New Method for Measurement of Surface Pressure Using Magnetic Tape

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A new method of surface pressure measurement has been developed using magnetic tape as a sensor—instead of the usual strain gage, piezogage or semiconductor—within a diaphragm-type pressure transducer. The method is based on the idea that a pressure value applied to the diaphragm is related to the deflection of the diaphragm, and the deflection can be related to the value of magnetization strength sensed in the tape. The merit of the new method is that it can be easily applied for measurement of pressure distributions on model surfaces because many pressure transducers are contained in a single sheet only about 1-mm thickness. The proposed method can be used in the high-temperature, short-duration measurement conditions, and so it is well suited to hypersonic wind-tunnel use. The sheet can be bonded onto a model surface. In this study, experiments using the new pressure sensor were performed in a hypersonic gun tunnel at a Mach number of 10 for a duration time of 10^{-2} s. Pressure distributions around two models in hypersonic flow were measured successfully.

Nomenclature

E = modulus of elasticity
F = natural frequency
H = distance between magnetic tape and lead wire
I = electric current
k = thermal diffusivity
Mf = magnetic field
R = diaphragm radius
t = diaphargm thickness
T = temperature at place x and time τ
Td = initial diaphragm temperature
Tg = gas temperature outside the boundary layer
x = distance from diaphragm surface
λ = thermal conductivity
μ = Poisson's ratio
ρ = mass density of diaphragm material
τ = time from start of gas flow

Suffix

1 = diaphragm
2 = gas

I. Introduction

In recent years, the study of hypersonic flows has become very important for the development of supersonic airplanes such as the HST. In experimental studies, the lift and drag of flying bodies are often determined from measurements of surface pressure distributions.

However, for pressure distributions measurement one must prepare a large number of pressure sensors such as the usual strain gage, piezogage, semiconductor, etc., or operate the wind tunnel the same number of times as the number of measuring positions. Cooper and Hankey[1] prepared 25 pressure sensors and operated a wind tunnel twice in order to obtain pressure values at 43 positions. Vidal and Bartz[2] carried out the measurement of surface pressure values of a plane by preparing a large number of pressure transducers. Moreover, for experiments using these pressure sensors, one must make a large number of pressure taps in the model. As a countermeasure, Howkins[3] reported a method for measuring pressure values by using carbon paper. This method can obtain pressure values without making pressure taps, but it is very difficult to measure pressure values at an arbitrary time, and this method can obtain only a peak value of pressure during the operation of a wind tunnel.

In order to solve these problems, the authors have suggested a new pressure measuring method by using magnetic tape as a sensor. The method is based on the idea that a pressure value applied to a diaphragm is related to the deflection of the diaphragm, and the deflectionn can be related to the value of magnetization strength sensed in the tape and, therefore, the pressure value is obtainable by reading the value of the magnetized strength. In the proposed method, the pressure transducer can be made 1-mm thick including the magnetic tape. Therefore, a large number of pressure taps are containable in a thin sheet, and even if bonded onto a model surface, the flowfield around the model is not disturbed because the sheet is so thin. For these reasons, using the present method, pressure distributions can be measured by just bonding the sheet without making a large number of pressure taps in the model.

II. Experimental Principle and Procedure

The experimental principle of the present pressure measuring method, which utilizeds magnetism as a sensor, is illustrated in Fig. 1. When an electric current is generated in a lead wire by applying a voltage to both ends of the lead wire, a magnetic field occurs around the wire. If a magnetic tape is place in the field, the tape is magnetized. In this case, the strength of the magnetization is related to the strength of the magnetic field. That is, if the electric current in the lead wire is constant, the strength of the magnetization is related to the distance between the lead wire and the magnetic tape. The magnetic field Mf around the wire becomes

$$Mf \sim I/H \tag{1}$$

If the magnetic tape is used as a diaphragm for a pressure receiver, the tape is deflected according to the pressure value. The maximum deflection value ΔH of such a tape, clamped at the edges and subjected to a uniform pressure P, has a linear relation with the pressure P. If the electric current flowing through the lead wire is constant while the pressure is applied to the diaphragm, the magnetic tape is magnetized according to the deflection value ΔH of the diaphragm. Consequently, the pressure value applied to the diaphragm can be obtained

Received Dec. 9, 1987; revision received Aug. 19, 1988.

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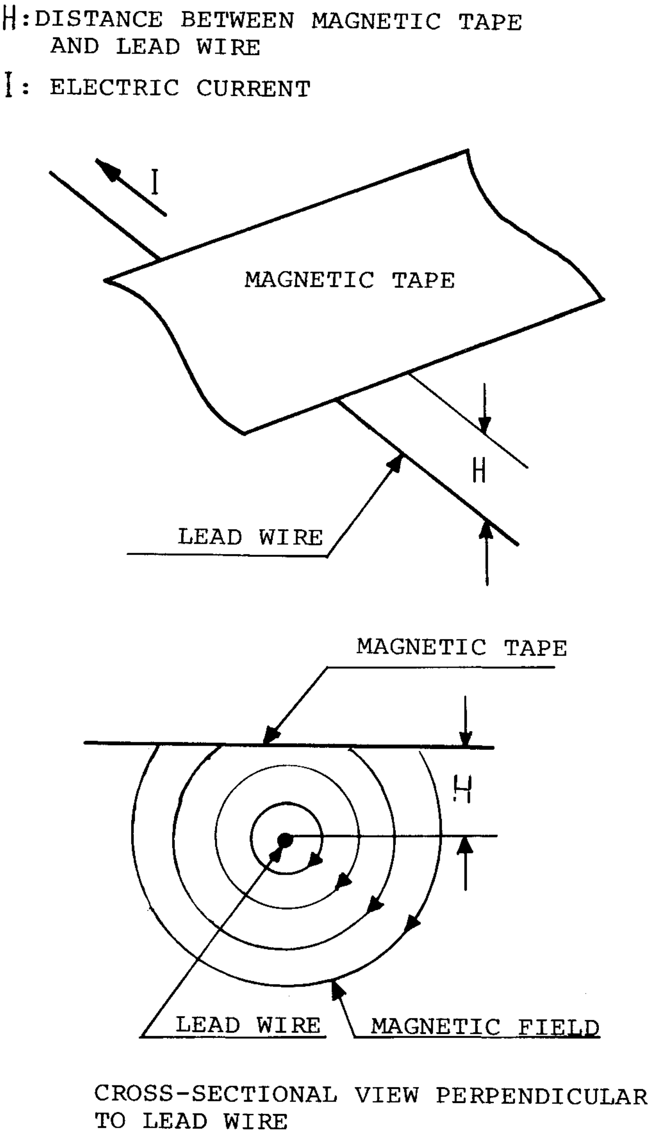

Fig. 1 Illustration of measuring principle of pressure by using magnetic tape.

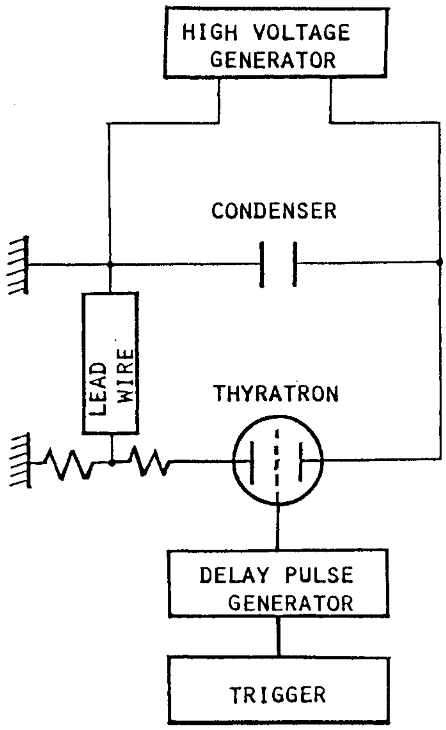

Fig. 2 Electric circuit.

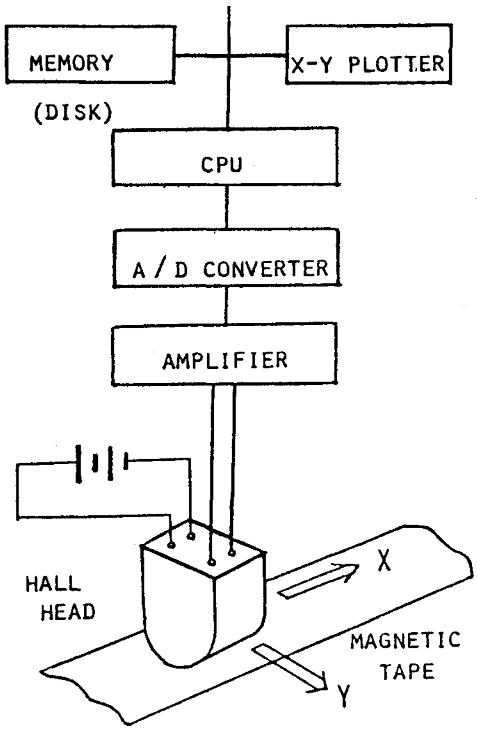

Fig. 3 Measuring system of magnetization strength of magnetic tape.

by using the calibration curve between the pressure and the magnetization stength.

The electric current for applying voltage to both ends of the lead wire is shown in Fig. 2. By this circuit, the voltage is applied to the lead wire while the freestream is obtained. Since it is necessary to flow a large electric current in order to magnetize the magnetic tape, there occurs the possibility of generating heat from the lead wire. For this reason, the electric circuit is designed so that the duration time of applying voltage to the lead wire is only a few microseconds.

The system for measuring the magnetization strength of the magnetized tape is shown in Fig. 3. The magnetization strength is expressed as an output voltage, and the output voltage is obtained by sliding a magnetic reading head.

The authors investigated the relation betwen the output voltage and the distance of the lead wire and the magnetic tape under the parameter of the applied voltage to the lead wire. The results are shown in Fig. 4. The results indicate that when the applied voltage is too low, the output voltage is also low, and reading the voltage becomes more difficult. On the other hand, when the applied voltage is too high, there occurs the possibility of saturation of the output voltage. Based on these results, the applied voltage of 1000 V was used throughout these experiments.

The pressure transducer designed and used in these experiments is shown in Fig. 5. The structural features are: a hole 6 mm in diameter is made in a thin plastic film 12 mm in width, a magnetic tape is settled on the upper side of the film, and a lead wire placed under the film as shown in Fig. 5. In the structural features, a large number of pressure sensors can be arranged continuously in the thin sheet. Furthermore, when we read the magnetization strength, a large number of pressure values can be read simultaneously since it can be read longitudinally along the thin sheet by sliding the magnetic reading head. Moreover, the pressure measurement can be performed by just bonding the sheet, which contains a large number of pressure sensors onto a model surface, because it is

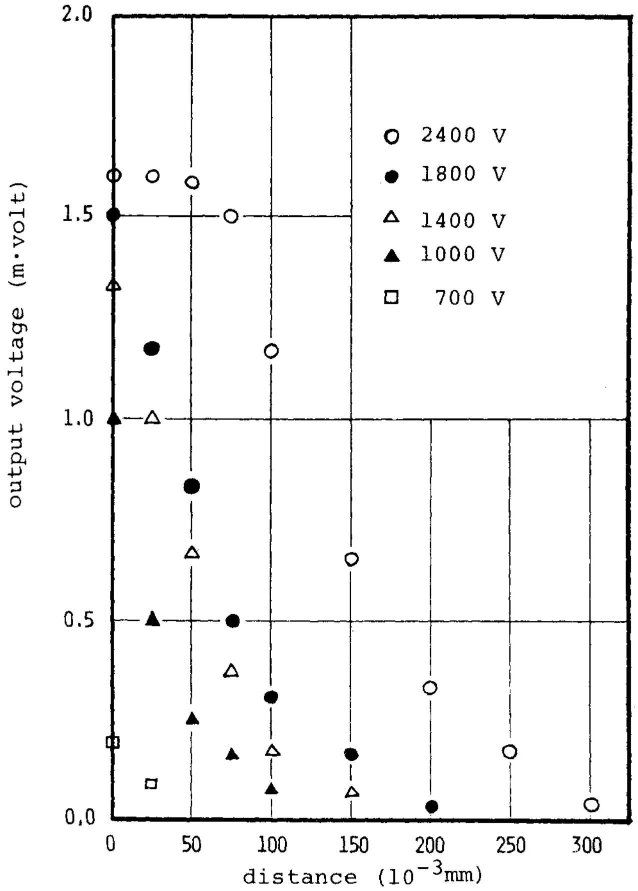

Fig. 4 The relation between gap length and magnetization strength.

considered that the flowfield around the model is not disturbed since the sheet is so thin. From these reasons, it is confirmed that this pressure transducer using a magnetic tape is very suitable for pressure distribution measurements.

An example obtained by measuring the distribution of the magnetization strength on the surface of the magnetic tape is shown in Fig. 6. In this experiment, a uniform pressure was applied to the diaphragms of the five pressure transducers in a sheet. Since the lead wire is arranged in the center of the diaphragms, the magnetization strength becomes largest at the center. The value of the pressure is obtainable by using the calibration curve shown in Fig. 7.

III. Characteristics of Pressure Transducer

As described in the experimental principle, the present pressure transducer is a diaphragm type. Therefore, when we use such a tape of pressure transducer, the particulars of the pressure transducer such as response time, diaphragm temperature, sensitivity, pressure range, and accuracy must be considered.[4] Especially, for experiments using hypersonic gun tunnels, the response time of the pressure transducer and the temperature of the diaphragm are very important because the duration times of hypersonic gun tunnels are usually very short and gas temperatures around hypsersonic vehicles become considerably high.

Concerning the response time of the present pressure transducer using a magnetic tape, we had to investigate the natural frequency of the diaphragm and the magnetization time of the magnetic tape, which is called the switching time of the magnetic tape.

For a clamped diaphragm vibrating with no fluid-inertia effects, the natural frequency F is given by[5]

$$F = \frac{10.21}{R^2}\sqrt{\frac{Et^2}{12\rho(1-\mu^2)}} \quad \text{rad/s} \qquad (2)$$

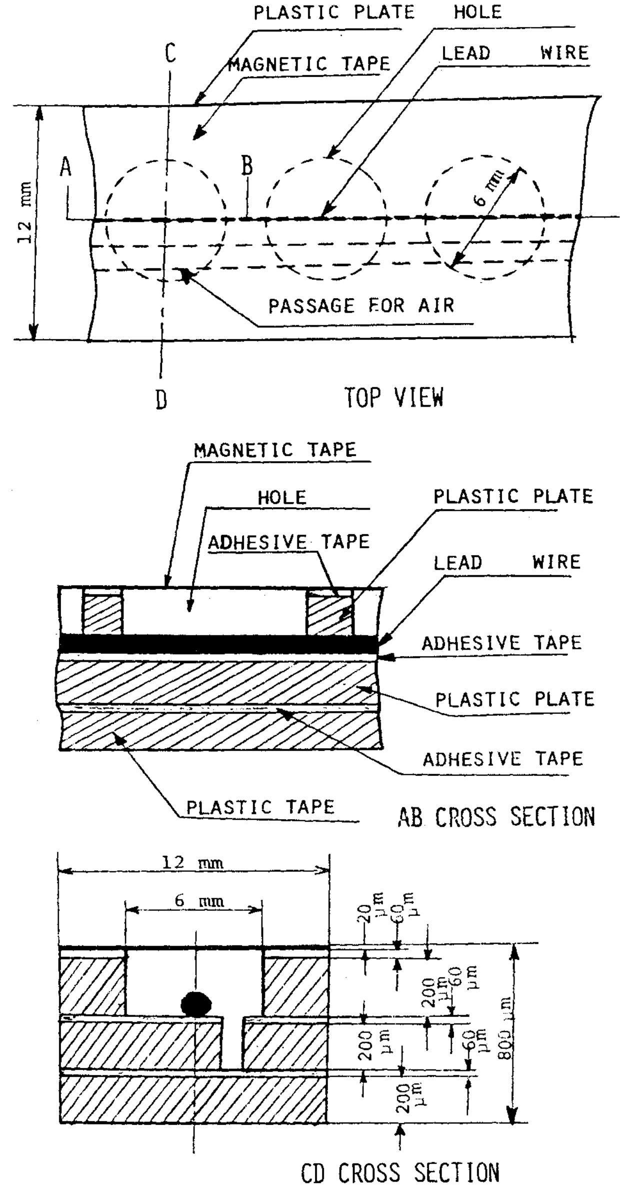

Fig. 5 Pressure transducer.

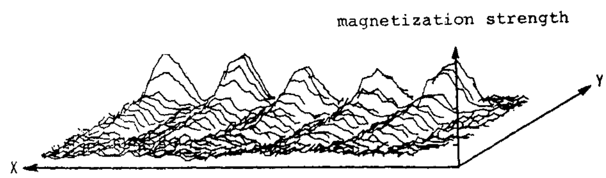

Fig. 6 The distribution of magnetization strength of the surface of the magnetic tape.

Since the duration time of the hypersonic gun tunnel used in these experiments is about 10^{-2} s, the natural frequency F should be larger than the order of 10^3 rad/s. For this reason, we had to select suitable values of the mass density ρ, the radius R, the thickness t, the modulus of elasticity E, and the Poisson's ratio μ so that the natural frequency F would be larger then the order of 10^3 rad/s. In our pressure transducer, the diaphragm is made so tht the natural frequency is 4×10^4 rad/s, and this value is considered large enough for measurements using the hypersonic gun tunnel.

As for the magnetizaton time of the magnetic tape, it is considered to be of the order of 10^{-9} s, or shorter.[6] This response time of 10^{-9} s is considered short enough for pressure measurements using any hypersonic tunnel, shock tunnel, etc.

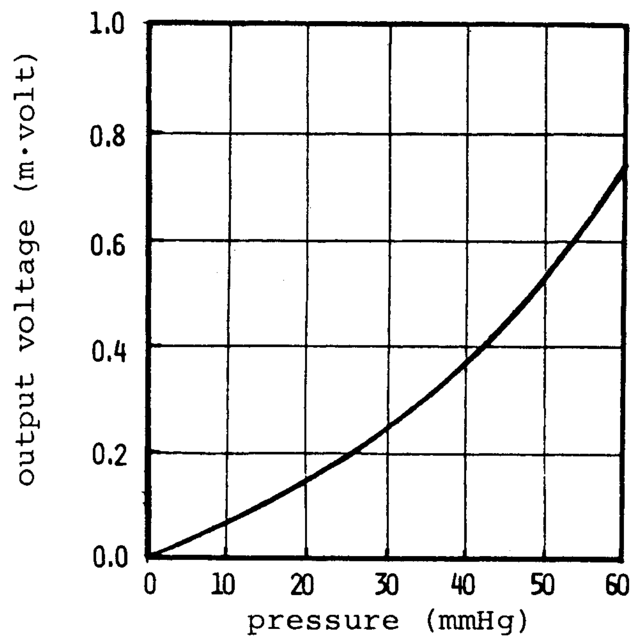

Fig. 7 Calibration curve between the pressure and output voltage.

It is also very important to investigate the temperature rise of the diaphragm because the temperature of the gas around hypersonic vehicles becomes considerably high. Therefore, the authors estimated the temperature rise of the diaphragm of the pressure transducer. In this estimation, the temperature of the gas outside the boundary layer around a hyersonic vehicle was assumed to be constant, and the gas inside the boundary layer was assumed to be still. The temperature of the diaphragm can be obtained by solving the following simultaneous equations with the above assumptions.

$$\frac{\partial T_1}{\partial \tau} = k_1 \frac{\partial^2 T_1}{\partial x^2}, \qquad x_1 \geq 0 \tag{3}$$

$$\frac{\partial T_2}{\partial \tau} = k_2 \frac{\partial^2 T_2}{\partial x^2}, \qquad x_2 \leq 0 \tag{4}$$

$$\lambda_1 \frac{dT_1}{dx_1} = \lambda_2 \frac{dT_2}{dx_2} \qquad \text{at} \qquad x_1 = x_2 = 0 \tag{5}$$

$$T_1 = T_2 \qquad \text{at} \qquad x_1 = x_2 = 0 \tag{6}$$

The results of calculation indicate that the temperature of the diaphragm surface rises only on the order of $(Tg - Td) \times 10^{-3}$. In our case, the gas temperature Tg was on the order of 10^3 K and, therefore, it is found that the temperature of the diaphragm surface rises only a few degrees. Consequently, it is considered that the effects of the high-temperature gas in the present pressure measurements are negligible.

As for the sensitivity of the pressure transducer, the output voltage in relation to the distance of the deflection of the diaphragm was 20 m · V/mm, as indicated in Fig. 4, when applied voltage is 1000 V. From this, it is considered that the sensitivity of the magentic tape is great enough for reading the output voltage. Therefore, the magneic tape is usable as a sensitivity pressure sensor.

Concerning the pressure range of the pressure transducer, diaphragm-type pressure transducers are usable for low pressure or high pressure based on selecting the suitable thickness, diameter, modulus of elasticity, etc. of the diaphragm. In these experiments, the pressure transducer was designed to measure the pressure value of 60 mm Hg at the maximum.

As for the accuracy of the pressure transducer, it is considered that the pressure transducer using magnetic tape is considerably accurate, as is shown in the experimental results indicated in Figs. 8 and 9.

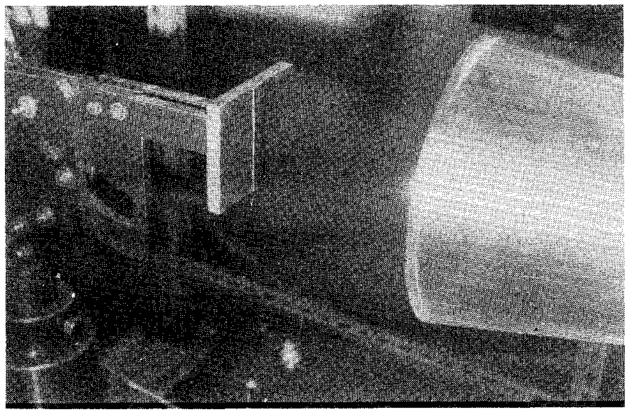

Fig. 8 Test section.

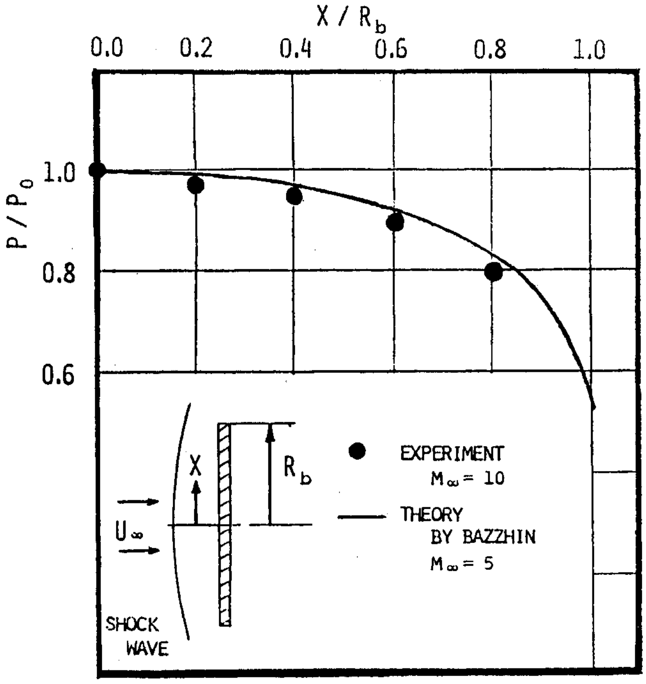

Fig. 9 Pressure distribution on the surface of a flat plate.

The procedure for using the pressure transducer is as follows:

1) A thin sheet including a magnetic tape and a lead wire is bonded onto a model surface.

2) The model is set in the test section.

3) The wind tunnel is operated, and the model surface is subjected to air pressure.

4) An electric current is generated for about 2 μ s in the lead wire while the freestream is obtained by using the electric circuit shown in Fig. 2.

5) The magnetic tape is magnetized according to the strength of the air pressure.

5) The magnetization strength is read by the measuring system shown in Fig. 3.

7) The pressure value applied to the model surface is obtained by using the calibration curve shown in Fig. 7.

IV. Pressure Distribution Measurements

As described in the introduction, it is troublesome to measure pressure distributions on the surface of bodies in experiments using tunnels of short duration such as hypersonic gun tunnels, shock tunnels, etc. Therefore, the authors attempted to measure pressure distributions by using the present pressure tranducer in order to show that it is usable for experiments using a hypersonic gun tunnel whose main characteristics are a Mach number of 10, duration time of 10^{-2} s, stagnation

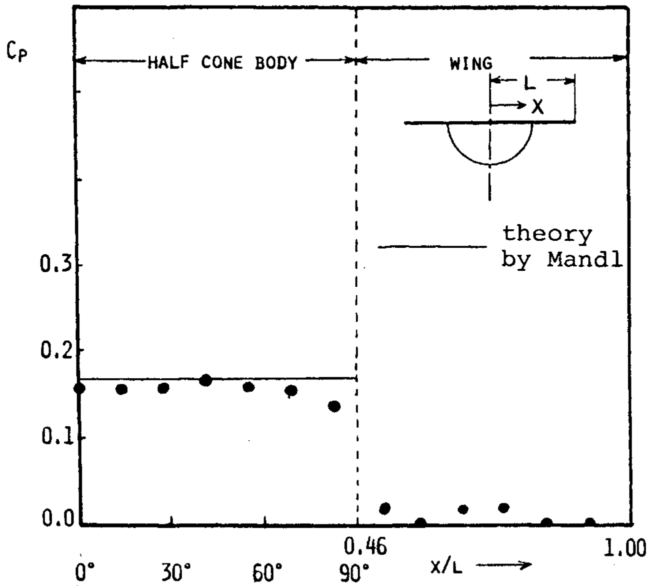

Fig. 10 Pressure distribution on the surface of a half-cone body with a delta wing.

temperature of 1000K, dynamic pressure of 35 mmHG, and nozzle exit diameter of 15 cm.

First, a pressure distribution on the surface of a flat plate was measured. Figure 10 shows the test section including the flat plate placed perpendicularly to the hypersonic flow. One can see that the sheet, which contain five pressure transducers, is bonded onto the model surface. The result of the measurement is shown in Fig. 8, and the calculation results using the integral relation by Bazzhin[7] is also indicated in the figure. The figure shows that the results of both agree comparatively well. From this, it can be seen that the present method is usable for the measurement of pressure distributions.

Next, the authors measured a pressure distribution on the surface of the model with a more complicated shape. The model is a half-cone body with a delta wing, a fundamental figure of hypersonic vehicles. The semi-apex angle of the cone is 15 deg, and the semi-apex angle of the delta wing is 30 deg. The experiment was carried out under the condition that the angle of attack of the model was 0 deg. The result of the measurement is shown in Fig. 9, and the theoretical result obtained by P. Mandl[8] is also shown in the same figure. The figure shows that the results of both agree well. From this, it is considered that the proposed method is usable for the measurement of pressure distributions on the surface of complicated model shapes.

V. Conclusions

In experimental studies of the aerodynamics of aircraft, measurements of pressure distribution on their surfaces are constantly performed. However, it is very troublesome to carry out these measurements as they require much time and hard work. In order to solve this problem, a new method of surface pressure measurement has been developed by the authors: the method has two special features:

1) The proposed pressure transducer is a diaphragm type that utilizes a magnetic tape as the sensor. The method is based on the idea that a pressure value applied to the diaphragm made of magnetic tape is related to the deflection of the diaphragm, and the deflection can be related to the value of magnetization strength of the magnetized magnetic tape; therefore, the pressure value can be obtained by reading the value of the magnetization strength.

2) The merit of the present method is that it can be easily applied for measurement of pressure distributions on model surface because many pressure transducers are contained in a single thin sheet and, therefore, we can peform pressure distribution measurements by just bonding the thin sheet onto a model surface without disturbing the flowfield.

The proposed method can be used in high-temperature, short-duration measurement conditions, and so it is well suited to hypersonic wind-tunnel use. In this study, the model experiments using the present pressure sensor were performed using a hypersonic gun tunnel whose characteristics were a Mach number of 10 and duration time of 10^{-2} s. The measurements of pressure distributions around the flat plate and the semicone body with a delta wing were carried out successfully.

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