurements, where the dyes are excited by a sinusoidal modulated light and the luminescence of the probe follows the excitation frequency with a lifetime-dependent delay. This phase shift is measured. Even though these approaches can be related to each other by a Fourier transform, the required setup for a time based experiment is cheaper and less complex (Stich, 2009).

1.3 PSP at IAE

Pressure sensitive paint measurement techniques have been introduced to ITA (Instituto Tecnológico de Aeronáutica) and IAE (Instituto de Aeronáutica e Espaço) in 2009. The first experiments used an intensity based approach, and attained satisfactory results considering the far from ideal conditions of the experiment (Pedrassi, 2009). Since then, the standard approach at IAE has changed to lifetime measurement, having been applied in many experiments, especially in research related to the Brazilian space program and airfoil study (Avelar, *et al*., 2014).

However, the Institute still lacks know how in more complex PSP applications, such as low-speed measurements or high frequency ones. The development of such techniques would greatly expand the range of studies that can be performed at IAE. A special area of interest would be transient regimes, the study of which could bring important insights in many areas. Some examples are the aerodynamic behavior of an accelerating rocket, with obvious applications to the space program, and aeroacustics, an important line of research at ITA. Low speed measurements, on the other hand, could be applied on a variety of studies, from automotive design to flap behavior during landing.

Having this in mind, it is important to determine to what extent the development of such techniques would expand IAE's capabilities. Therefore, a preliminary study to understand the limitations of the current methods is required.

2 EXPERIMENT DESCRIPTION

The experiments were conducted at the Pilot Transonic Wind Tunnel (TTP), located at IAE, in São José dos Campos.

Figure 2. The Pilot Transonic Tunnel

The test section is 30cm wide, 25cm high and 80cm length, with slotted walls and 830W of power. The tunnel operates at a pressure range of 0.5 to 1.25 bars, and its nominal Mach range is 0.2 to 1.3, although in this experiment, speeds as low as Mach 0.05 were obtained. It operates in a conventional, closed, continuous circuit, driven by a main compressor, combined with an intermittent injection system, which operates for at least 30 seconds (Falcão Filho, Mello, 2002).

The model setup is shown in Fig.3

Figure 3. Model Setup

The airfoil was a NACA0012, with chord length of 83mm, with no transition strip. In order to reduce paint wear, total pressure was reduced to 80000kPa. Two angles of attack were studied: 0° and 10°. For the 0° experiment, Mach number ranged from 0.05 to 0.82, while for 10° Mach number ranged from 0.05 to 0.55, resulting in Reynolds of up to 1.2×10^6. The reason for a lower top boundary for Mach number at 10° AoA is that at Mach 0.50 the airfoil stalled.

The PSP measurements were made using a commercial system from Innovative Scientific Solutions, Inc. (ISSI). The model was first painted with FIB basecoat (ISSI FB-200) and then with UniFib 400 (ISSI UF-400). In addition to the painting, the model also had a series of five pressure taps for results comparison. The images were captured by a PCO.1600 CCD camera. The chosen approach was time domain lifetime, with both time gates after the pulsated light source. Both gates were 30μs wide, the first one starting immediately after the light pulse and the second immediately after the first one. For each condition and each time gate, four images were taken, which were averaged and used to calculate the ratio "$R_{12}(p,T)$" used in eq. 3. All PSP results were processed using OMS ProImage. To reduce temperature related errors, all image ratios were further divided by a single image ratio taken at wind off conditions "$R_{12}(p_{ref},T_{ref})$". These ratio of ratios were then related to pressure according to eq. 3 and filtered through a Gaussian filter in order to reduce instabilities.

3. RESULTS

The main goal of the experiment was to determine how well the paint behaved at low speeds and which was the minimum Mach number required to attain acceptable results. Pressure data was obtained using a calibration provided by the paint manufacturer, and then corrected according to the pressure taps data. This procedure was used because a regular shift between PSP and pressure taps data was observed. A possible reason for this is that the paint used was more than a year old, its design shelf life, and its properties might have changed. To further explore this hypothesis, a new calibration will be performed in the future.

Since our object of study was the paint itself, and not the airfoil, it was considered enough to compare PSP data with pressure tap data. In addition, the experiment was performed at lower Reynold numbers than usual, and there was a high probability that the flow remained laminar throughout the whole model, while most data available is for models in turbulent - or at least not completely laminar - flow. All these factors make C_p comparison uncertain, and it wouldn't contribute at all to our conclusions.

For Mach numbers below 0.15, the paint performed poorly, as can be seen in Fig. 4:

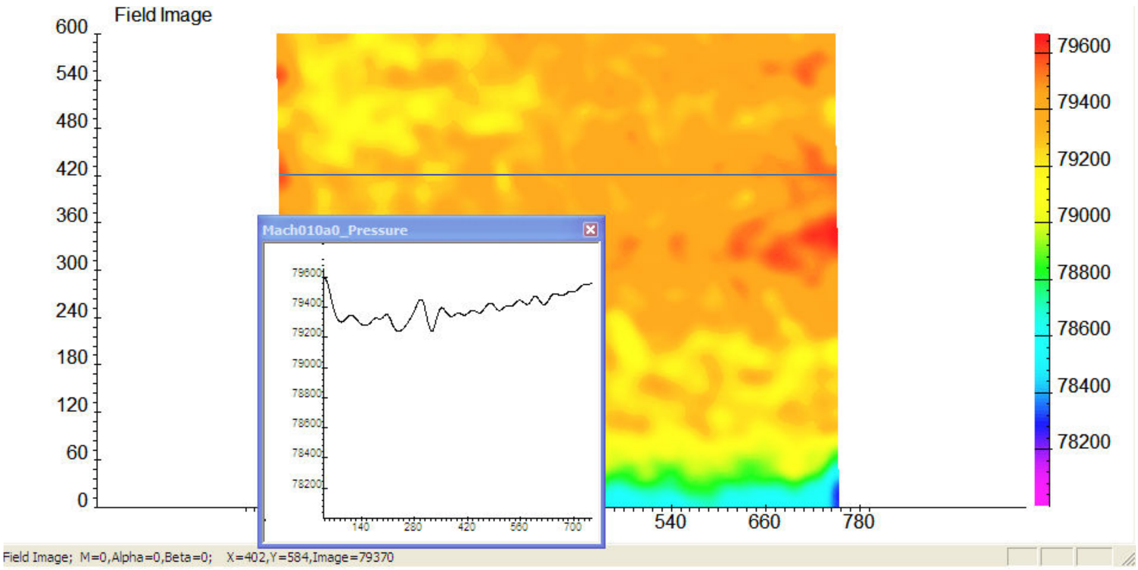

Figure 4. Pressure distribution for Mach=0.1 and AoA=0°

These results were expected, since the paint used was not designed to work at such low speeds. PSP provides a measurement of absolute pressure, and pressure variations at this speed are much smaller than the absolute pressure, resulting in a very low signal to noise ratio. The UniFIB paint has a pressure sensitivity of 0.7% per kPa, while pressures varied by a range of only 400Pa, resulting in around 0,28% maximum change in luminosity intensity. The oscillations seen in Fig. 4 are a direct consequence of this.

At Mach = 0.15, results begin to coincide with pressure tap data, although instability is still considerable. This can be seen on Fig. 5, where it should be noted that the pressure range is smaller than 1000Pa, which is around 1,25% of total pressure. The same problems seen at Mach = 0.1 can be seen at this speed. Another important source of error for these low speeds is the tunnel itself, since it was not designed to work at these speeds, and therefore might have caused velocity oscillations during the test (Falcão Filho, Mello, 2002).

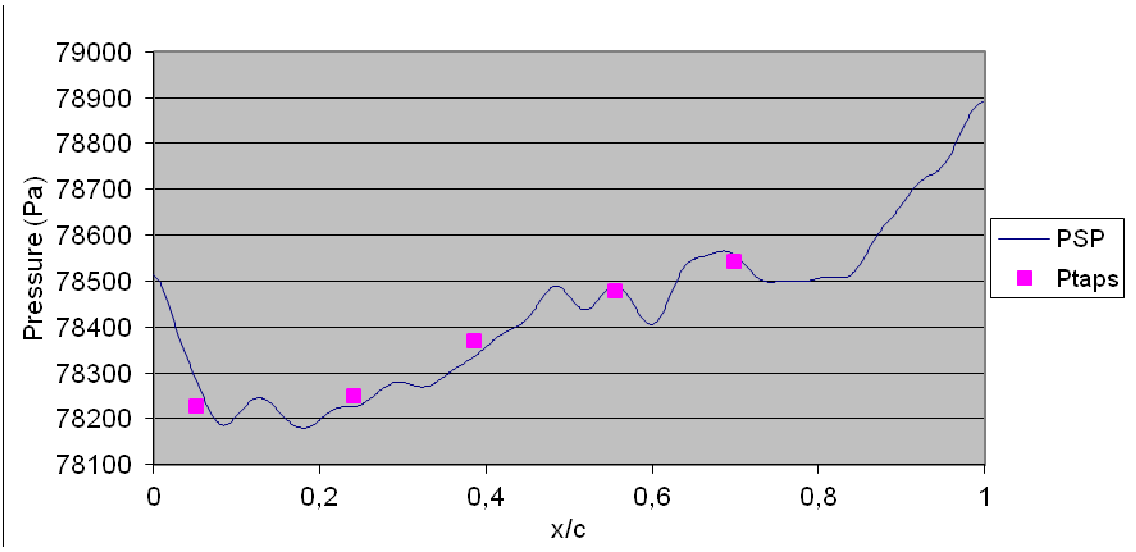

Figure 5. PSP and Pressure Tap data for Mach = 0.15 and AoA = 0°

At this same Mach number, but with an angle of attack of 10°, results were considerably better, as can be seen in Fig. 6:

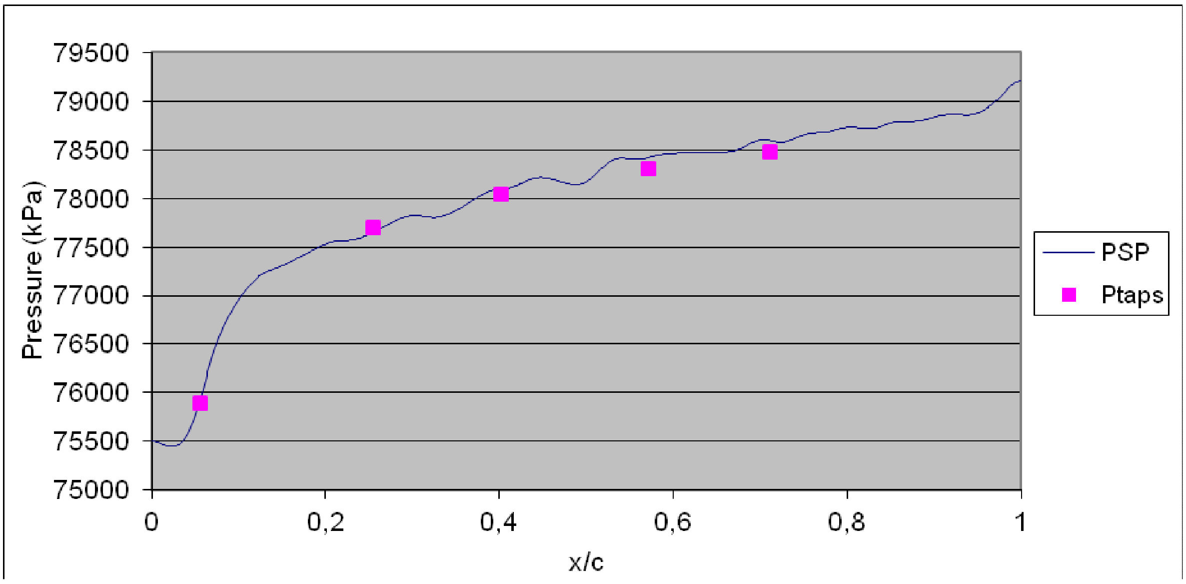

Figure 6. PSP and pressure tap data for Mach = 0.15 and AoA = 10°

Results are in good agreement with pressure tap data, and oscillations are much smaller, a direct consequence of the higher pressure range, which is around 3500Pa. Therefore, UniFIB-400 can be used at relatively low speeds, provided some other aspect of the experiment allows for higher pressure variation. In this case, the higher angle of attack caused a strong pressure differential throughout the chord.

For the 0° experiment, good results are obtained only for Mach numbers equal or higher than 0.3. For Mach number of 0.2, the same instabilities shown in Fig.5 and Fig.6 are seen. For Mach = 0.3, however, the pressure distribution is much better defined, as seen in Fig. 7:

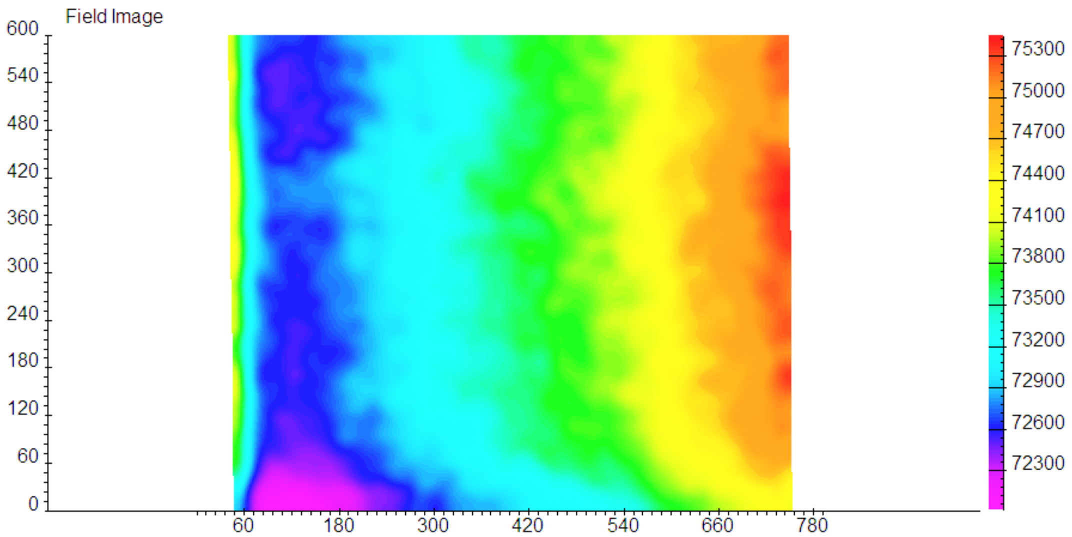

Figure 7. PSP measured pressure distribution for Mach = 0.3 and AoA = 0°

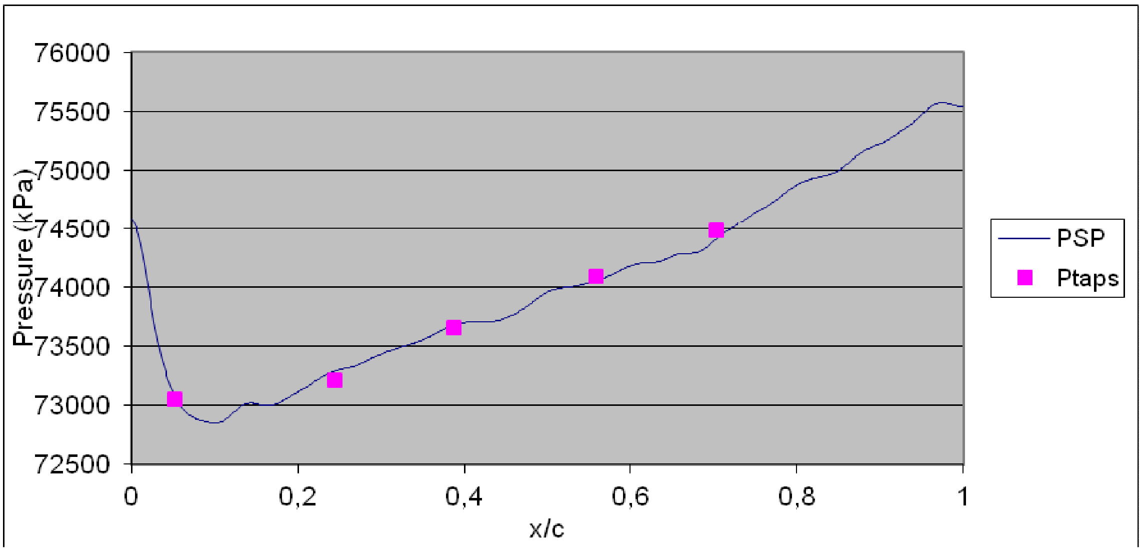

Figure 8. Comparison between pressure data from PSP and pressure taps for Mach - 0.3 and AoA = 0°

Except for the region near the model base, pressure distribution at the airfoil is well defined and in good agreement with the pressure taps data. The anomaly seen at the bottom of the airfoil is probably related to model dealignment or some form of interaction with the tunnel walls, resulting in lower pressures.

4. CONCLUSIONS

In order to determine the limitations of the current PSP experimental setup at IAE, the behavior of UniFIB-400 paint at low speeds was analyzed for two different angles of attack. At zero angle of attack, the paint didn't perform well for Mach numbers lower than 0.3, although PSP data and pressure tap data coincided for Mach numbers as low as 0.15. This was due to the low pressure gradients at these speeds, which resulted in very small luminosity variations and, finally, low signal to noise ratios. For 10° of angle of attack, results were considerably better. The paint performed well for Mach numbers as low as 0.15. This was caused by the much higher pressure gradients caused by the high angle of attack. Temperature gradients, a common source of errors at PSP measurements, didn't compromise any results. This indicates that the ratio of ratios method is well suited for reducing Temperature related errors, but it also should be noted that speeds were low, resulting in much lower temperature variations when compared to PSP experiments performed at more usual Mach numbers.

To further develop IAE's capabilities at low speed PSP measurements, techniques must be developed that allow for measurements at Mach numbers lower than 0.3 without the instabilities seen in the present experiment. This might be attained by using more sensitive paints, or by reducing the sources of errors, such as flow velocity fluctuation and temperature gradients.

6. ACKNOWLEDGEMENTS

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