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Improvements of the Primary Measuring System in the T-38 Wind Tunnel

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The Mach number is the main similarity parameter in high-speed flows and its measurement is of fundamental importance in wind tunnel testing. Errors in measuring the Mach number are propagated as significant errors in the determination of aerodynamic coefficients. In a recent effort to improve the quality of measurements in the supersonic speed range of the trisonic T-38 wind tunnel of the Military Technical Institute (VTI) in Belgrade, an upgrade of the system of transducers and probes used to measure the test section flow parameters has been made, accompanied by an upgrade in the pressure-transducer-calibration system

Key words: **wind tunnel, wind tunnel testing, measuring system, pressure measurement, pressure transducer, pressure probe, calibration.**

Introduction

SINCE the Mach number is the main similarity parameter in high speed flows, its measurement is of fundamental importance in wind tunnel testing. Many types of tests results in high-speed wind tunnels are sensitive to various extents to errors in Mach number determination. For example, at Mach 3, a one percent error in the Mach number will result in an approx. 3.5 percent error in the computation of the force coefficient, Fig.1, [1].

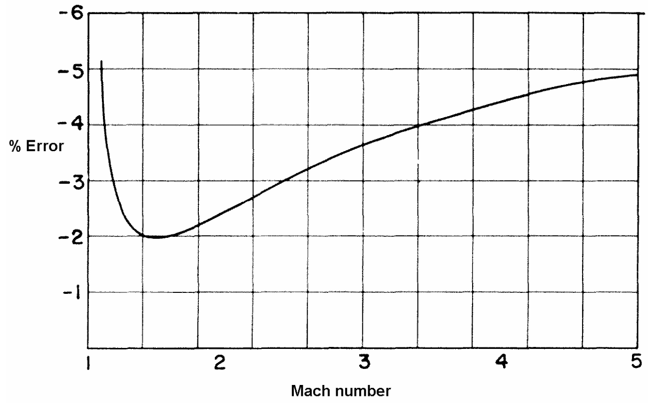

Figure 1. Error in the force coefficient for the 1% error in the Mach number, [1]

Wind tunnel model production and force measuring standards are sufficiently precise to permit measurements of coefficients to within 1 percent or better; therefore, the Mach number must be known to better than, approximately, 1/3 percent to maintain such accuracy. It will be assumed that, in order to know the Mach number to within 1/3 percent, pressure calibration measurements should be made to approximately 1/10 percent accuracy, and errors of this magnitude cannot be disregarded [1]. It is clear that pressures in a wind tunnel circuit must be measured with high accuracy.

In a recent effort to improve the quality of measurements in the supersonic speed range in the T-38 wind tunnel [2] of the Military Technical Institute (VTI) in Belgrade, an analysis has been made of the methods of measurements of the parameters of the flow in the test section of the wind tunnel. Based on that analysis, an upgrade of the system of transducers and probes (the so-called primary measuring system) used to measure these parameters has been made, accompanied by an upgrade in the pressure-transducer-calibration system.

Determining the Mach number in the T-38 wind tunnel

The Mach number in the lower supersonic speed range of the T-38 wind tunnel is calculated [3] from the values of two measured pressures: the stagnation pressure P_0 in the wind tunnel settling chamber and the static pressure P_{st} in the wind tunnel test section. The measurement points for these pressures are shown in Fig.2. The settling chamber pressure is measured by a transducer connected to a Pitot probe while the test section static pressure is measured by a transducer connected to a wall orifice. The Mach number M and the dynamic pressure q are then calculated from isentropic relations (1) and (2), κ being the ratio of specific heats for the air.

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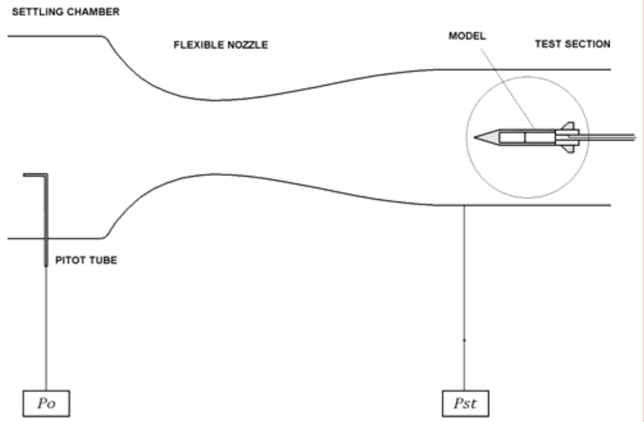

Figure 2. Measurement points of relevant pressures for the Mach number calculation

$$M=\sqrt{\frac{2}{\kappa-1}\left[\left(\frac{P_{st}}{P_0}\right)^{\frac{\kappa-1}{-\kappa}}-1\right]}=\sqrt{5\left[\left(\frac{P_{st}}{P_0}\right)^{\frac{-1}{3.5}}-1\right]} \quad (1)$$

$$q=\frac{\kappa}{2}p_{st}M^2=0.7p_{st}M^2 \quad (2)$$

The Mach number in a supersonic stream can also be calculated, using the Rayleigh's relation (3), from the measured settling chamber stagnation pressure P_0 and the stagnation pressure P_0' measured behind a normal shock wave in the supersonic flow in the test section; the equation, rearranged as (4) is solved for the Mach number iteratively. Both pressures are to be measured using the transducers connected to the Pitot probes, Figures 3 and 4.

$$\frac{P_0'}{P_0}=\left(\frac{\frac{\kappa+1}{2}M^2}{1+\frac{\kappa-1}{2}M^2}\right)^{\frac{\kappa}{\kappa-1}}\left(\frac{1}{\frac{2\kappa}{\kappa+1}M^2-\frac{\kappa-1}{\kappa+1}}\right)^{\frac{1}{\kappa-1}}=\left(\frac{\left(1.2M^2\right)^{1.4}}{\left(1+0.2M^2\right)^{1.4}\left(\frac{7M^2-1}{6}\right)}\right)^{2.5} \quad (3)$$

$$M=\sqrt{5\left(\left(\frac{P_0}{P_0'}\right)^{\frac{1}{3.5}}\frac{1.2M^2}{\left(\frac{7M^2-1}{6}\right)^{\frac{1}{1.4}}}-1\right)} \quad (4)$$

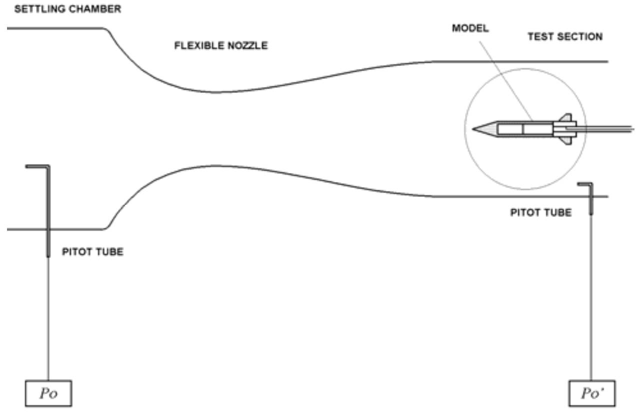

Figure 3. Measuring points of two stagnation pressures for the Mach number calculation

Figure 4. Pitot probes in the settling chamber (left) and in the test section (right) of the T-38 wind tunnel.

It has been shown [4] that the sensitivity of the Mach number calculation (1) to the errors in the measured pressures increases with the Mach number, and that the sensitivity of the Mach number calculation from relation (3) to the errors in the measured pressures decreases with the Mach number. Approximately at Mach 1.6, the sensitivities to errors of both methods are similar, and therefore, ref. [4] states that, above Mach 1.6, it is better (i.e. more accurate) to calculate the Mach number from two measured stagnation pressures (Fig.3) than from one stagnation pressure and one static pressure (Fig.2).

On the other hand, a recent internal analysis [3] performed in the VTI for the T-38 wind tunnel showed that, taking into account the envelope of the operating pressures of the wind tunnel and the necessary ranges of the pressure transducers to be used, the boundary for switching between the two methods of measurements for the calculation of the Mach number is not at Mach 1.6 but between Mach 2.25 and 2.5 (Fig.5). Therefore, it has been decided that, in the future, the method of the calculation of the Mach number from two measured stagnation pressures is to be used in the T-38 wind tunnel at Mach 2.5 and above.

Provisions for the measurement of the test section stagnation pressure in the upper supersonic speed range have already existed in the T-38 wind tunnel but were practically never used because the initial-design location of the Pitot probe in the test section interfered with the flow around the model; furthermore, the said measurement setup complicated accurate measurements of the model base pressure, making the described measurement concept unusable. Instead, the measurement of the wall static pressure (configuration shown in Fig.2) was used at all supersonic Mach numbers, although it was known that the configuration was not an optimum one. However, a convenient location for a Pitot probe, where there is no interaction with the model, has recently been determined, and the probe will henceforward be used in the "upper supersonic" configuration of the wind tunnel test section, from Mach 2.5 upwards. The consequences of the use of this measurement configuration on the accuracy of the measurement of the model base pressure will be determined in soon-to-be-executed wind tunnel tests.

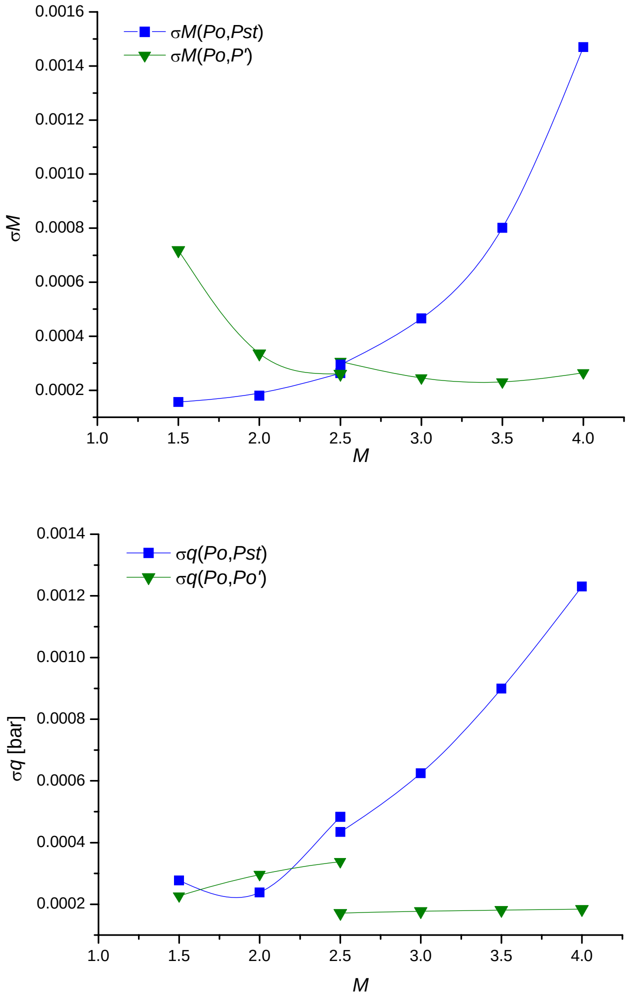

Figure 5. Expected accuracy (standard deviation) for two methods of measuring the Mach number and dynamic pressure in the T-38 wind tunnel, [3]

Replacement of the pressure transducers

The initial configuration of the primary measuring system in the T-38 wind tunnel comprised several *Mensor 11603* pressure transducers of various ranges with quartz Bourdon-tube sensing elements, [5]. Transducer ranges were switched for tests at Mach 3 and above. The nominal accuracy of the transducers was 0.04% FS (Full Scale) but they were routinely calibrated to about 0.02% FS using three *Mensor QM/C* pressure controllers / secondary standards available in the pressure calibration laboratory at the site.

The operation of the 11603-type transducers was not completely satisfactory. The accuracy of the transducers was acceptable but, as they were actually electromechanical devices, each comprising an electronic module but also a miniature servo motor, their response was slow and the transducers sometimes exhibited unexpected shifts in the output, so that an additional reference transducer, measuring the atmospheric pressure, became necessary to monitor and correct the behaviour of other transducers. In addition, over time (more than 27 years since the installation) a number of transducers failed and a necessity developed to replace the complete system.

Several digital pressure transducers of the latest technology generation were, therefore, procured in order to replace the transducers in the transonic and supersonic configuration of the primary measuring system in the T-38 wind tunnel: *Mensor CPT6100* transducers with the ranges of 17 bar, 7 bar and 3.5 bar, and a *Mensor CPT*6180 with the range of 1.4 bar.

The *Mensor CPT*6100 digital pressure transducers [6] are self-contained pressure-sensing devices that provide high-accuracy pressure measurements, Fig. 6, Fig. 7. The accuracy of the transducers is 0.01% FS. This type of transducers incorporates a low-hysteresis micro-machined silicon strain gauge sensor with electronically compensated pressure linearity over a specified temperature range. Communication with the data acquisition system is via an analogue 0-10V output or a RS-485 serial bus. The procured transducers are to be used for the measurement of the settling chamber stagnation pressure, the test section stagnation pressure and the test section static pressure, transducer ranges being switched as suited to particular test conditions.

The *Mensor CPT*6180 high-precision pressure transducers [7] are self-contained pressure sensing devices similar to the *CPT*6100, but with better accuracy (0.01% IS-50 (0.01% of reading down to 50% full scale) instead of 0.01% FS) and better long-term stability (calibration interval is 1 year). Communication with the data acquisition system is via a RS-485 serial bus only. The procured transducer is to be used as a reference, measuring the atmospheric pressure, for the purpose of monitoring the operation of other transducers.

Figure 6. *CPT* 6100 and *CPT* 6180 digital pressure transducers, [6, 7]

The main characteristics of the *CPT*6100 and *CPT*6180 pressure transducers are shown in Table 1.

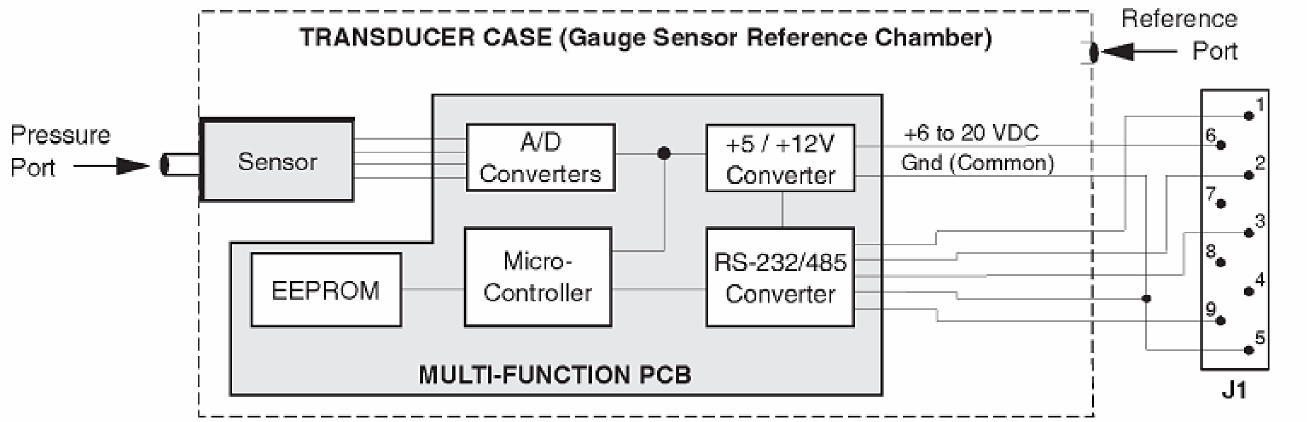

Figure 7. Functional diagram of the *CPT* 6100 and *CPT* 6180 transducers, [6, 7]

Table 1. The main characteristics of the *CPT*6100 and *CPT*6180 pressure transducers

Characteristic	CPT6100	CPT6180
Accuracy	0.01% FS	0.01% IS-50
Operating temperature range	0 to 50°C	
Warm up	10 minutes	
Calibration interval	180 days	1 year
Mechanical shock	3 g maximum	
Analogue to digital conversion	50 samples/s	
Overpressure limit	150 % full scale	120 % full scale

Replacement of the pressure calibrator

A normal operation of a wind tunnel facility requires frequent recalibrations of pressure transducers. For that purpose, the pressure calibration laboratory in the VTI used three *Mensor QM/C* high-precision pressure controllers / manometers of the year 1971 design. The sensing elements in the controllers were Bourdon tubes made of quartz. The calibrators were electro-optical-mechanical devices, each comprising a servo-system for tracking the deformation of the sensing element, the movement being transferred to a mechanical counter. The operation of the calibrators was completely manual. After several malfunctions of the devices in the last couple of years, it was decided to replace them, and one *Mensor CPC*6000 calibrator was obtained instead, to replace all three *QM/C* devices.

The *Mensor CPC*6000 automated pressure calibrator [8], Fig.8, is a latest-generator pressure calibrator that can be operated either in the standalone mode or connected to a remote computer. It incorporates oscillating quartz crystals as sensor elements. The principle of operation of the calibrator is that the pressure-dependent natural oscillating frequency of a quartz cylinder is monitored and, after being processed and linearized by an embedded microprocessor, it is converted to pressure units and displayed or used to control the delivered pressure. The sensor elements are designed as individual modules (Fig.9) that can be easily exchanged in the calibrator when a change of the operating pressure range is desired. The procured unit has a dual-channel capability so that two pressures can be controlled or measured simultaneously. As two sensor modules per channel can be installed, the calibrator can, at any time, provide four different ranges of pressures. The operating medium is instrumental nitrogen.

The manual user interface is through a colour touch screen, Fig.10. To communicate with external programs for automated control, the *CPC*6000 is equipped with IEEE-488, RS-232 and 100 Mbit Ethernet interfaces.

Figure 8. Mensor *CPC6000* pressure calibrator, [8]

Figure 9. Replaceable sensor modules for the *CPC6000* calibrator, [8]

Figure 10. Preparation for calibration with the *CPC6000* in the pressure laboratory

The accuracy of the *CPC6000* calibrator is 0.01% IS-50, which is, in fact, better than the accuracy of the *CEC*-produced primary pressure standard available at the site with a recalibration interval of one year. Therefore, a procurement of a higher-accuracy primary pressure standard in the near future seems necessary in order to complete the calibration chain without need for costly periodic calibration of the *CPC*6000 at manufacturer's site.

Integration of new pressure transducers in the data acqusition system

The initial concept of integration of the new *CPT*6100 pressure transducers with the data acquisition system was to connect the analogue outputs of the transducers to analogue input cards of the *Teledyne*–produced wind tunnel data acquisition system (Fig.11). In this way, the simplest possible transition to the new transducers was intended to be achieved, because the earlier transducers were connected in the same way. On the other hand, as the reference *CPT*6180 transducer did not have an analogue output but only a RS-485 serial output, for this transducer a prototype of a special interface was designed and built about a *Microchip PIC*16*F*877 controller. The interface converted the serial data from the transducer to parallel data that was read by a digital input card of the data acquisition system.

The first calibration of the transducers showed that the operation of the digitally-connected *CPT*6180 transducer was superior by almost an order of magnitude to that of the transducers with the analogue connection, which appeared to be just marginally better than the old *Mensor*-11603 transducers. Therefore, an additional 3-channel RS-485-to-parallel interface, comprising three *PIC16F877* with a common clock, was built for the other transducers of the primary measuring system as well, so that the complete primary measuring system was digitally connected. The prototype of the interface was designed and made to be piggy-back mounted on a 3 x 16 bit digital input card of the *Teledyne* data acquisition system (Fig.12), so that cabling, housing and power-supply complications were eliminated and the interface was made very compact.

A repeated calibration of the pressure transducers justified the switch to the digital interfaces. Problems that were encountered with the analogue signals from the earlier transducers, caused by tolerances in the accuracy and linearity of analogue parts of the data acquisition system and the electromagnetic noise from surrounding devices, were completely avoided.

Figure 11. Front panel of the analogue unit of the *Teledyne* data acquisition system

Figure 12. Prototype of the RS-485-to-parallel interface piggy-backed on a parallel-digital-input card of the Teledyne data acquisition system

Calibration of the pressure transducers of the primary measuring system

The calibration of the new pressure transducers was performed through the data acquisition and reduction system, [9,10]. The transducers were mounted in place in the wind tunnel hall, Fig. 13. The pressure was supplied via 6 mm-dia. tubing from the *CPC6000* calibrator located in the pressure-calibration laboratory (0). A VTI-developed software program was used for data reduction.

After eight weeks of the transducers' use in supersonic wind tunnel tests with stagnation pressures up to 13.5 bars and high transient loads at the start and stop of the wind tunnel runs, a checkout of the calibration was made, by applying the pressures from the *CPC6000* calibrator and using the previously determined calibration coefficients to back-calculate the applied pressure. The differences between the applied and back-calculated pressures were then computed. The results obtained during the calibration and the checkout are shown in Table 2. It is obvious that the performance of the transducers is excellent, exceeding nominal specifications, and accuracy appears to be, in fact, limited by the 0.01% IS-50 accuracy specification of the *CPC6000* calibrator. A more accurate assessment of the accuracy of the transducers can be made only by using a primary measurement standard with an accuracy of 0.002% FS or better.

Figure 13. The new pressure transducers installed in the T-38 wind tunnel hall

Table 2. The results obtained during the calibration

Transducer type	Procedure	Maximum error, %FS	Standard deviation, %FS	Hysteresis, %FS
CPT 6100, range 17 bar	Calibration	0.002	0.001	0.002
CPT 6100, range 7 bar	Calibration	0.002	0.001	< 0.001
CPT 6100, range 3.5 bar	Calibration	0.002	0.001	< 0.001
CPT 6180, range 1.4 bar	Calibration	< 0.001	< 0.001	< 0.001
CPT 6100, range 7 bar	Checkout	0.005	0.003	-
CPT 6100, range 3.5 bar	Checkout	0.008	0.006	-
CPT 6180, range 1.4 bar	Checkout	0.004	0.002	-

Conclusion

The accuracy of the primary measuring system of the T-38 wind tunnel has been significantly improved by installing digital pressure transducers of the latest technology generation. The results obtained during the calibration showed that the accuracy has been improved almost by an order of magnitude relative to the replaced old pressure transducers, and a checkout of the calibration after eight weeks of the transducer use verified the stability of the devices. According to the results of the calibration and the first experiences in actual wind tunnel tests, it is expected that the reliability of calculation of the Mach number and dynamic pressure will be significantly improved, which was the primary reason for the executed modification.

The increased accuracy of the new transducers has also simplified the measurement setup, eliminating the need for exchanging transducers of different operating ranges, depending on test conditions. The capabilities of the new transducers were fully utilized by dispensing with the analogue processing of signals and turning to a completely digital interface. The new pressure calibrator has proved to be more convenient to use than the earlier aging models, and the confidence in the calibration results has been increased.

It was realized that the described upgrade of the pressure measuring and calibration system, while already improving the productivity and quality of measurements in the T-38 wind tunnel, cannot be considered complete until the primary pressure standard is procured as well.

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Poboljšanje primarnog mernog sistema u aerotunelu T-38

Mahov broj je glavni parametar sličnosti kod strujanja velikih brzina, i njegovo merenje je od fundamentalne važnosti u aerotunelskim ispiti-vanjima. Greške u merenju Mahovog broja se prenose kao značajne greške u određivanju aerodinamičkih koeficijenata. U nedavnom naporu da se poboljša kvalitet merenja u nadzvučnoj oblasti brzina u trisoničnom aerotunelu T-38 Vojnotehničkog instituta u Beogradu, izvedeno je unapređenje sistema davača i sondi za merenje parametara strujanja u radnom delu i praćeno je unapređenjem sistema za etaloniranje davača pritiska.

Ključne reči: **aerodinamički tunel, aerodinamičko ispitivanje, merni sistem, merenje pritiska, davač pritiska, sonda za merenje, kalibracija.**

Укрепление системы первычной системы измерения в аэродинамической трубе Т-38

Число Маха главный параметр сходства высокоскоростного потока, и его измерение имеет фундаментальное значение в аэродинамической трубе допроса. Ошибки при измерении числа Маха передаются как значительные ошибки в определении аэродинамических коэффициентов. В последнее время присущи усилия по улучшению качества измерений в области сверхзвуковых скоростей в трёхзвуковой аэродинамической трубе Т-38 Военно-технического института в Белграде, было сделано улучшение системы датчиков и зондов для измерения параметров потока в рабочей части, сопровождающееся повышением системы калибровки датчика давления.

Ключевые слова: **аэродинамическая труба, аэродинамические испытания, измерительные системы, измерения давления, датчик давления, датчик для измерения, калибровка.**

Amélioration du système primaire de mesurage dans la soufflerie aérodynamique T-38

Le nombre Mach est le paramètre principal de similarité chez le courant des grandes vitesses et son mesurage est de l'importance fondamentale pour les recherches dans la soufflerie aérodynamique. Les erreurs lors du mesurage du nombre de Mach se propagent comme les erreurs signifiantes dans la détermination des coefficients aérodynamiques. Dans l'effort récent pour améliorer la qualité de mesurage dans le domaine supersonique des vitesses dans le tunnel aérien tri sonique T-38 à l' Institut militaire technique de Belgrade on a effectué l'amélioration du système transducteur et des sondes pour le mesurage des paramètres du courant dans la chambre de travail, suivi par le perfectionnement du système d'étalonnage chez le transducteur de pression.

Mots clés: **soufflerie aérodynamique, essais aérodynamiques, système de mesurage, mesurage de pression, transducteur de pression, sonde de mesurage, calibrage.**