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Research Survey

Wind Tunnel Tests for a Pitot-Static Probe Designed to Measure Aircraft Speed and Altitude at Subsonic Compressible and Transonic Regimes

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Abstract

A pitot-static probe to measure speed and altitude of aircrafts over a range of flight speeds from 0.5 to 0.95 Mach was designed by means of computational fluid dynamics (CFD) analyses and its tests were carried out at ITU Trisonic Wind Tunnel. The goal of the design studies is to achieve acceptable low error rates in both speed and altitude measurements. The purpose of the wind tunnel tests is to verify the results obtained from the CFD analyses and to determine the characteristics of the designed probe under real flow conditions. In this paper, the parameters used in the design and their effects on the measurement performance of the probe are discussed. In addition, wind tunnel testing methods applied to obtain the characteristics of the designed pitot-static probe with high accuracy are given in detail in this article.

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Hava Aracı Hızını ve İrtifasını Sıkıştırılabilir Ses-Altı ve Transonik Rejimlerde Ölçmek İçin Tasarlanmış Bir Pitot-Statik Probun Rüzgar Tüneli Testleri

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Öz

0,5 ile 0,95 Mach aralığında uçuş hızına sahip hava taşıtlarında kullanılabilecek bir pitot-statik prob hız ve yükseklik ölçüm sisteminin tasarımı, hesaplamalı akışkanlar dinamiği (HAD) analizleri ve İTÜ Trisonik Rüzgar Tüneli’nde yapılan testler ile gerçekleştirildi. Tasarım çalışmalarının hedefi, hem hız hem de yükseklik ölçümlerinde, kabul edilebilir, düşük hata seviyelerine ulaşabilmektir. Rüzgar tüneli akış testlerinin amacı HAD analizlerinden elde edilen sonuçların doğrulanması ve tasarlanan probun gerçek akış şartları altındaki davranışının tespit edilmesidir. Bu çalışmada tasarımda kullanılan önemli parametreler ve bu parametrelerin ölçüm performansına etkileri tartışılmıştır. Ayrıca tasarlanan pitot-statik probun özelliklerinin yüksek doğrulukta elde edilmesi için uygulanan rüzgar tüneli test yöntemleri bu çalışmada detaylı olarak verilmektedir.

1. INTRODUCTION

The first description of a probe used to measure pressure for velocity determination was made by Henri Pitot in 1732 [1]. The pitot probe and the static pressure probe sense the total pressure and the static pressure, respectively. The pitot probe and the static probe can be combined into a single probe as shown in Fig. 1, which is called a pitot-static probe. Pitot-static probe is a very classical speed measurement technique that is widely used in a great number of applications and in several different geometries, for flow speeds from 1 m/s up to supersonic speeds. In this measurement technique based on the Bernoulli’s equation, two basic pressures, namely static and total, are used to determine speed and altitude. The static pressure (Ps) is the atmospheric pressure at the flight altitude of the aircraft and measured from the openings at the probe outer wall, which are generally more than one and parallel to the flow. The total pressure (P_0) is the sum of static and dynamic pressures, which is the pressure developed by the forward motion of the aircraft. The total pressure is sensed by a forward-facing opening at the center of the probe nose, which is perpendicular to the flow direction. Eventually, the dynamic pressure is obtained from difference between the total pressure and the static pressure.

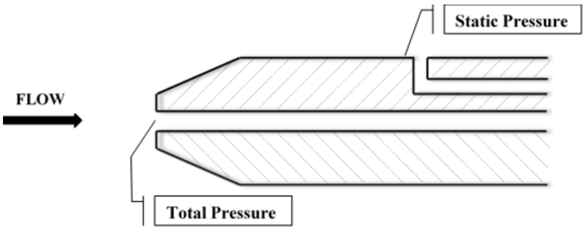

Figure 1. Pitot-static probe schematic representation.

Designing and locating the instruments for accurate pressure measurement is complicated by many factors. The total pressure along the streamlines past a body remains constant but the static pressure can vary widely from point to point along these streamlines due to changing velocity. For this reason, the measurement of total pressure is much easier than the measurement of freestream static pressure. At the high subsonic cruise speeds (e.g., even at some commercial jets maximum speed can reach up to Mach number of about 0.9) accurate static pressure measurements can be difficult by pitot-static probe, due to accelerated flow at the nose section of the probe and shock waves formed around the probe when the local speed becomes sonic. For this reason, especially in civil aviation, static pressure is sensed by a set of pressure taps placed in appropriate locations on the air vehicle's body. The total pressure measurement should be made with the pitot probe which is mounted away from boundary layer formed on the vehicle-surface, wake or engine exhaust. In this way both flight speed and flight altitude information can be measured with sufficient accuracy. For subsonic velocities, the Mach number and velocity are calculated with the help of the two measured pressures by the following isentropic equations [2].

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{P_0}{P_s}\right)^{(\gamma-1)/\gamma} - 1\right] \tag{1}$$

$$V^2 = a^2 M^2 = \frac{a_0^2 M^2}{1 + \frac{\gamma-1}{2} M^2} \tag{2}$$

Furthermore, military jets and missiles used in military aviation are both transonic and supersonic speed vehicles. In this speed range, the method of placing the static pressure taps on the vehicle's body is not suitable because the shock waves generated around the aircraft affect both the static and the total pressure distribution of airflow. The pitot-static probe should be used in such air vehicles instead of pitot probe/fuselage static pressure taps installation. For operations in the supersonic speed range, the pitot-static probes are designed in a completely different geometry and should be located at proper place of the vehicle so that they are prevented from being influenced by shock waves emanating from any part of the aircraft. The positon ahead of the fuselage nose is, certainly, the best location meets that requirement. Nevertheless, at supersonic speeds the pitot-static probe is still influenced by a strong bow shock wave that forms in front of the probe. Therefore the probe measures the total pressure ($P_{0,2}$) downstream of that shock wave instead of the freestream total pressure. The total pressure decreases because of the presence of the shock wave, so that the pressure measured by the probe is less than the freestream total pressure value. The total pressure loss through the shock wave must be taken into account in the computation of the pressure. Static pressure measurement is also very important, so the location of the static pressure taps on the probe surface should be placed where the freestream static pressure is measured correctly. The Mach number, in supersonic regimes, at the probe location can be calculated correctly by using the Rayleigh-Pitot equation given below which relates the probe total pressure ($P_{0,2}$) and the freestream static pressure (P_s) to the freestream Mach number (M) [2].

$$\frac{P_{0,2}}{P_s} = \left[\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)}\right]^{\gamma/(\gamma-1)} \frac{1 - \gamma + 2\gamma M^2}{\gamma + 1} \tag{3}$$

The basic geometric design parameters of a pitot-static probe are shown in Fig. 2. One of the important parameters in the pitot-static probe design is the nose geometry of the probe because it is the first surface where the flow encounters. The internal and external geometry of the nose directly determines the character of the flow region around the probe. It is important that the nose shape, the total pressure opening diameter (d_{Pt}), and the ratio of this diameter to the probe diameter (d_{Pt} / D) are determined appropriately so that the total pressure can be precisely measured and also the flow accelerating around the nose cannot adversely affect the static pressure measurement accuracy. Furthermore, the total pressure opening cannot be too small since the possible effects and dimensions of solid particles (such as dust, ice crystals and water droplets) that may be encountered during flight should be considered. In order to measure the freestream static pressure correctly, the first parameter to be considered is the ratio of the distance of the static pressure taps from the nose to the probe diameter (L_{Ps} / D). The static pressure on the probe is lower than the freestream pressure at locations near the nose due to flow acceleration. However, the pressure approaches the freestream pressure value with increasing the distance from the nose. In the subsonic speed range, the probe length (L) should be of sufficient size, in particular, that the static pressure measurement taps are not influenced by the presence of the stem downstream from the taps. Likewise, the height of the stem (h) (the distance between the probe and the aircraft fuselage) should be settled to ensure that both total and the static pressure measurements are not affected by the disturbances in the flow caused by the fuselage. In addition, the size and the shape of the static pressure taps contribute to the static pressure error. Best static pressure measurements are obtained with small, sharp edged holes, perpendicular to a wall, which is parallel to flow. Small hole diameters result in large response times and the holes are easily blocked by dust and dirt in the flow. Large holes, however, are less accurate by the amount of distortion they introduce in the flow field. The main sources of static pressure errors are eddies developing in the cavity, fluid turbulence, Mach number effects, and stagnation of the fluid in the holes depending on orifice geometry and burrs. In the foregoing discussion, only the aerodynamic aspects of the design of pitot probes have been considered. For operational use, the probe would have to allow for the installation of an electric heating element for deicing and drain holes for the evacuation of any water that may be ingested.

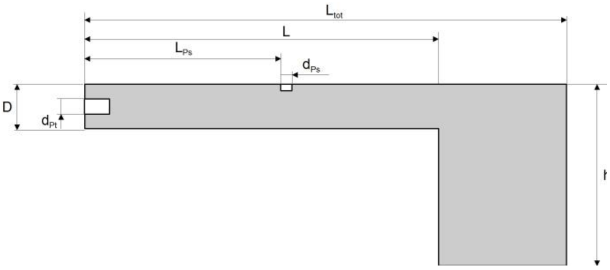

Figure 2. Geometric design parameters of a pitot-static probe.

Since the 1900s, many experimental and computational studies have been performed to measure speed and altitude of an aircraft with higher accuracy and to understand the flow conditions around the probes. In the period from 1900 to 1915, the fundamental principles of speed measurement with a probe were discussed by White, Zahm, Gregory, Guy, Rowse, and Groat [3-8]. In 1925, Kumbruch et al tested the sensitivity to inclination and to turbulence of Prandtl, Brabbée, and Rosenmuller Pitot-Static probes, moreover, they described special forms of Prandtl's Pitot-Satic Probe for making measurements in dusty and humid air flow [9]. In 1935, comparative tests were made, by Merriam and Spaulding [10], on seven conventional pitot-static probes to determine their static, total and dynamic pressure measurement performance. In this study, the effect of geometry and location of the pressure taps, probe wall thickness, diameter of the inner tube, also stem and nose design were investigated. In another study during the same year, Kiel [11] showed that the range of flow direction insensitivity, up to $M = 0.6$, extended to ±43º by placing the pitot probe into a shield with venturi geometry. Three types of service pitot-static probes and a standard Prandtl-type pitot-static probe were calibrated at speed range from 67 m/s to 270 m/s also a high speed pitot-static probe was designed and calibrated over the same speed range in the same study by Hensley [12] in 1942.Rayle, Jr. [13] investigated the influence of pressure taps geometry on static pressure measurements in 1949. Cylindrical shaped pitot-static probe with ogival nose were tested at the several angles of attack, up to 10º, at supersonic speeds by Hasel and Coletti in 1951 [14]. Furthermore, McClanahan [15] tested various conical-shaped probes in 1951, because of the need to develop an angle of attack and yaw measuring instruments at transonic speeds. From 1951 to 1954, NACA conducted a series of wind-tunnel tests [16-21] to determine the inclination effect on the 54 pitot probe designs. The investigation was conducted for angle of attack up to 67º and at Mach numbers ranging from 0.26 to 2.4. The pitot probe configurations were included shielded probe based on the Kiel design [11] and simple probes, non-shielded probes, with cylindrical, conical, and ogival nose shapes. The effect of the external nose shape, the shielding, varying the size of the pressure opening, cutting the nose with a slant angle, and changing the internal entry shape of the probes were obtained from that precious and long-term work. Gracey and Scheithauer [22], in 1954, tested different arrangements of static pressure taps to reduce the effects of inclination of airstream on static pressure measurements at an angle of attack range from -15º to 45º and at Mach number range of 0.2 to 0.68. In 1957, Larson et al. [23] conducted an investigation to determine the static pressure measurement errors for nose-boom airspeed installations of 17 airplanes. In the same year, Centolanzi [24] conducted an experimental study to determine the characteristics of a 40º cone for use in measurement of Mach number, total pressure, and flow angles simultaneously at supersonic speeds. In 1959, Richardson and Pearson [25] conducted calibration tests of a combined pitot-static probe, vane-type flow direction transmitter, and stagnation temperature element over a range of Mach numbers from 0.60 to 2.87. In 1962, Horvath et al. [26] described the use of a pitot-static probe to measure some physical properties of the upper atmosphere and its superiority over other measurement techniques (grenade, sodium vapor, and falling sphere). Larson and Webb [27] performed a study on flight calibration of speed and altitude measurement of X-15 airplane from low subsonic speeds to high supersonic speeds. Two pressure-type airspeed-altitude system was investigated in this study: the first system is nose-boom installation, which provides both static and total pressure sensing, and the other system is incorporation of flush static openings and a pitot probe located ahead of the canopy of X-15. In 1971, Webb and Washington [28] worked on two types of pitot-static probes used on the XB-70 airplane, a compensated and an uncompensated pitot-static probe, and compared the calibration methods, probe behaviors, and probe characteristics over a Mach number range from low subsonic to supersonic. In 1974, Becker and Brown [29] investigated pitot probe response in turbulent flows such as turbulent jets and flames, and examined the detection of turbulence intensity by the use of pitot probe. In 1981, Christiansen and Bradshaw [30] conducted an experimental study to investigate the effect of turbulence on several different types of pressure probes by performing measurements in turbulent flow on the centerline of a circular jet. In 1981, Stephenson [31] conducted an experimental study on use of Pitot probes under the conditions of very high altitude, low Reynolds number or high Knudsen numbers. In 1985, Cho and Becker [32] presented the effect of turbulence on the response of static pressure probes by theoretically and experimentally. In 1991, Chebbi and Tavoularis [33] experimentally investigated the response and also the yaw sensitivity of pitot-static probes in very low Reynolds number range (Re < 1). In 1994, Humm et al. [34] experimentally investigated the effect of the probe size and geometry on the quality of fast-response pressure measurements in turbomachines. In 1997, Ranga Raju et al. [35] conducted an experimental study to understand the variations in the velocities measured by pitot probe from the true velocities in regions of strong velocity gradients such as turbulent shear flows and size and shape of pitot probes and also to develop a correction for that "displacement effect". In 2001, Wysocki and Drobniak [36] compared the already-proposed correction methods for the displacement effect, the difference between pitot probe measurements and true values under conditions of large velocity and pressure gradients. In 2001, Porro [37] designed and developed series of fast response pitot, static and multi-hole pressure probes to use in a supersonic flow. In 2003, Etemad et al. [38] presented a numerical study of calculation of correction factor for pitot probes in most Newtonian, pseudoplastic, and dilatant fluids at low Reynolds number. In 2007, Latif et al. [39] designed a more advanced aerodynamic compensation pitot-static probe than the ogival pitot-static probe that provides the desired compensation in both subsonic and supersonic flow at the same axial location. Several important numerical and experimental studies [40 and 41] of an averaging Pitot tube presented in 2008. In 2009, Sun et al. [42] presented precious study that focuses on the influence of the measurement performance of the improperly installed pitot tube.

In this study, the characteristics of a pitot-static probe that is designed for aircrafts with flight speed between 0.5 and 0.95 Mach. For such flows it is not possible to measure static pressure on the fuselage. Tests of the designed pitot-static tube were performed in ITU Trisonic Wind Tunnel. Wind tunnel testing methodology and key results obtained are presented in this article.

2. EXPERIMENTAL SETUP

2.1. Wind Tunnel

Experiments were carried out in the trisonic blowdown wind tunnel at the Istanbul Technical University. The wind tunnel air was supplied by tanks with a volume of 90 m^3 at a pressure of about 2.7 MPa. The test section was 15 cm wide by 15 cm tall and has a length of about 50 cm. Windows with a diameter of 24 cm at the wind tunnel sidewalls provided optical access to the test section. Tests were conducted at temperature of $T_0 = 296$ K and the nominal values of the freestream Mach number were changed by approximately 0.05 Mach intervals in the range from 0.5 to 0.95 Mach.

2.2. Pressure Measurement Setup

A schematic of the measurement system is shown in Fig. 3. Thanks to the traversing mechanism that can be mounted between the test section and the diffuser, it is possible to perform pressure distribution measurements by scanning the y and z axes at the desired x location by using the wind tunnel's standard static or total pressure probes. The Pitot-Static Probe was mounted on the floor of the test section as shown in Fig. 3. The locations of the sensing points of the pitot-static probe and the Tunnel Probe were the same in all experiments, in the x and the z-axes.

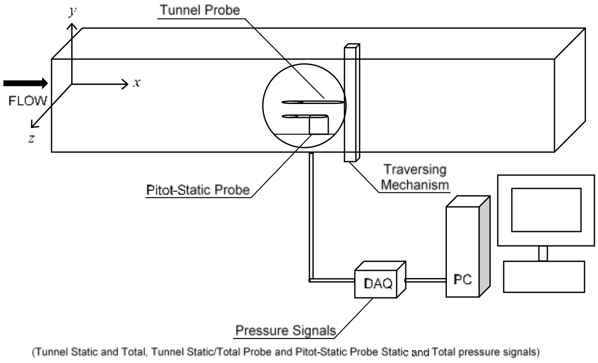

Figure 3. Schematic view of experimental setup.

In the performed experiments, three different Mach numbers were measured as described below:

I. Mach-Tunnel (M_T); obtained by using the total pressure measured from the stagnation chamber of the tunnel and the static pressure measured on the side wall of the test section.

II. Mach-Pitot-Static Probe (M_{PS}); obtained by using the total and static pressures measured by Pitot-Static Probe.

III. Mach-Tunnel Probe (M_{TP}); obtain by using static pressure measured by the Tunnel Probe and total pressure of tunnel's stagnation chamber or by using total pressure measured by the Tunnel Total Probe and static pressure measured on the side wall of the test section.

Pressure measurements were conducted by individual high-accuracy static pressure sensors (from Honeywell) with a range of 0–200 kPa. The pressure signals acquired from all high-accuracy transducers were digitized at a rate of 100 Hz with an A/D data acquisition card (NI PCI-6014) installed in a computer. The A/D cards were controlled by an in-house LabView code. This program acquires the pressure data during the experiment and reports the Mach numbers measured by Tunnel, Tunnel Probe and Pitot-Static Probe simultaneously. When the desired freestream Mach number is obtained during the experiment, pressure data is acquired for about 10-15 seconds, which may vary if needed. The combined accuracy for the total and static pressure measurements associated with the sensors (accuracy, nonlinearity, hysteresis, and repeatability) and data acquisition card (reading error, offset, noise, and temperature drift) was calculated to be about 0.2% of full-scale output. The uncertainty in the Mach number calculations was estimated as 0.5%.

3. RESULTS AND DISCUSSION

3.1. Determination of Flow Structure in the Test Section

The characteristics of the pitot-static probe can only be obtained by knowing the flow conditions to which the probe is exposed. Pressure measurements were made at approximately M = 0.5, 0.7, 0.9 and 0.95 in the empty test section, both to obtain the structure of the free stream and to determine if there was any undesirable pressure gradient. All pressure measurements in the *y*-axis were carried out in the *x* and *z* axes positions where the pitot-static probe meets the flow. In pressure measurements, the tunnel's standard probes were approached to the test section walls up to 10 mm due to physical constraints. The static and total pressure distributions obtained on the *y*-axis are presented in Fig. 4 and Fig. 5, respectively.

It was observed that the static pressure remained fairly constant up to about 110 mm from the lower wall and slightly decreased in the area near the upper wall. Furthermore, it is seen that there are losses in the total pressure due to the boundary layer developed on the lower and upper walls. There is no significant loss in total pressure in the region between approximately *y* = 45 mm and *y* = 125 mm at all velocities examined. In the light of these information, it was evaluated that it is appropriate to position the pitot-static probe at *y* = 55 mm for the accuracy of the tests.

3.2. Determination of Characteristics of the Pitot-Static Probe

The characteristics of the Pitot-Static Probe in measurements are given in Fig. 6. All pressures reported herein are given as percentage difference. Figure 6a shows that the difference between the static pressure measured by the Pitot-Static Probe and the flow static pressure which is measured by Tunnel Static Probe essentially remains constant from M = 0.5 to M = 0.8, shortly after however, the difference has increased significantly at higher speeds than M = 0.8. One of the possible reasons for the Pitot-Static Probe's high static pressure measurement is that at high speeds the flow around the probe nose accelerates to supersonic speeds and results in shock wave in this region. It is obvious that flow separation occurs on the surface where static pressure taps exist due to the probe nose shock wave/boundary layer interaction occurring in this region. This separation region is close to static pressure taps, resulting in an increase in static pressure. In addition to the above hypothesis, another factor that may cause an increase in the amount of error in the static pressure measurement of the Pitot-Static Probe at speeds higher than M = 0.8 is the rise in the effective turbulence level due to the flow at transonic velocities.

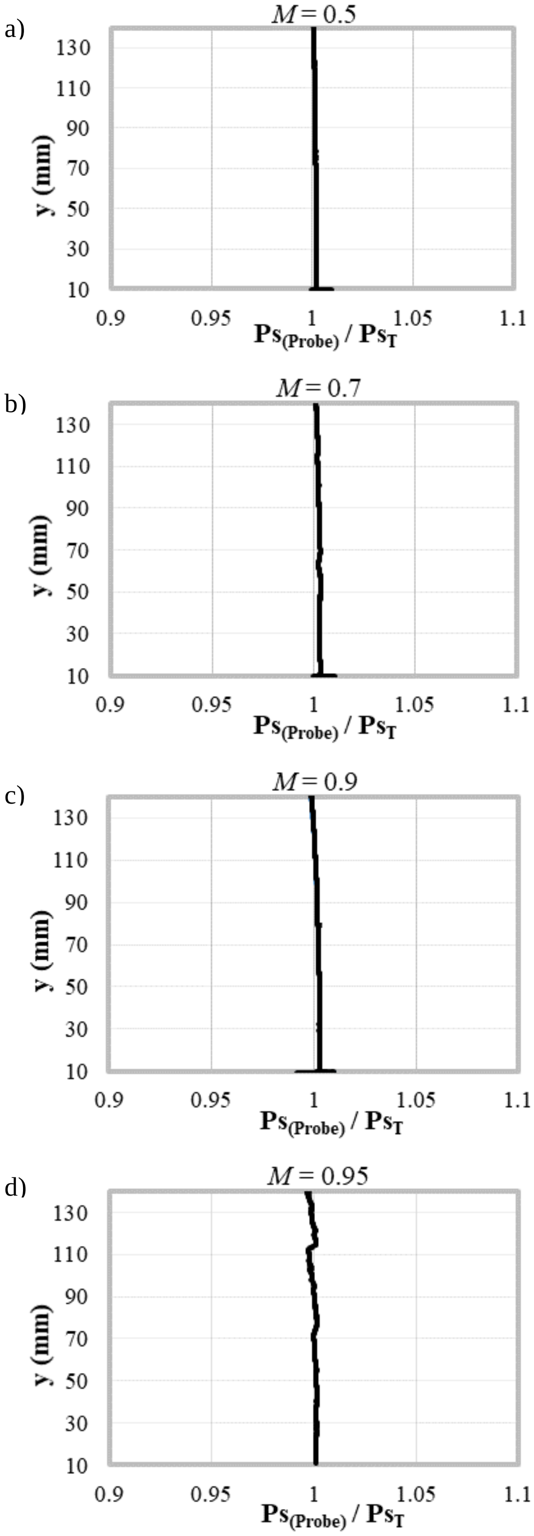

Figure 4. Static pressure profiles in the y-axis.

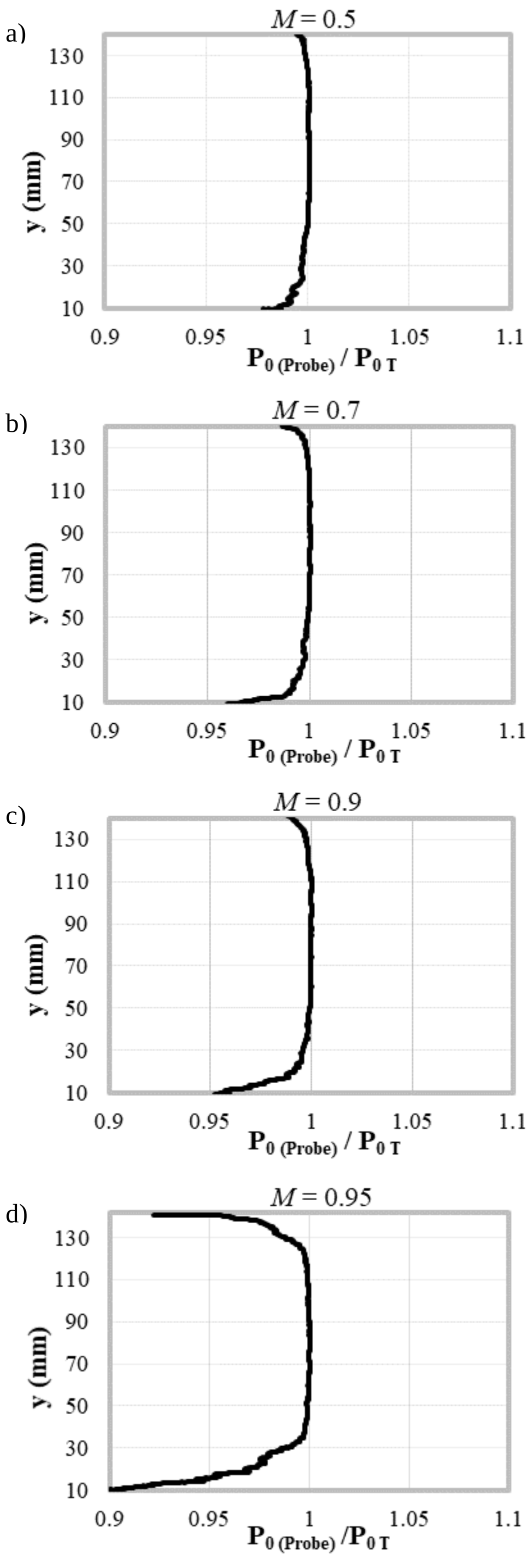

Figure 5. Total pressure profiles in the y-axis.

The total pressure measured by the Pitot-Static Probe is quite accurate as clearly observed in Fig. 6b. The difference between the total pressure measured by the Pitot-Static Probe and the freestream total pressure which is measured by Tunnel Pitot Probe is less than 0.2%. Figure 4c shows that the Mach number of the Pitot-Static Probe is very close to the Mach number measured with the reference Tunnel Probes at the speed range of 0.6 - 0.85 Mach. At a speed less than M = 0.6 and greater than M = 0.85, the difference is acceptable even if the difference slightly increases at some speeds.

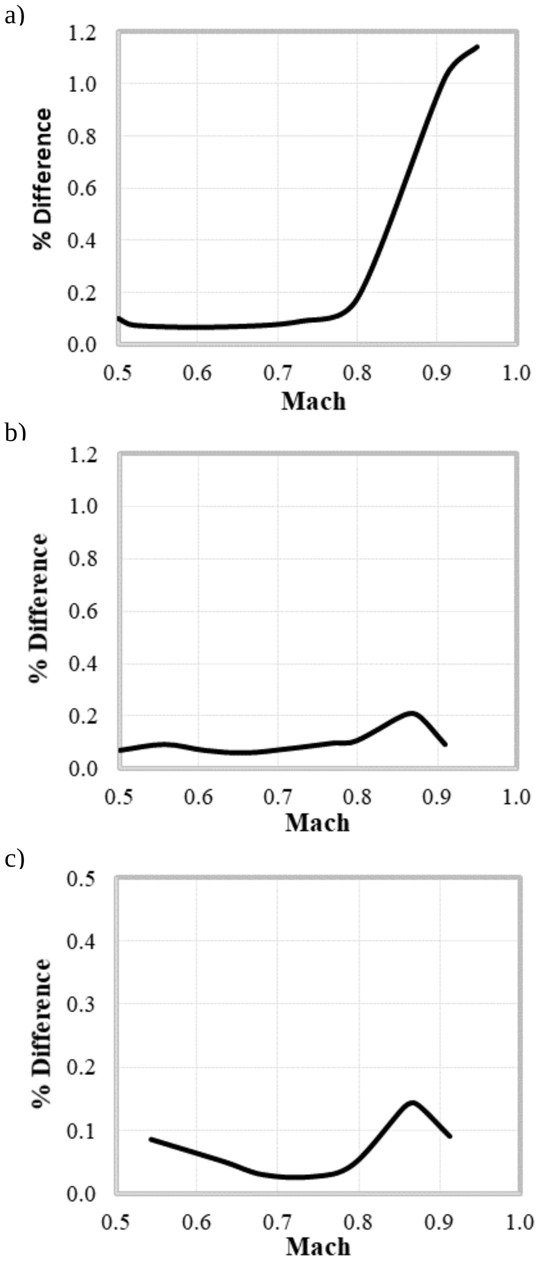

Figure 6. The difference between a) the static pressure measured by the Pitot-Static Probe and by the Tunnel Probe, b) the total pressure measured by the Pitot-Static Probe and by the Tunnel Pitot Probe, c) the Mach number measured by the Pitot-Static Probe and by the Tunnel Probe.

4. CONCLUSION

In this study, wind tunnel tests of a pitot-static probe designed to measure altitude and velocity from high subsonic velocities to transonic velocities were performed. First, the structure of the flow in the wind tunnel test section at speeds between M = 0.5 and 0.95 was obtained. As a result of the pressure distributions, the position of the Pitot-Static Probe in the test chamber was determined. Then, high precision static and total pressure probes of the wind tunnel were placed in positions that would not interact with the Pitot-Static Probe. These high precision probes were used as reference in obtaining the measurement accuracy of the Pitot-Static Probe. Tests were carried out by increasing the free stream velocity in 0.05 steps from Mach 0.5 to 0.95. The results showed that the designed Pitot-Static Probe measures the static pressure, total pressure and Mach number with an average error of 0.38%, 0.1% and 0.07%, respectively.

5. ACKNOWLEDGMENTS

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