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# INSTRUMENTATION IN WIND TUNNELS

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16. Abstract Requirements in designing instrumentation systems and measurements of various physical quantities in wind tunnels are surveyed. Emphasis is given to sensors used for measuring pressure, temperature, and angle, and the measurements of air turbulence and boundary layers. Instrumentation in wind tunnels requires accuracy, fast response, diversity, and operational simplicity. Measurements of force, pressure, attitude angle, free flow, pressure distribution, and temperature are illustrated by a table and a block diagram. The LDV method for measuring air turbulence and flow velocity and measurements of skin friction and flow fields using laser holograms are discussed. The future potential of these techniques is studied.

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# INSTRUMENTATION IN WIND TUNNELS

K. Takashima

This article deals with considerations involved in /194* wind tunnel instrumentation. This instrumentation is generally categorized into the functions of detection, signal adjustment, digitalization and documentation, though it may also be thought of simply in terms of data processing and output. Except for the detection devices, all other instrumentation has become very convenient to use owing to the remarkable progress that has been made in electronic technology. Also, since these functions are common to many measurement systems, ample reference materials are available for them. On the other hand, development for the detection component has not matched that of electronic technology. And, according to those performing the experiments, that is, those who are gathering detailed information on the physical phenomena in question, detection devices are extremely vital. Once the values which show physical phenomena are transformed into quantities of electricity, the problem generally becomes simple and in most cases it is possible for the ordinary signal system to carry out the commands from the measurement system.

Accordingly, we will give the electronic signal recording component very simple treatment here and focus our discussion on the detection component. This consists of actual examples from the seven large wind tunnels in use by Kokiken [Aviation Technology Research] and foreign research and development.

*Numbers in the margin indicate pagination in the foreign text.

First of all, since guidelines on conditions to be met vary somewhat for large and small wind tunnels, attention will be given to the problem of which conditions should be considered most important. Next, measurement of ordinary physical values and special values will be explained. Last of all, fields where research is hopefully forthcoming will be discussed from the point of view of those who use measuring instruments and those who perform wind tunnel experiments.

## 2. Requirements for Wind Tunnel Measurement

The following are set forth as requirements for wind tunnel measurement:

(i) Increased precision: Accurate measurement of physical values.

(ii) Large data processing capacity: Obtaining the maximum amount of experimental information from each measuring point.

(iii) Ease of operation: A high level of experience is not required, and anyone is able to carry out the simple procedure for operation.

(iv) A large variety of measurements: Many types of experimental feedback which are treated with flexibility.

(v) Rapid response: Reduced measurement time and increased data productivity.

(vi) Low cost

The items listed above have a very significant bearing on the usability of some measuring systems in wind tunnels. With large wind tunnels it is necessary to stress data productivity, ease of operation, and quick turnaround.

Even with the same devices and the same measurement methods, definite changes are required between small and large wind tunnels. In most cases, large wind tunnels involve remote measurement and, therefore, many difficulties occur when arranging things to the experimenter's satisfaction.

For example, consider the use of an oil film or the oil-drop method for making the flow around the model visible. In small wind tunnels, a photo can be taken of the form of the flow for each set of experimental conditions, new oil can be applied, and one can proceed on to the next experiment easily. By contrast, in large wind tunnels, the operation must be stopped, pressure must be returned to atmospheric levels, and people must enter the tunnel, all of which takes time. For photography, scaffolding and illumination are problems, and a large amount of /195
time is required for the transition to the next experiment.

These considerations have made the problem of data productivity in large wind tunnels a topic of discussion for some time now. The expense of the large wind tunnels used to develop airplanes and rockets is tremendous, and if the data-producing devices perform poorly, costs can spiral up out of control. In order to improve data productivity, improvements must be made in experimental preparations and wind tunnel operating methods, while measurement time must be reduced.

If measurement time can be reduced by half, then the same operating cost could generate twice the data, which would be a great stride forward in efficiency. One of the measures being taken to achieve this is the use of highly responsive sensors. Processing measurement signals is ordinarily ten times as fast as response time for sensors.

Recently, in developments involving the use of a low-temperature wind tunnel used for testing high Reynolds coefficients, special attention has been paid to data productivity [1]. This is because, when people enter the testing area to change the form of the model, temperature near the area being tested increases, the nitrogen gas is replaced by air, etc., and this makes it necessary to replace the air with low-temperature nitrogen before resuming operations, which makes placing the model time-consuming. Furthermore, the liquid nitrogen used in operations is expensive, which makes a rise in productivity that much more appealing.

## 3. Measurement of Ordinary Values

### 3.1 Pressure Measurement

The main physical values which should be measured in a wind tunnel are pressure, temperature, force, and attitude, and the system for measuring them is shown in Figure 1. Of the values listed above, the one which normally assumes a key role is the measurement of pressure. This measurement is divided into several main categories: measurement of free flow "stagnation point" pressure, static pressure in the measurement area, wind velocity (Mach number) and dynamic pressure, and measurement of values for surface pressure on the model.

#### 3.1.1 Measurement of Free Flow

The devices used to measure "stagnation point" pressure (total pressure), test area static pressure, dynamic pressure, etc., are manometers with many different testing ranges, dynamic balance pressure converters (a combination of a differential transformer and a diaphragm, and a quartz pressure transducer

Table 1 Kokiken. Instruments Used to Measure Wind Velocity (Mach Number) in Large Wind Tunnels

| | (1) 風洞名 | (2) 型式 | (3) 風速, マッハ数 | (4) 測定部(m) | (5) 測定項目 | (6) 圧力計 | (7a) レンジ (kPa) | (7b) 備考 | |
|---|---|---|---|---|---|---|---|---|---|
| (8) | 大型低速風洞 (LWT) | 回流 (15) | 1~60 m/s | 5.5×6.5 | 動圧 (17)<br>静圧 (18) | オートマノメータ (20)<br>同上 (21) | 2.94<br>105 | クオーツ圧力変換器に変更を検討中 | (26) |
| (9) | 突風風洞 (GWT) | 回流 (15) | 3~67 m/s | 2×2 | 動圧 (17)<br>静圧 (18) | 同上 (21)<br>同上 (21) | 7.85<br>105 | | |
| (10) | 遷音速風洞 (TWT) | 回流 (15) | 0.2~1.4 | 2×2 | 集合胴圧 (19)<br>静圧 (18) | クオーツ (22)<br>同上 (21) | 158<br>158 | 水銀オートマノメータの使用を中止 | (27) |
| (11) | フラッタ風洞 (FWT) | 吹出式 (16) | 0.7~1.5 | 0.6×0.6 | 集合胴圧 (19)<br>静圧 (18) | 差動トランス付ブルドン管 (23)<br>同上 (21) | 490<br>392 | | |
| (12) | 二次元風洞 (TWWT) | 吹出式 (16) | 0.2~1.15 | 0.3×1 | 集合胴圧 (19)<br>静圧 (18) | 力平衡型 (24)<br>同上 (21) | 1,570<br>784 | 集合胴との差圧検出 | (28) |
| (13) | 超音速風洞 (BWT) | 吹出式 (16) | 1.4~4.0 | 1×1 | 集合胴圧 (19)<br>静圧 (18) | 同上 (21)<br>同上 (21) | 1,960<br>101 | クオーツ圧力変換器の使用を検討中 | (29) |
| (14) | 極超音速風洞 (HWT) | 吹出式 (16) | 5, 7, 9, 11 | 直径 0.5 | 集合胴圧 (19)<br>静圧 (18) | 同上 (21)<br>バリアブルリラクタンス (25) | 10,800<br>3.4 | 力平衡型使用中止 | (30) |

Key: 1) Name of wind tunnel; 2) Type; 3) Wind speed (Mach No.); 4) Measurement area (m); 5) Items measured; 6) Pressure measurement instrument; 7a) Range (kPa); 7b) Remarks; 8) Large, low-velocity wind tunnel (LWT); 9) Gust-type wind tunnel (GWT); 10) Transonic wind tunnel (TWT); 11) Flutter wind tunnel (FWT); 12) Two-way wind tunnel (TWWT); 13) "Supersonic" wind tunnel (BWT); 14) Hypersonic wind tunnel (HWT); 15) Circulation; 16) Blow-through; 17) Dynamic pressure; 18) Static pressure; 19) Total pressure; 20) Automanometer; 21) Same as above; 22) Quartz; 23) Differential transformer with Bourdon tube; 24) Force-balance type; 25) Variable reluctance 26) Conversion to quartz transducer being studied; 27) Use of mercury automanometer discontinued; 28) Sensing of differential pressure in total pressure tube; 29) Use of quartz transducers being studied; 30) Use of force-balance transducer discontinued.

(with liquid crystal vibrators) which has extremely good reproducibility [2]. Table 1 shows results from Kokiken's seven wind tunnels. Depending on the wind tunnel, several transducers with different measurement ranges are used, and each is put into service depending on the pressure level.

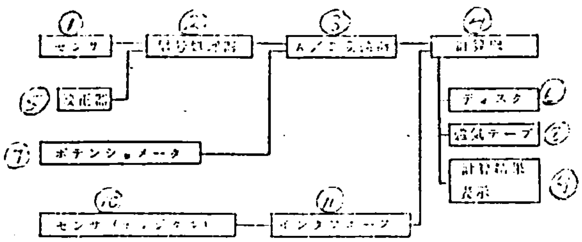


Figure 1 Block Diagram of Wind Tunnel Measurement System

Key: 1) sensor; 2) signal processor; 3) AC/DC transformer; 4) calculator; 5) rectifier; 6) disk; 7) potentiometer; 8) magnetic tape; 9) display of calculation results; 10) sensor (digital); 11) interface.

Generally speaking, among larger wind tunnels the circulation type have a long air-flow time which is more than adequate for calculation time, and without taking poor responsiveness into account, a tendency to stress increased precision has been observed. Furthermore, measurements near the normal pressure level or with small differentials between one pressure and another are frequently taken with a liquid-surface-simulation type automanometer and, given the discussion above concerning the importance of response time, use of a quartz-type pressure transducer is being contemplated. In this case, however, measurement of several kPa (several millimeters in a water column) of pressure would create some problems, even for the quartz transducer, which has excellent reproducibility.

It should be noted that the mercury automanometer which has been used for twenty years in 2 m-transonic wind tunnels will be discontinued and superseded by a quartz-type device in order to eliminate the slowness of mercury and the friction created by the moving parts.

The two-way wind tunnel is a variable-pressure wind tunnel capable of achieving high internal pressure [3], where stagnation-point pressure is taken in terms of absolute pressure and measurement area static pressure is detected by means of the pressure differential in relation to stagnation-point pressure. Because of the relationship of the low Mach number to the required measurement range, it is hoped that precision can be increased [4].

The use of quartz-type pressure transducers in supersonic wind tunnels to increase precision is under study.

Because of the nature of air flow in hypersonic wind tunnels, a high pressure ratio is necessary, and to measure the stagnation-point pressure a transducer with a measuring range of around 10 MPa is needed, whereas for the measurement area static pressure several hundred millimeters w.c. is low. In such /196 cases, the transmission measurement system was quite large, and there were response problems with the force-balance type transducer which was used initially; therefore, a variable reluctance pressure transducer is now being used.

### 3.1.2 Measurement of Pressure Distribution, etc.

Model surface pressure distribution, etc., used to be measured with a manometer, the procedure being that, after photography, a reading of the liquid column was taken. This was a cumbersome procedure that precluded handling large amounts of data. Currently, a scanning valve is frequently used for this purpose. This consists of a changeover switch for multiple pressure channels, which allows the pressure signal that has been switched over to be changed into an electrical signal by a pressure transducer. One transducer can process pressure signals from about 48 channels, and the measurement time required per channel is around 0.5 seconds for a circulation-type wind tunnel and 0.1 seconds for a blow-through type. Since the scanning valve is comparatively close to the measurement orifices, the transmission lag of the pressure tubes is smaller than the measurement time by one or two decimal places.

Recently an electronic switch-over valve, like that shown in Figure 2, has come into use. With this valve, each channel is equipped with a semiconductor-type pressure converter, and each pressure signal is converted to an electric signal by its own converter, and this low-level electric signal is scanned electronically. The measurement time is shortened, but costs for each channel are currently increased almost tenfold.

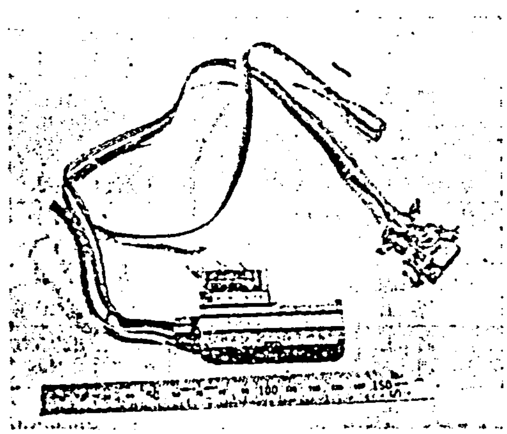

Figure 2 Electronic Switch-Over Valve

To increase responsiveness, an extremely small semiconductor distortion gauge-type converter is placed inside a probe, and this reduces the transmission lag caused by the pressure tube (fig. 3) [5].

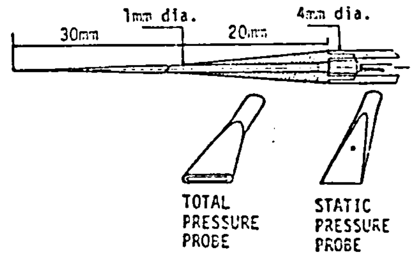


Fig. 3 Probe containing transducer

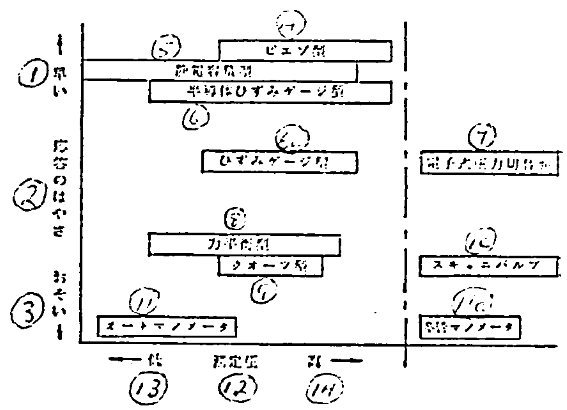

Figure 4 Responsiveness and Range of Pressure Gauges

Key: 1) fast; 2) responsiveness; 3) slow; 4) piezo type; 5) static capacity type; 6) semiconductor distortion guage type; 6a) distortion gauge type; 7) electronic pressure-switching valve; 8) force balance type; 9) quartz type; 10) scanning valve; 11) auto-manometer; 11a) multi-tube manometer; 12) pressure measured; 13) low; 14) high.

A general idea of the responsiveness and measurement range of converters commonly used in wind tunnels is given in figure 4.

## 3.2 Temperature Measurement

Overall airflow temperature is measured with thermocouples appropriate for the temperatures in question (copper-constantan, iron-constantan, chromel-alumel, platinum-platinum rhodium). Temperature-measuring resistors have also been used.

In hypersonic wind tunnels where air becomes heated or in experimental engine-turbine blade wind tunnels where gas is used as fuel, the overall temperature can reach several hundred degrees. In low-temperature wind tunnels where liquid nitrogen is evaporated, the temperatures reach 100 K, and normal ("room") temperature wind tunnels are also widely used, so the range of temperatures to be measured is very wide.

Experiments which measure the distribution of temperature over a model rarely utilize normal-temperature wind tunnels. In the majority of cases, they use hypersonic wind tunnels where temperature is measured by thermocouples implanted in the surface of the model.

In high-temperature wind tunnels a thermocamera is used to photograph heat distribution.

A variant experiment performed with normal-temperature wind tunnels is to use the slight temperature differences between a model exposed to layered airflow and one exposed to turbulent airflow and measure the transition points with thermocouples or thermistors implanted into the model and crystals which change color in response to temperature applied to the model's surface [6].

## 3.3 Measurement of Force

The pyramid-type scale often used in low-velocity wind tunnels converts force into electric charge by means of a distortion gauge-type load cell.

In high-velocity wind tunnels an insertion-type scale, inserted into the model, is used to convert both the three axes of force and the moment into an electrical charge.

Though there are many types of measurement ranges for scales, their vertical force (≈"lift") is on the order of 9,800 N (1,000 kgf). In some cases an axis of force does not have the proper relationship with force and moment, working in other directions, and so the problem of setting it apart for measurement has prompted the appearance of many devices, which generally consist of flexures inserted into the two ends of a sensor, which causes the sensor not to serve as a resistance element for any direction other than the specific one. Figure 5(a) shows various types of force-measuring sensors, while 5(b) shows various types of flexures [8]. In some cases a ball with a load cell feely moving around it is used instead of a flexure.

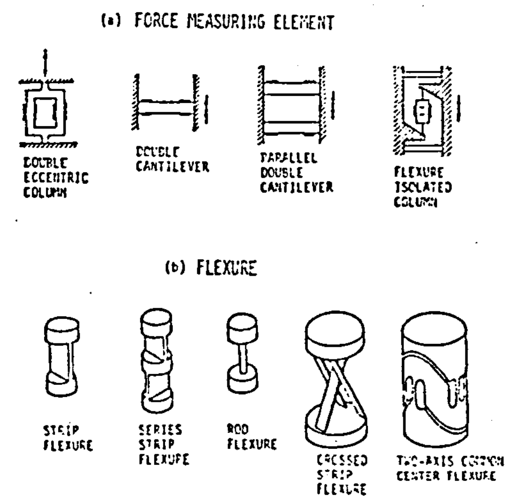


Figure 5 Free-measuring sensors and flexures

Even with such devices, the force or moment cannot be measured separately for some directions. When measuring with scales, the values for moment or axial force are sometimes affected by moment and axial force in other directions, and so the measured value, $X_i$ (i = 1,...6), compared to the true value $X'_i$ (i = 1,...6), without taking exponential elements into account, is expressed as

$$X'_i = \sum_{j=1}^{6} a_{ij} X_j \quad (i=1,\cdots,6)$$

where $a_{ij}$ is a coefficient of interaction between axes and must be determined beforehand based upon the scale adjustment figure, which is determined by the static load. Generally speaking, axial force and rotating moment are greatly affected by force and moment in other directions.

Structurally speaking, there are two types of insertion-type scales. One type, a floating-spool type consists of a stationary spool linked to a floating spool by a load cell, illustrated in Fig. 6, with the floating spool on the model side and the stationary spool on the support side. Installation of the load cell is shown in Fig. 7.

The figure shows how the cell was made to take advantage of the thickness of the inner and outer tubes. The scale made by the Amerian Company TASK has this form. Generally speaking, when a scale is used, the outwardly radiating petal-like formation of the sensors, which is used to differentiate the six component forces, must be precise. Consequently, with this type of scale, the assembly of components is extremely important.

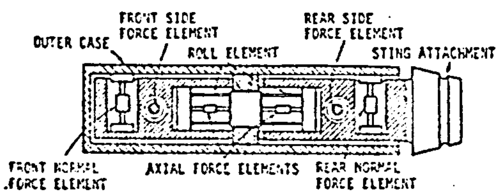


Figure 6 Floating-spool type insertion scale

Another structure is shown in Figure 8, where a variety of grooves are cut into a long piece of material and distortion gauges are attached to sensors so that the value to be measured can be detected [8]. The Boeing Company manufactures this type, which is called the moment or compound type.

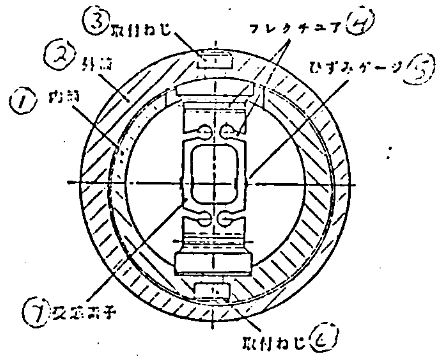

Figure 7 Installation of sensing element

Key: 1) inner tube; 2) outer tube; 3) installation screw; 4) flexure; 5) distortion guage; 6) installation screw; 7) sensing element

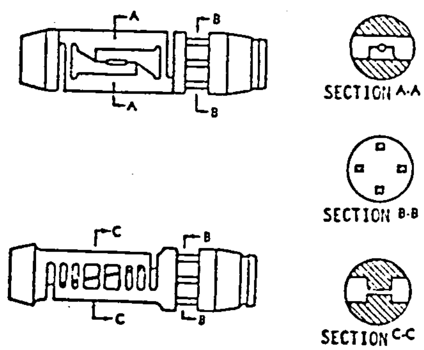


Figure 8 Compound scale

Each of the two types has strengths and weaknesses. The floating spool type, in its smaller forms, is quite adequate, showing a small degree of interference interaction from other moments and axes of force, but it is easily affected by temperature. The moment type is greatly affected by interference, yet exhibits very little drift during prolonged usage. In actual use, the two seem evenly matched.

Entirely new types of scales are the magnetic-force type and the model-supporting type, and since their use entails no effect on air flow because of support structure, they are the object of very strong interest. They are being developed in places like

America [9], though they are not yet in use. This is due to problems such as control of the large electrical charges needed for the magnetic force type. Studies are under way concerning use of the magnetic force-type scale which utilizes ultraconduction in low-temperature wind tunnels, which were mentioned earlier in the text.

### 3.4 Measurement of Attitude Angles

The angles of attack, banking, and yaw are measured /198 by transmitting the rotation movement of the component that affects attitude changes to a potentiometer or a shaft encoder. For example, in Figure 9 the angles of tilt θ and rotation Φ of the string attachment, which is supporting the model, are being detected. The angles of attack α and yaw ø are given by the following formulas:

$$\alpha = \mathrm{Sin}^{-1}(\sin\theta\cos\varphi/\sqrt{1-\sin^2\theta\sin^2\varphi})$$
$$= \mathrm{Sin}^{-1}(\sin\theta\cos\varphi/\cos\psi)$$
$$\psi = \mathrm{Sin}^{-1}(\sin\theta\sin\varphi)$$

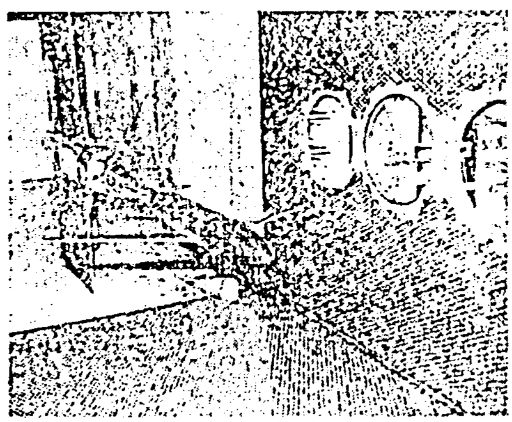

Figure 9 Determining tilt and rotation angles

In this case, the angle obtained is not the angle in relation to the airflow, but a geometric angle based upon a base axis (eg.

water-level axis). To find the true angles of attack and yaw, the angle between the direction of air flow or the scale or the supporting string attachment and the base axis must be determined and used to compensate while calculating. These are quantities which are determined when airflow is being tested or scales are being adjusted.

In some cases, the model's attitude is measured without any relation to the angle of the support apparatus when a vibrator-type potentiometer or an accelerometer which is used to determine the force of gravity is installed on the model to determine the attitude in relation to the gravity axis.

In experiments where the model is subjected to a large load, that is, experiments involving a high Reynolds stress value, it is necessary to consider using the method of adjusting the angle described above. For example, in the RAE 5 m-high-pressure-low-velocity wind tunnel, the pitch and banking angles are measured with an accelerometer inserted into the model, while experiments are being performed in which the angle of yaw is measured with a laser beam that sweeps the surface of the model, using the signals from three detection devices imbedded in the surface of the model as triggers which prompt calculation of changes in the angle of the detection devices and subsequent calculation of yaw [10].

For the transonic wind tunnel (NTF) under construction in Langley, stress photography, moire fringe observations, and surface distortion detection using microwaves are being developed to observe changes in the model surface produced by high-load experiments [11].

Angle measurement is usually precise to 0.01-0.05°.

## 4. Special Measurement

The measurements discussed under section 3 are those with highest priority in wind tunnel experiments. Since many different types of experiments with different use-related objectives are conducted, values other than those mentioned above may need to be measured. Even if only air flow conditions are being considered, temperature can be low, normal, or high, pressure can be low, normal, or high, velocity can be low, transsonic, supersonic, or hypersonic, and using the combination of factors most suited to the experimental objective can lead to many different ramifications. Here, factors held in common and particular factors such as turbulence of air flow, inter-strata linkage measurement, simulated propulsion experiments, dynamic-stable experiments, and, finally, measurement of field of flow must be considered. Wind direction is often measured (yawmeter [7], five-hole Pitot tube [12], revolving probe [13]) with ultrasonic-wave current meters [12], and thermoconductive measurement [14,15].

### 4.1 Measurement of Turbulence

Turbulence of air flow involves changes in velocity, pressure, and temperature, with changes in velocity often being the only concern when low-velocity flows are involved. Up to now, velocity turbulence sensors have generally consisted of hot-wire or hot-film devices, and much reference material is available on the subject [16]. The hot wire is made of platinum with a diameter of less than 5$\mu$m and length of around 1 mm, while the hot film is a wedge which consists of 1 mm film at the end, or a cone-shaped quartz probe with platinum film (width 0.2 mm, thickness several micrometers) formed upon it by deposition or some other method. The fine wires are usually used at temperatures of 300-400°C, with turbulence frequencies of 100 kHz, though there are systems which reach 500 kHz to 1 MHz [17].

According to various intended usages, many types of probes are available commercially, including those which make tri-axial velocity changes detectable with a single probe.

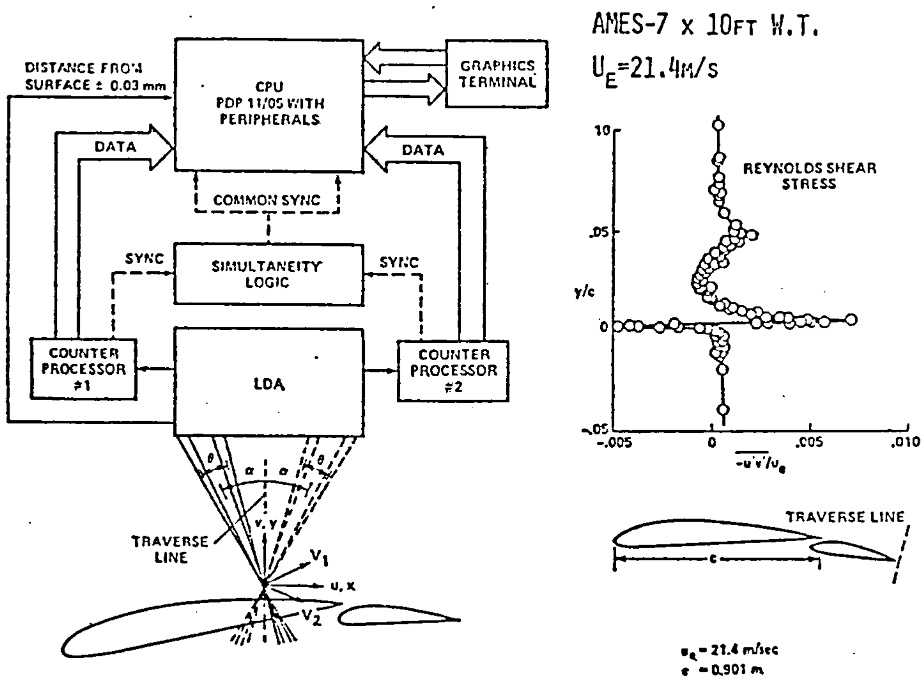


Fig. 10 A two-dimensional LDV for measuring Reynolds stress

Recently, a laser current velocimeter (Laser-Doppler Velocimeter or LDV) has been used to measure turbulence. There is much reference material available concerning use of the LDV [18]. LDV, being a non-contact type of measurement, has the advantage of not altering the flow it is measuring. When turbulence is being measured, the laser beam is split in two by a beam splitter as it emanates from its source, and the path of each of these beams is focused on the desired position and an interference grill (25-50 lines) is made. Wind velocity and turbulence are shown in the light and dark areas formed by windborne particles caught on the grill, which reflect the diffused light which is shone on them. When this method is used in a wind tunnel, problems may arise concerning data processing methods and the introduction of particles into the air flow, but it makes two- or three-dimensional measurement possible, which, it is anticipated, will prove very useful. Though this method is used extensively in laboratory-scale wind tunnels, there are not yet many examples of use in large tunnels. Figure 10 shows an example of the use of two-dimensional LDV to measure Reynolds stress in the wake of a model wing in a 7' x 10' low-velocity wind tunnel at NASA [19]. While detailed data are being /199 obtained in this manner, the use of LDV in large wind tunnels is still considered to be in the development stage. Hopes are for advances in the future.

Comparison of the hot wire and LDV reveal that the hot wire is considerably cheaper and also easier to apply to low velocity wind tunnels, and so it is widely used. It is, however, inferior in range of applications to LDV. It cannot be used with an unclean air flow because it breaks easily, nor can it be used with high-temperature flows or reactive gases. Though two- and three-dimensional velocity measurements can be considered easier with LDV, LDV has the problems touched upon earlier, so neither is a clear choice. Rather, there is a tendency to consider combined use of the two methods.

In high-velocity wind tunnels, pressure changes (noise) are a recurring problem [20]. The frequency range being measured goes up to 20 kHz, and a microphone (pressure converter) with a high natural frequency is used for measuring. The sensor involved consists either of a condenser microphone or a small pressure transducer which utilizes a semiconductor gauge. When the sensor is imbedded in the tip of the probe, care should be taken that the environment of the sensor does not introduce additional sound.

## 4.2 Boundary Layers and Flow-Related Measurements

### 4.2.1 Pressure Measurement

The hot wire and LDV mentioned above in section 4.1 are often used in measurement of boundary layers, being devices which measure velocity directly. An indirect method of measuring velocity involves use of a probe to measure local pressure. The area to be measured is extremely small, so the probe must be carefully designed. Figure 11 gives cross-section examples of three probes which face respectively, upward, forward, and downward with respect to the flow, and are used to measure flow direction and velocity. Together the probes are 1 mm wide with each being 0.089 mm thick, which are extremely small dimensions [21]. Depending upon the type of wind tunnel involved, this type of probe may be installed on the model wings, or the technique of placement used to form a traverse line.

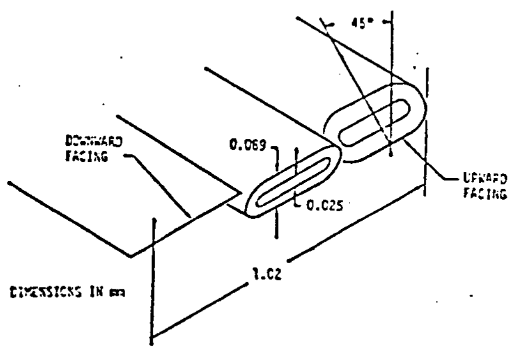


Figure 11 Small Probes

### 4.2.2 Surface Friction

The measurement of surface friction can be described as a method which proves a host of theories concerning boundary layers. There are direct and indirect measures involved in this type of measurement. Figures 12 (a) and (b) both show examples of small scales used to measure surface friction directly [22, 23]. Figure 12 (a) shows a device utilized in supersonic experiments in which measurement is accomplished by automatic balancing of the bends created in a sensor beam by surface friction. In order to avoid shifts in the orientation of the

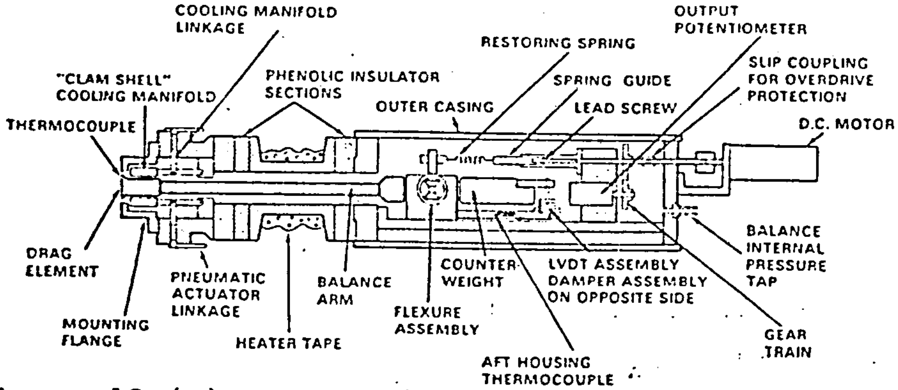


Figure 12 (a) Automatic balance-type scale for measuring surface friction

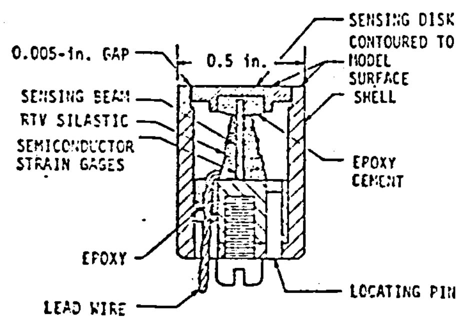


Figure 12 (b) Surface friction transducer [23]

sensing surface because of the effects of temperature, /200
an absolute temperature of 89° is maintained. Scales are adjusted with 1.5-3.5 g actual load.

Figure 12 (b) shows a device which measures bends in the sensing beam and calculates friction according to the magnitude of these bends. The sensing surface is made to be contoured to the conical form of the model. Measurement power is $10^{-4}$ - 1.7 x $10^{-2}$ Newtons.

Indirect methods of measuring make use of a Preston Tube or an obstacle panel which are ultimately pressure measurement techniques [12, 24]. Or hot wires may be imbedded in the model surface, which is essentially a utilization of the hot-wire technique [25], etc.

### 4.3 Experiments Involving Models with Simulated Propulsion [26]

Experiments involving installation of engines which work from air pressure, etc., on the model and simulate engine functions require measurement of the functioning of the model engine. Items to be measured are the engines's internal pressure (distortion gauge sensor, 3,400 kPa), temperature of engine bearings (thermocouple, 200°C), vibration (accelerometer, 2 G), rmp (non-contact type, 70,000 rpm), etc. Care should be taken that the rigidity of the pipes providing the external supply of air not affect the measurement of any other air force [27], which may be technically difficult.

### 4.4 Dynamic Stability Testing [28]

The purpose of this sort of experiment is to measure the drag (moment) created by the force of the air on the aircraft during movement, such as changes in altitude. The experimental methods are to subject the model to forced vibration and measure the force of the air with a special scale, and then to cause the model to vibrate naturally, observe its motion (coordinates) and calculate the drag (29).

The scale used for the forced vibration method has recently been equipped with sensors capable of determining derivative coefficients of alternation, etc., and has had its data-processing capabilities enhanced. In the observation of motion, rather than using new sensors, more research is taking place on processing already obtainable coordinate data.

Dynamic stability experiments, in general, present difficulties in the measurement of small amounts of drag under conditions where forces of great magnitude, such as inertia and static air force, are at work, though use of torque feedback in the sensing system to diminish the effects of the large-magnitude forces is undergoing experimentation [30].

## 4.5 Measurement of Field FLow

Methods which make the flow visible have been effective in enhancing overall control and increasing direct observability of the field of flow. They have appeared in large numbers [31]. A comparatively new method is use of a small tuft, 0.02-0.05 mm in diameter--small enough not to alter the force of air applied to the model--to observe the characteristics of the air flow [32]. Using a tuft made of strands of nylon treated with fluorescent material and subjected to ultraviolet light makes it easy to photograph the process. For observation of high-velocity regions a holographic interferometer which uses laser beams in coming into use.

Holographic interferograph within 2-dimensional slot

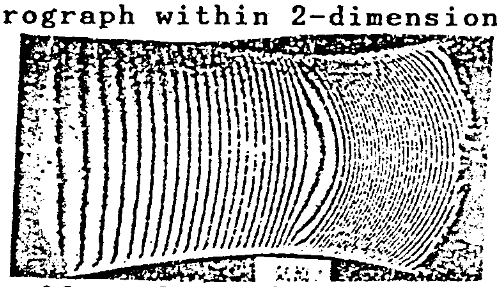

Figure 13 Holographic interferograph

Figure 13 shows the result obtained with the dual hologram interference method applied to an isodense line graph taken from within a two-dimensional slot [34].

This type of field of flow measurement and a slight variation on it, optical display of field of flow, are both being used. In the latter, a pressure probe traverses a field of flow horizontally and vertically. Its signal is transmitted by a LED (light emitting diode) installed on the probe, and converted into a polychromatic optic signal which is then photographed. The color of the LED signal varies according to the input signal level, and pressure changes within the field of flow are displayed as changes in color. Aspects of the field of flow for the airflow path or a cross-section, such as the magnitude of associated flows, are reflected in change of color and thus can be holistically understood, and it becomes easy to read the isobaric lines (lines of the same color) [32, 35].

## 5. Hopes for the Future

This is the era of smaller and lighter devices, and accordingly the general tendency is for sensors to become smaller and higher in velocity. Pressure sensors have moved from manometers to quartz pressure transducers or from multi-tube manometers to scanning valves or electronic switch valves. It is hoped that semiconductor-type pressure sensors will be developed, and become smaller, more precise, and cheaper. Furthermore, research and development on probes, which are closely related to sensors, is extremely important.

Measurement methods used in the past have been inexpensive and easy to use. Development of a new method which serves as a contrast, non-contact measurement with lasers, is highly desirable. The data gathering and complex processing required by this process will, of course, have to be done by computer. In such cases, the tendency is for optical methods not to replace the older methods, but be used together with them.

It is hoped that a simpler, more convenient methodology will be developed for hot-wire technology, which utilizes the computer for all its calculations.

## 6. Concluding remarks

This article has been principally concerned with the sensors used in wind tunnel sensing systems in the measurement of pressure, temperature, force, and angles. Measurement of such phenomena as boundary layers and turbulence was touched upon and observations were made on areas for future development.

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