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João Batista P. Falcão Filho*
Institute of Aeronautics and Space
São José dos Campos - Brazil
jb.falcao@ig.com.br

Ana Cristina Avelar
Institute of Aeronautics and Space
São José dos Campos - Brazil
anacristina@iae.cta.br

Maria Luísa C.da C. Reis
Institute of Aeronautics and Space
São José dos Campos - Brazil
mluisareis@iae.cta.br

*author for correspondence

Historical review and future perspectives for Pilot Transonic Wind Tunnel of IAE

Abstract: The Pilot Transonic Wind Tunnel of Institute of Aeronautics and Space (PTT Pilot Transonic Wind Tunnel) is an important result of a tremendous effort to install a high speed wind tunnel complex (TTS acronyms for Transonic and Supersonic Tunnels, in Portuguese) at the IAE, to support Brazilian aerospace research. Its history is described below, starting from the moment the TTS project was first conceived, highlighting each successive phase, mentioning the main difficulties encountered, and the solutions chosen, up until the final installation of the Pilot facility. A brief description of the tunnel's shakedown and calibration phases is also given, together with the present campaigns and proposed activities for the near future.
Key words: *Aerodynamics, Calibration phase, Experimental tests, Pilot installation, Transonic wind tunnel.*

LIST OF ABBREVIATIONS

AEB	Brazilian Space Agency
ALA	Aerodynamics Division of the IAE
AEDC	Arnold Engineering Development Center (USA)
ARA	Aircraft Research Association Ltd. (England)
BAe	British Aerospace (England)
CFD	Computational Fluid Dynamics
CNPq	National Council for Scientific and Technological Development (Brazil)
CTA	General-Command of Aerospace Technology
DFVLR	Deutsche Forschungs-Und Versuchsanstalt für Luft-Und Raumfahrt e. V. (Germany)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (Germany)
EEI	Industrial Engineering College (São José dos Campos)
FINEP	Brazilian National Agency for the Financing of Project and Studies (Brazil)
GTTS	Work group for the installation of transonic and supersonic wind tunnels facility in Brazil
IAE	Institute of Aeronautics and Space (of the CTA)
JAXA	Japan Aerospace Exploration Agency
ONERA	Office National D'Etudes et Recherches Aeroespatiales
NAL	National Aerospace Laboratory (Japan)
NASA	National Aeronautics and Space Administration
NLR	National Lucht-En Ruimtevaartlaboratorium (Netherlands)
PSP	Pressure Sensitive Paint
PTT	Pilot Transonic Wind Tunnel (at the Aerodynamics Division of the IAE)
TA-2	Brazilian Subsonic Industrial Wind Tunnel at the Aerodynamics Division of the IAE
TsAGI	Central Aero-Hydrodynamic Institute (Russia)
TTS	Transonic and Supersonic Wind Tunnels (Brazil)
UNITAU	University of Taubaté
UNIVAP	University of Vale do Paraíba
USP	University of São Paulo

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INTRODUCTION

The Pilot Transonic Wind Tunnel of Institute of Aeronautics and Space (PTT - Pilot Transonic Wind Tunnel) originated from the TTS-Project (Complex of Transonic and Supersonic Wind Tunnels).

The TTS-Project was created in the mid-eighties with the aim of building a high speed aeronautical complex of wind tunnels, as a suitable tool for the Brazilian aeronautical industry. This effort would allow aerodynamic tests in the high speed range (up to Mach number 4), reaching strategic goals of safety and up-to-date testing for new Brazilian aerospace projects for the Air Defense. At that time, the only industrial wind tunnel was the subsonic TA-2, with a test section of dimensions 2 m 3 m. The first step was carried out in 1985, with the creation of a work group to study the problem. The first task was to contact potential national users through technical meetings to draw up an extensive report to fully support the idea for the next phases of the project. Embraer, Avibrás, D. F. Vasconcelos, and Engesa companies; and the IAE/CTA research institute were contacted at that time (David *et al.*, 1985). After processing the collected information, a first technical specification for two industrial facilities was undertaken: one continuously driven transonic wind tunnel (test section of 2 m x 2.4 m and Mach number from 1.2 to 1.4); and another intermittent supersonic blowdown wind tunnel (test section of 1.2 m x 1.2 m and Mach number from 1.2 to 4.0). Embraer appeared as the main client for both wind tunnels, with about 52 per cent of the occupation time (GTTS, 1986, Escosteguy, 1987). The first conception of the tunnels was at that time a very modern installation including some technological challenges. Some important references in transonic tests were consulted during the initial specifications (Davis *et al.*, 1986, Wu and Moulden, 1976, Goethert, 1961, Reed *et al.,* 1977, Pope and Goin, 1978, Steinle and Stanewsky, 1982, Eckert *et al.*, 1976). The transonic wind tunnel would be continuously driven not only by a main compressor but also by an injection system, which would help to enlarge the operational tunnel envelope, without penalizing the installed power. Because of this new feature, a pilot transonic wind tunnel was conceived in order to test this challenging new idea, and a special concern was raised about the optimization of running conditions by setting the automatic system parameters in a combined action of the main compressor and the intermittent injection system. This tunnel is a 1/8th scale down of the planned industrial transonic facility, completely representative of its functions and subsystems.

With the specifications defined, the work group sought a specialist company as a partner for the project. Figure 1 shows the operational envelopes of the wind tunnel facilities (present subsonic TA-2, planned transonic and supersonic wind tunnels, and the Pilot Transonic Tunnel).

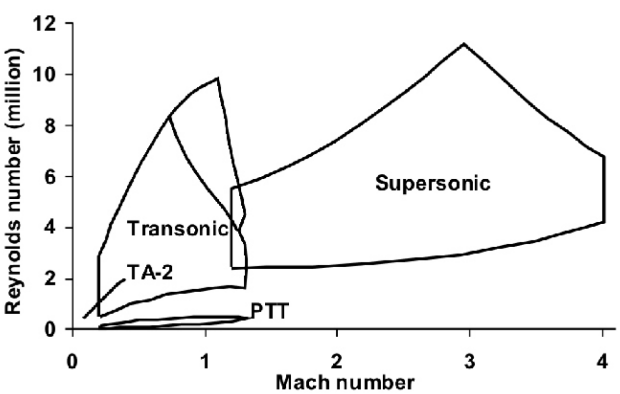

Figure 1: Operational envelopes of the wind tunnels in the planned facilities of CTA - Reynolds number is based on typical chord.

After completion of the technical and commercial analysis the Sverdrup company was chosen. During two technical visits (one to Europe and another to the USA) the GTTS work group contacted ONERA, DFVLR, NLR, BAe, ARA in Europe (Nogueira and Passos, 1986a), and FluiDyne, Calspan and Sverdrup, in USA (Nogueira and Passos, 1986b). The work group spent a 6-month period at Sverdrup Technology Inc., which was responsible for the development of the conceptual design of the industrial transonic facility (Sverdrup, 1987a) and of the detailed design for a scaled down 1/8th pilot transonic facility (Sverdrup, 1987b).

For several reasons, mostly related to budget restrictions, only the pilot facility design was completely built. Table 1 summarizes the main events during the TTS Project and shows perspectives for the near future under the present test campaigns.

In order to emphasize the importance of government participation in this kind of effort, it should be mentioned that, a wind tunnel project has a typical investment return of around 20 years, which generally makes them not very attractive to private companies, although these are also potential users.

Therefore, wind tunnel projects are naturally considered a government issue. Moreover, it is considered a government issue also because it should be a political and strategic decision to invest in the technological strengthening of the nation's Aerospace power. It is also worthwhile to set forth the pioneering work done by the GTTS team in creating the possibility of a high speed aerodynamic test facility in Brazil, which today possesses only one subsonic industrial installation, while other countries with lesser aeronautical traditions, such as South Africa, Indonesia, Holland, China and Iran, have their own.

Some important issues were assessed during the TTS project development, and they are worth noting. For example, the installation site definition. Considering criteria of the proximity of existing tunnel installations (subsonic tunnel TA-2), the availability of shared resources (technical team, computing, electricity, model shop etc.), the proximity of potential clients, allowing quick exchanges of people and materials, the availability of electricity and water (as obtained from the suppliers at that time), the installation of the TTS close to the lake in IAE, near the TA-2 subsonic tunnel facility, was a common sense solution among other possible sites considered.

Figure 2 shows the selected site for the TTS project. Other important aspects were also considered, such as potential for future expansions, the environmental impact (cutting of trees, noise, chemically treated water leakage impact, etc.), interference in non-industrial areas, easy access, access to high voltage electric cables, easy access for employees, site preparation, installation of security and costs. After that, the chosen site was thoroughly investigated, and land sounding was performed, annual temperature and wind cycles, water availability and physical-chemical properties were determined, a study of the renewable water source from the lake was considered and availability of electrical energy was investigated by the source supplier.

To perform these studies, the TTS technical team consulted competent sectors, such as INPE, Eletropaulo, Sverdrup Technology Inc., and other CTA divisions and institutes.

Table 1: Main events during TTS Project.

Year	Events
1985	● Creation of the TTS technical team;
1986	● Contact with potential users (technical report made);
1986-1987	● Technical specification definition for two industrial wind tunnels (one transonic and one supersonic); ● Possible installation site analysis and definition, based on natural and available resources; ● Graphic conception to comply with operation and security requirements; ● Research for international and national expertise in wind tunnel design and industrial support;
1988-1989	● Research for environmental data and land characteristics to support the idea of installation nearby the TA-2 site; ● Conceptual design of the TTS wind tunnel complex with the help of Sverdrup Technology Inc. (USA); ● Restriction from US DoD to the Supersonic Project; ● Brazilian government economic restrictions led to the Pilot Transonic Tunnel design; ● Conceptual design of PTT, and definition of systems and components, by Sverdrup Technology Inc. (USA);
1990-1992	● Search for financial resources from Air Ministry, DIRENG and FINEP research funding organization to proceed with the Industrial Transonic Facility; ● Technical studies of Pilot Transonic Tunnel aerodynamic circuit;
1993-1995	● Detailed design of the Pilot Transonic Tunnel with open aerodynamic circuit, driven only by injection system; ● Construction and Installation of the Open Circuit Pilot Transonic Tunnel at ITA;
1996-1997	● Use of US$ 3 million (90% from Air Ministry, 10% from FINEP) in the complete aerodynamic circuit design and construction of the pilot facility; ● Installation of the Pilot Transonic Tunnel at ALA; ● Search for alternatives for a low cost Industrial Transonic Facility at TsAGI (Russia);
1998-1999	● Search for resources to start-up TTP main components (inverter, motors, compressors), circuit alignment and systems integration main program;
2000-2001	● Aerodynamic circuit alignment; ● Start-up of main power group and other tunnel components; ● Automatic control systems integration and main control program based on LabView platform; ● Data control and acquisition equipment installation;
2002-2004	● Tests for automatic control systems adjustments; ● Systems integration tests; ● Pilot Transonic Tunnel Calibration tests;
2004	● Damage caused by an atmospheric electric discharge on the main inverter;
2005-2006	● Search for financial resources and from FINEP to fix the main inverter; ● Calibration tests performed using injection system with open aerodynamic circuit;
2007-2010	● Resources approved by FINEP to fix and modernize the control systems for the PTT; ● Development of project from VLS Associated Technologies (AEB) to obtain know-how in sounding vehicles technology, by performing tests with VS-30; ● Development of project from VLS Associated Technologies (AEB) to obtain know-how in Pressure-Sensitive-Paint (PSP) in sounding vehicles testing, by performing tests with VS-40

Special computing programs were developed to calculate the noise distribution in the nearby area based on the noise source data provided by Sverdrup Technology Inc., and to evaluate the impact of a high pressure air reservoir burst. All this information is documented in the TTS project (GTTS, 2009) and presenting the results here would be too long.

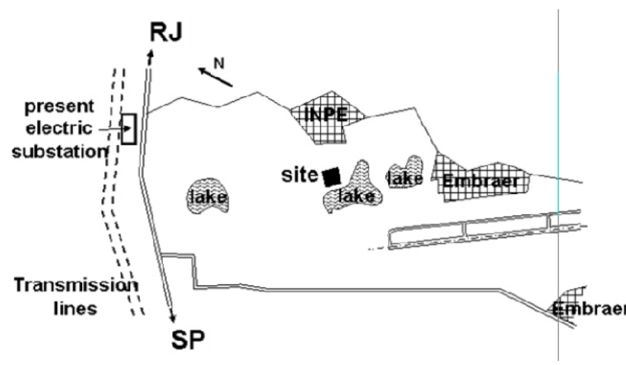

Figure 2: Proposed TTS installation site.

The project has inspired many theoretical studies to clarify specific technical aspects of the wind tunnel, among them, Master Degree thesis (Falcão Filho, 1996) and Doctoral Degrees dissertations (Fico Jr., 1991; Falcão Filho, 2006), besides many other scientific reports (Nogueira *et al*., 1988; Nogueira and Falcão Filho, 1998; Ortega and Escosteguy, 1988; Falcão Filho, 1990; Ortega and Fico Jr., 1991; Fico Jr. and Ortega, 1993; Escosteguy and Nogueira, 1997; Vieira *et al*., 1997a, 1997b; Falcão Filho *et al*., 1998, 2000a, 2000b, 2000c; Falcão Filho, 2000; Escosteguy, 1998; Falcão Filho and Ortega, 2007a, 2007b, 2008).

The TTS project had, in chronological order, the following heads: Flávio de Carvalho Passos (Lieutenant Colonel, 1985-1986), Marcos Luiz Pereira (Colonel, 1986), Sidney Lage Nogueira (Civilian, 1986-1987), Wilson Cavalcanti (Lieutenant Colonel, 1987-1988), Roberto Kessel (Colonel, 1988-1990), Sidney Lage Nogueira (Civilian, 1990-1997), and João Pedro Caminha Escosteguy (Civilian, 1997).

The original TTS project for building industrial facilities for high speed tests was practically interrupted in 1997, when the PTT was still under construction. At that time, the GTTS technical team prepared a report considering some of the possible options to be adopted in order to attain the original goal of having a high speed aerodynamic tests capability in Brazil. Part of the work group went to Russia (in TsAGI) for 10 months, sponsored by the CNPq agency, for a scientific expertise analysis of the original conceptual design for a lower cost transonic wind tunnel design as an alternative solution (Neiland, 1997). Table 2 shows the four possible situations set forth at that time, which are still under consideration by our authorities. The estimated cost values in Table 2 refer to the present time, taking into account monetary inflation over this period.

Table 2: Four alternatives for the TTS project continuation. Costs in millions of US$ and the electric power installed in MW.

	Description	US$ millions	MW	Advantages	Disadvantages
1	Original conception	150	110	Very modern and versatile installations	Expensive; Long period until fully operational (8 years)
2	Revision based on the Russian proposal made in 1997	90	80	Cost reduction	Limited productivity; Long period until fully operational (6 years)
3	Development of a blow-down trisonic project	50	30	Considerable cost reduction	Limited tests capabilities and productivity;
4	Acquisition of an existing blow-down trisonic facility	30	20	Short period to become fully operational (2 years)	Limited test capabilities and productivity; Eventual technical problems to be detected

Under the new idea of having only the pilot transonic tunnel, the GTTS work group extended the original conception to obtain a more versatile facility. So, the tunnel would be useful not only to test the new technological challenges for the industrial facility, such as the combined operation with the injection system, but also to perform all kinds of academic tests and tests with simple configuration models.

Main Characteristics of the Pilot Transonic Facility

The PTT (Pilot Transonic Tunnel) is a modern installation, with a conventional closed circuit, continuously driven by a main compressor of 830 kW of power, and with an intermittent injection system which operates in a combined mode, for at least 30 seconds. Its test section is 30 cm wide and 25 cm high, with slotted walls. The tunnel has automatic pressure controls (from 0.5 bar to 1.25 bar), Mach number (from 0.2 to 1.3), temperature and humidity, in test section. Figure 3 shows its operational envelope.

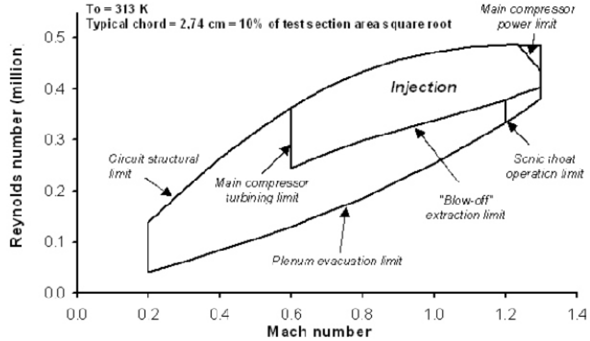

Figure 3: PTT's operational envelope.

All subsystem automatic controls use National Instruments data transfer cards with LabView computer interface. Technical details regarding PTT can be found in Falcão Filho and Mello (2002).

The tunnel is a 1/8th scale down from the industrial transonic project, and it was initially designed to study the innovative features of the industrial facility, specifically concerned with the injection system operation in combination with the conventional main compressor operation. It was also designed for training the technical team in high speed tests, to perform basic research and academic research assessment, to produce tests in developing new aerodynamic transonic profiles, tests with simple geometry vehicles, qualitative tests of airplane basic configuration, anemometric tests, and others. To accomplish this, the tunnel has three sets of six multi-component internal balances manufactured by MicroCraft for measuring forces and moments, two modules of 16 pressure channels PSI (Pressure Sensitive Instrument) for pressure distribution tests, a Schlieren visualization system, hot-wire equipment, and will have in the near future a PSP (Pressure Sensitive Paint) technique to determine pressure distribution over the model surface. In addition, the tunnel possesses a 2D probe positioning system, angle of attack remotely controlled system and re-entry flap capability. Figure 4 shows a partial view of the aerodynamic circuit of the PTT.

Figure 4: Partial view of the PTT aerodynamic circuit.

In addition to Sverdrup Technology Inc. (USA), which was responsible for the project design, many other national companies and inner sectors from CTA worked together with the PTT technical team during the design, construction, installation and shakedown tasks of the tunnel project. Among them, IAE (manufacture of many internal parts of the aerodynamic circuit), Embraer (manufacture of some internal parts of the plenum chamber), ABLE (all detailed drawings), INNOBRA (aerodynamic circuit manufacture), M. C. Rocha (tubing installation and aerodynamic circuit alignment), NavCon (integrated control program development), and other components and systems suppliers, ABB (main power generation and control), Martin Bianco (auxiliary compressors and dryers), KMS (high pressure air reservoirs), HITTER (control valves), Masoneillan (injection system control valve), ALPINA (cooling tower), ITAIPU (high voltage electrical transformer).

Shakedown and Calibration Results

From 2002 to 2004, and also more recently, the PTT was subjected to many tests to set subsystem automatic control parameters, installed characteristics and working limits (operational envelope) determination, known as shakedown procedures. The phase where many attempts to assess to all functional characteristics of the tunnel are made over a relatively long period of time is called calibration phase, and it is fundamental in order to guarantee precision levels and productivity, for future tests. During this period of time, all the technical and operational characteristics of the tunnel are documented and used as a reference for future tests.

Due to an atmospheric electric discharge which caused the main inverter failure, the calibration phase had to be shortened and limited in many aspects. Some procedures and results will be investigated only in the near future. However, many other significant outcomes have been already obtained, as described in Table 3.

Table 3: PTT Shakedown and calibration reports .

	Description	Documentation
1	Preliminary Tests with PTT in Open Circuit	Escosteguy, 2000
2	Injection System Behavior in Open Circuit	Falcão Filho and Mello, 2001
3	Preliminary Calibration Results of PTT	Falcão Filho, 2003
4	Schlieren System Installation in PTT	Miranda, 2004
5	Numerical Study of Injection System Operation	Falcão Filho and Ortega, 2007
7	Longitudinal Mach Number Distribution in Test Section (I)	Silva and Falcão Filho, 2007
8	Reservoirs Polytropic Coefficient Determination	Goffert and Falcão Filho, 2008
9	Longitudinal Mach Number Distribution in Test Section (II)	Zanin *et al.*, 2008a
10	Multi-Component Internal Balance Calibration	Tagawa *et al.*, 2008
11	Injection System Behavior in Closed Circuit	Goffert *et al.*, 2008a
12	Calibration of Flow-meter by insertion turbine	Goffert *et al.*, 2008b
13	Dryer System Analysis	Zanin *et al.*, 2008b
14	Parameters Identification for Injection System	Truyts *et al.*, 2008
15	Calibration Uncertainty Estimation for Internal Balance	Reis *et al.*, 2008

Figure 5 shows one of these results where a Mach number distribution along the nominal test section can be seen. This kind of graphic is used to establish optimum operational conditions at a determined Mach number, by analyzing reentry flaps and plenum chamber forced mass flow extraction effects.

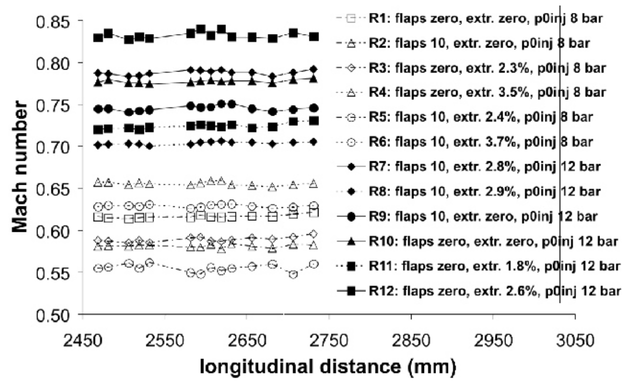

Figure 5: Test section longitudinal Mach number distribution.

Another result is the calibration of internal balances which makes it possible to carry out analysis of aerodynamic loads acting on the model being tested in wind tunnels. A calibration rig was mounted in the PTT area (Fig. 6) and a methodology was developed for the assessment of the uncertainty of the loads supplied by the internal balance. The methodology follows international standardization and it is presented in Reis (2008).

Figure 6: Internal balance calibration rig.

Sounding Vehicles Tests

As a transonic wind tunnel, the PTT is a suitable tool to be used to investigate important effects in the transition range. Particularly for IAE sounding vehicles, some physical phenomena can be more precisely assessed and be used for CFD code comparisons. These ideas inspired the proposals for a project, approved for implementation over the period 2007 until 2010, sponsored by the AEB agency through VLS Associated Technology Projects, to perform a complete test campaign with the sounding vehicle Sonda III, named “Realização de Ensaios do VS-30 no Túnel Transônico Piloto do IAE” (Tests Development with VS-30 in the IAE Pilot Wind Tunnel), with financial resources in the order of R$ 300,000.00, with the objective of achieving know-how about sounding vehicles tests. This way, the PTT technical team will be able to help the IAE in its vehicles design research area. Figure 7 shows the Sonda III model installed in the PTT test section to perform forces and moments tests. A new model is currently being prepared with pressure taps in order to analyze pressure distribution on its surface. The experimental data will be compared with CFD results.

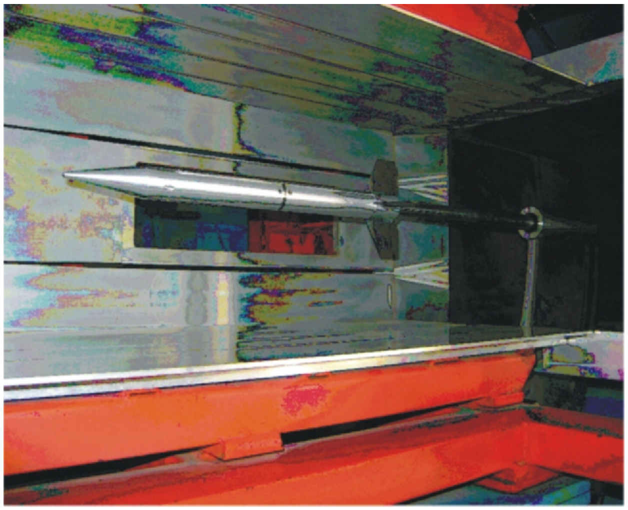

Figure 7: Sonda III installed in the PTT test section.

To support the new PTT activities, a maintenance Project sponsored by FINEP, "Projeto MCT/FINEP/CT-INFRA PROINFRA 01/2006", costing around R$ 220,000.00, is presently underway to fix the main inverter unit and modernize the tunnel's automatic control system.

To implement these projects, the PTT technical group has welcomed the assistance of many undergraduate students from some outstanding universities (ITA, UNITAU, USP-São Carlos, EEI, UNIVAP) who have participated in academic tasks of scientific initiation (PIBIC-IAE), sponsored by a grant from the CNPq, among other academic activities. Each contribution is either documented by internal reports or reported in conferences (Goffert and Falcão Filho, 2008, Goffert *et al.*, 2008a, 2008b, Zanin *et al.*, 2008a, 2008b, Tagawa *et al.*, 2008). It should be noted that a wind tunnel with these characteristics has an important role in the training of undergraduate and graduate students, since it is ideally suited to performing basic research in aerodynamics.

FUTURE PERSPECTIVES

New technological advances are expected with a new project, approved for implementation between 2008 and 2010, also sponsored by the AEB agency through VLS Associated Technology Projects, to perform tests with the sounding vehicle VS-40. The project title is "Implantação da Técnica de Tintas Sensíveis a Pressão no Túnel Transônico Piloto da ALA para Realização de Ensaios em Modelos de Veículos de Sondagem" (Implementation of the Pressure Sensitive Paint Technique in the Pilot Transonic Wind Tunnel of ALA for Tests in Sounding Vehicles Models). Resources in the order of R$ 200,000.00 are being used to acquire special equipment (camera, paints, special devices etc.), and for training courses.

In the PTT, as with almost all practical aerodynamic testing or basic fluid mechanics experiments, surface pressure measurements are of fundamental importance.

Until recently, wind tunnel pressure measurements were performed solely by the use of pressure taps, which need to be connected to transducers. This complicates the model design, it is time-consuming and expensive. In the 1980s the use of the optical measurement method of Pressure Sensitive Paint (PSP) to acquire surface pressure was developed (Denovan *et al.*, 1993, Troyanovsky *et al.*, 1993, Volan and Alati, 1992, Peterson and Fitzgerald, 1980, Kavandi *et al.*, 1990). This method uses a special coating (paint) and digital-imaging technology to obtain surface pressure information at high resolution, and has recently emerged as a powerful tool for global pressure distribution. The fundamental operating principle of PSP is the oxygen quenching of luminescence from the paint.

Light intensity emitted by the paints is measured by a photo-detector, and is inversely proportional to the local air pressure. More details about the PSP principle can be obtained in Liu and Sullivan (2005) and also in the reviews by Bell *et al.* (2001) and Liu *et al.* (1997). Conventional paint formulations were first applied to wind tunnel testing in the late 1980s and early 1990s, when the initial tests demonstrated that PSP could successfully resolve the chordwise pressure distribution on a wind tunnel model (Gregory *et al.*, 2008).

This method is especially effective for the higher-speed flows (transonic and higher), where the pressure levels and differences are in a much higher percentage of the ambient pressure. The main advantage of the PSP technique is that, in principle, a full spatial distribution of the surface pressures can be obtained, with the spatial accuracy determined by the characteristics of the camera lens and charge-coupled device (CCD). The richness of information that can be extracted from the images permits the investigations of complex flows and comparisons with CFD results. It also offers savings in terms of model instrumentation cost and model construction time. Initially the investment required is, typically US$ 50,000.00, which can be amortized over several tests.

Nowadays PSP is a well-established surface pressure measurement method, used in transonic wind tunnels in several research institutions around the world: NASA (Ames, Langley and Glenn), Boeing Seattle, Boeing St. Louis, Purdue University, Arnold Engineering Development Center (AEDC), University of Florida, Air Force Laboratory Wright-Patterson, in USA, British Aerospace (BAe) and DERA, in England, DLR, in Germany, ONERA, in France, National Aerospace Laboratory and JAXA Aerospace Research Center, in

Japan, TsAGI, in Russia, among others. A review of PSP paints used for high-speed and unsteady aerodynamics was presented by Gregory *et al.* (2008), and it was shown that significant strides have been made in the development of PSPs for unsteady measurements, although there remains a substantial amount of work to be undertaken to further develop the technology. A lot of research has also been done in improving PSPs for use in low-speed conditions. One company, JAXA, has already achieved results with PSP in low-speed conditions for the development of aircrafts.

The PTT wind tunnel work group is seeking new partnerships with universities and aeronautical companies to maintain and develop its research activities in the high speed realm. In this sense, a new project with Embraer has just come up with the aim of Silent Jet Research, sponsored by FINEP. The tunnel installation will have its capacity increased to perform tests on high speed jets over long periods inside a specially constructed fully instrumented anechoic chamber.

Further applications are being considered for the PTT, like, new transonic airfoils development, research on unsteady aerodynamics, tests of special flight devices, such as trailing cones and anemometers.

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