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Трехкомпонентные аэродинамические тензовесы

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В статье рассматривается воздействие потока на модели, исследуемые в аэродинамических трубах. Для определения силового воздействия потока на исследуемую модель предложен более точный и надёжный метод непосредственного измерения сил и моментов с помощью аэродинамических тензометрических весов. При решении плоской задачи для симметричной модели при нулевом угле скольжения предлагается конструкция трёхкомпонентных весов, измеряющих подъёмную силу, силу лобового сопротивления и момент тангажа. Для исключения взаимодействие между поддерживающими устройствами и моделью, которое вызывает возмущения в потоке вблизи модели, весы располагаются вне модели и рабочей части аэродинамической трубы. Компоненты аэродинамической силы и момента, действующие на модель, измеряются при помощи тензодатчиков сопротивления, преобразующих деформации упругого элемента в изменение электрического сопротивления, которое измеряется прибором, соединенным с соответствующей измерительной схемой. Выбор тензодатчиков в качестве весовых элементов обусловлен их весьма малыми размерами и весом, возможностью измерения очень незначительных относительных деформаций упругих элементов, малой инертностью, что позволяет измерять не только статические, но и динамические нагрузки, а также возможностью дистанционных измерений. Для компенсации влияние различных источников погрешностей, повышения чувствительности и обеспечения большей точности измерений тензодатчики соединены по мостовой схеме и включены во все четыре плеча моста. Деформация горизонтальной измерительной балки вызывает изменение сопротивления не только в тензодатчиках, измеряющих момент тангажа, но и в тензодатчиках, предназначенных для измерения подъемной силы. Так как конструкция весов не позволяет электрически разделить эти компоненты, то влияние момента тангажа на величину подъемной силы определяется в процессе тарировки и оценивается с помощью специального графика влияния, построенного по результатам тарировочных данных. При тензометрических измерениях выходные величины сил и момента, действующих на испытуемую модель, получаются в виде соответствующих показаний прибора, измеряющего электрические сигналы, пропорциональные приложенным силам. Для перевода приборных данных в величины сил и моментов производится совместная тарировка весов и приборов с целью получения тарировочных коэффициентов. Дополнительные составляющие аэродинамических сил и моментов, создаваемые державкой, определяются путем её продувки в присутствии модели. Приведены расчетные зависимости для определения составляющих аэродинамического воздействия. Величины коэффициентов аэродинамических сил и моментов даются в поточной системе координат. Дано заключение о том, что использование тензометрических весов позволяет значительно сократить время проведения эксперимента и повысить точность определения исследуемых параметров по сравнению с весами механического типа.

Ключевые слова: тензометрические весы, сила лобового сопротивления, подъемная сила, момент тангажа.

Three-component aerodynamic load cells

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The article examines the effect of flow on models studied in wind tunnels. To determine the force effect of the flow on the model under study, a more accurate and reliable method of directly measuring forces and moments using aerodynamic strain gauge balances is proposed. When solving a plane problem for a symmetrical model at zero slip angle, a design of three-component scales is proposed that measures the lift force, the drag force and the pitching moment. To eliminate the interaction between the supporting devices and the model, which causes disturbances in the flow near the model, the scales are located outside the model and the working part of the wind tunnel. The components of the aerodynamic force and moment acting on the model are measured using resistance strain gauges, which convert the deformation of the elastic element into a change in electrical resistance, which is measured by an instrument connected to an appropriate measuring circuit. The choice of strain gauges as weight elements is due to their very small size and weight, the ability to measure very small relative deformations of elastic elements, low inertia, which makes it possible to measure not only static but also dynamic loads, and the possibility of remote measurements. To compensate for the influence of various sources of errors, increase sensitivity and ensure greater measurement accuracy, the strain gauges are connected via a bridge circuit and included in all four arms of the bridge. Deformation of the horizontal measuring beam causes a change in resistance not only in the strain gauges that measure the pitching moment, but also in the strain gauges designed to measure the lift force. Since the design of the scales does not allow for electrical separation of these components, the influence of the pitching moment on the magnitude of the lift force is determined during the calibration process and is assessed using a special influence graph constructed from the results of calibration data. In strain gauge measurements, the output values of forces and moments acting on the model under test are obtained in the form of corresponding readings from a device that measures electrical signals proportional to the applied forces. To convert instrument data into values of forces and moments, a joint calibration of scales and instruments is carried out in order to obtain calibration coefficients. Additional components of aerodynamic forces and moments created by the holder are determined by purging it in the presence of the model. Calculated dependencies for determining the components of the aerodynamic impact are given. The values of the coefficients of aerodynamic forces and moments are given in the flow coordinate system. The pledge has been given.

Keywords: strain gauge scales, drag force, lift force, pitching moment.

Introduction

The flow effect on the models studied in wind tunnels is reduced to forces continuously distributed over the streamlined surface of the model. These forces are characterized at each point of the surface by pressure and tangential stress. By integrating these loads over the surface, it is possible to find the total aerodynamic characteristics. A more accurate and reliable method for determining the total aerodynamic forces and moments is the direct method of measuring the forces and moments using aerodynamic scales. The problems of complex automation of a multifactorial experiment cannot be solved by traditional measuring systems with mechanical transducers. To solve the problems of measurements during aerodynamic tests and to increase the level of their automation, it is necessary to use strain gauge measuring systems [1–4].

One of the main features of aerodynamic scales is the number of components measured. Depending on this number, scales can be three-, four-, and six-component.

Six-component balance measures the magnitudes (components) of the projections of the total aerodynamic force onto three selected mutually perpendicular coordinate axes and three components of the total moment relative to these axes [5–8].

Three-component aerodynamic balance measures two components of the total aerodynamic force (lift force *Y* and drag force *X*) and the longitudinal moment about the transverse axis (pitch moment M_z) [9].

Depending on the location of the aerodynamic balance relative to the model and the wind tunnel, they are divided into two types: balances located outside the model and the working part of the tunnel, and balances located inside the model or holder.

Design and operating principle of the device

In the aerodynamic laboratory of the Department of Aircraft, three-component scales of the first type were developed.

The scales operate using the strain gauge method of measuring forces and moments. The elastic force elements (beams) are designed so that they have the lowest rigidity relative to one of the axes. When a load is applied along this axis, the greatest deformation of this element occurs. In other directions, the rigidity of the elastic element is significantly greater, and if forces act in the direction of other axes, then the deformation of the elastic element is practically absent. The beams have such small deformations that the displacements of the model caused by them can be neglected. Measurement of small deformations of elastic elements is performed using strain gauges that convert the magnitude of the deformation into a change in electrical resistance, which is then measured by a device connected to the appropriate measuring circuit.

The choice of strain gauges as weighing elements is due to their very small size and weight, the ability to measure very small relative deformations of elastic elements, low inertia, which allows measuring not only static but also dynamic loads, as well as the possibility of remote measurements [10–12].

The stress state on the surface of the elastic element to which the sensor is glued can change from point to point, so the change in sensor resistance is proportional to some average stress in a section with a length equal to the sensor base. In order for the sensors to record the stress at a point, the aerodynamic scales use sensors with a small base (7 mm) with a resistance of 200 Ohm. The strain gauges are connected in a bridge circuit and are included in all four arms of the bridge, which allows for a significant increase in sensitivity and ensures greater measurement accuracy.

In aerodynamic scales located outside the model, the decomposition of the total aerodynamic force and moment into components is carried out using elastic links, which simultaneously perform the role of measuring elements. The structural diagram of the scales is shown in Fig. 1.

The model is installed in the flow using a tail L-shaped holder to eliminate the effect on the flow at the location of the working part where the model is installed. During blowing in a wind tunnel, the sum of two aerodynamic forces is measured, one of which acts on the model, and the other on the devices supporting this model, placed in the flow. To find the force acting only on the model, the component due to the supporting devices is subtracted from the total force. This component is determined as a result of blowing the supporting devices without the model.

The drag force *X*, the lift force *Y* and the pitching moment M_z are given in the flow coordinate system, when the *OX* axis is directed along the flow, the *OY* axis is perpendicular to it upwards. The center of pressure of the model is taken as the origin of the coordinates.

The drag force *X* acting on the model is transmitted through the balance stand to four vertical beams I (only two of them are shown in Fig. 2, *a*). The elastic elements have very low resistance to bending in the plane of action of the force *X* and significant rigidity in the perpendicular plane. This component *(X*) causes an S-shaped bending of the beams (Fig. *2, a*). Sensors glued to opposite sides of the beams are included in the adjacent shoulders of the bridge (Fig. 2, *b*), and the bridge reacts only to the drag force X. The other components (Y, M_z) are sources of tension or compression and do not cause imbalance of the bridge.

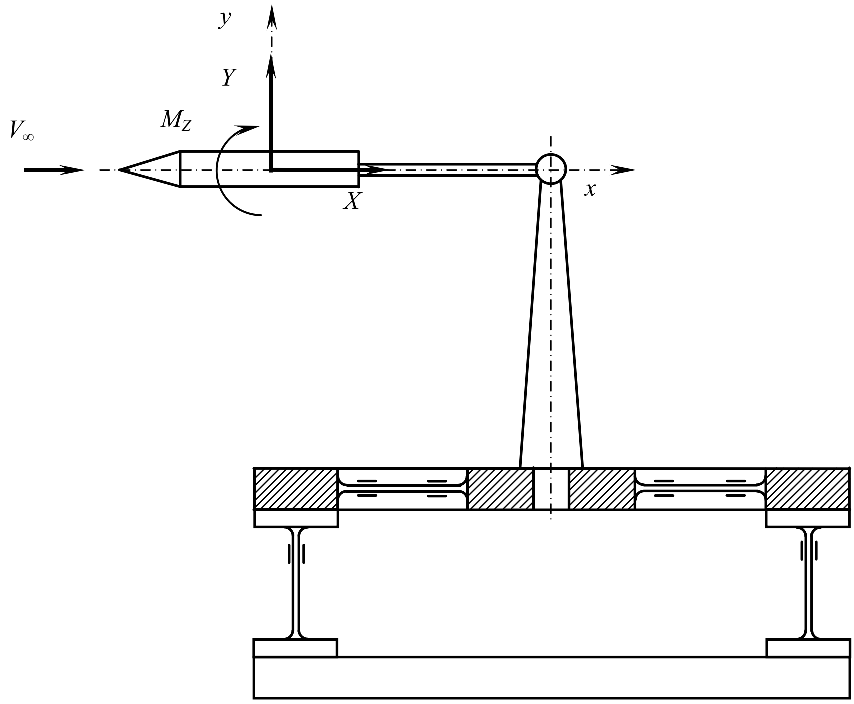
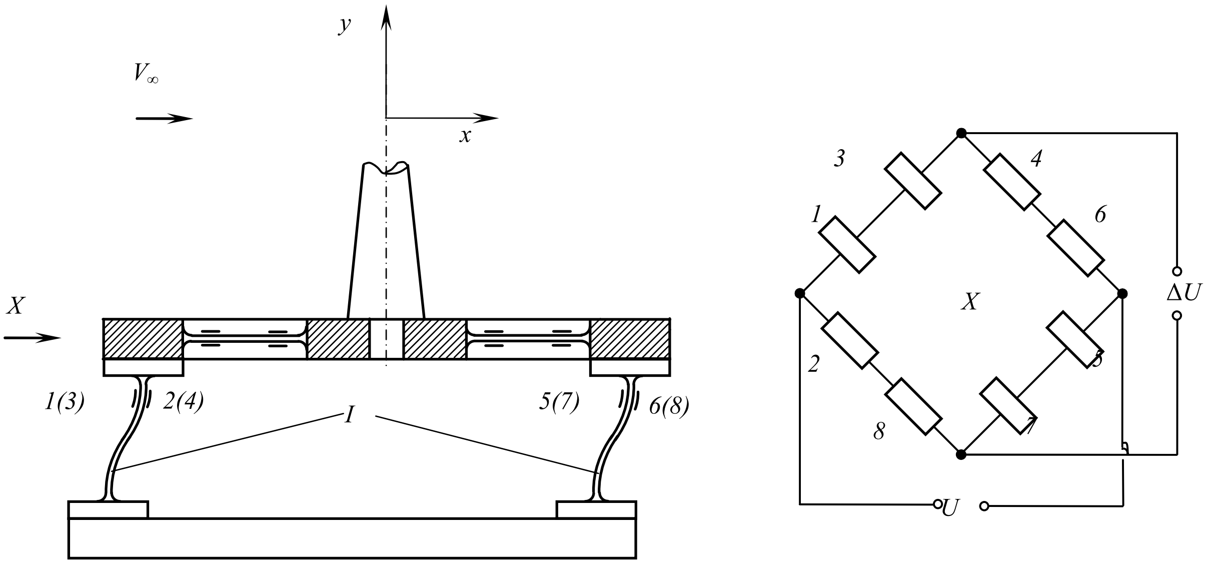


Рис. 1. Конструктивная схема аэродинамических тензовесов

Fig. 1. Design diagram of aerodynamic strain gauges



а *б*

Рис. 2. Измерение силы лобового сопротивления:
а – схема деформации измерительных элементов; *б* – электрическая схема соединения тензодатчиков

Fig. 2. Measurement of drag force:
a – deformation diagram of measuring elements; *b* – electrical connection diagram of load cells

To measure the lifting force Y and the pitching moment M_z, a horizontal beam II is used with a holder fixed to it.

Under the action of the lifting force Y, an S-shaped bending of the elastic elements of this beam occurs (Fig. 3). In order to obtain output signals proportional only to this component, strain gauges 9–12 are included in the measuring bridge, mounted on the lower and upper surfaces of the sensitive plates in the central part of beam II. The diagram of the inclusion of sensors in the bridge is shown in Fig. 3, *b*. Sensors 9, 11 and 10, 12 are included in different arms of the bridge. If a lifting force acts on the elastic elements of beam II, then these sensors register deformations of different signs and a signal appears at the bridge output.

The pitch moment M_z is perceived by elastic elements located along the OX axis (Fig. 4, *a, b*). Strain gauges 13–16 are installed on the peripheral part of the sensitive plates of beam II, included in the measuring bridge, which reacts to the deformation of the elastic elements bending only under the action of the pitch moment. The deformation of the horizontal beam II causes a change in resistance not only in the strain gauges measuring this moment, but also in strain gauges 9, 11 and 10, 12, designed to measure the lift force. Thus, there is a certain influence of the pitch moment on the value of the measured lift force.

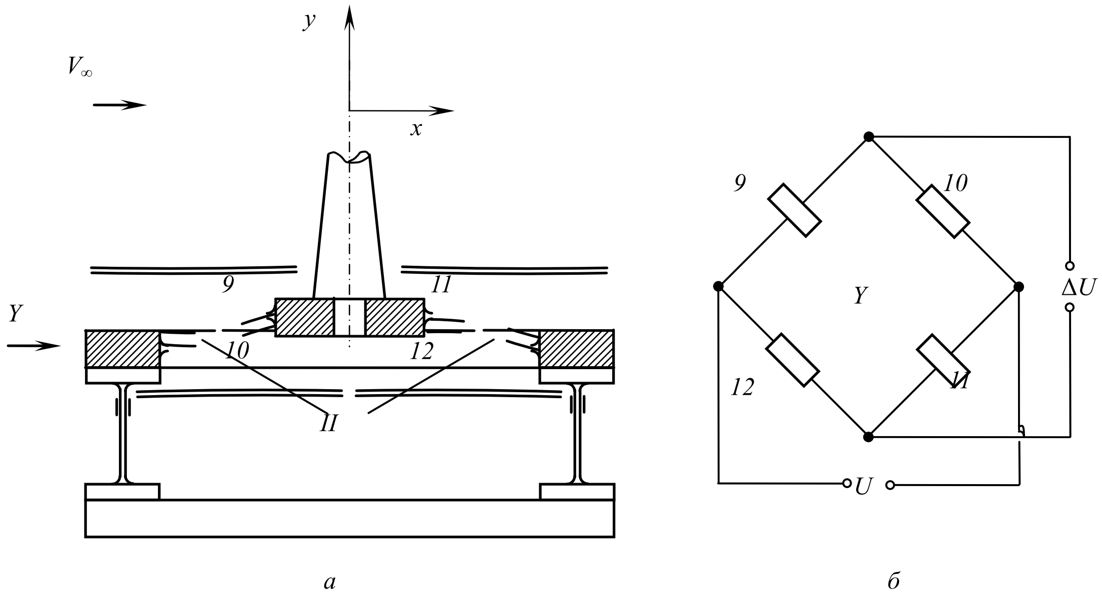


Рис. 3. Измерение подъемной силы:
а – схема деформации измерительных элементов; *б* – электрическая схема соединения тензодатчиков

Fig. 3. Measurement of lifting force:
a – diagram of deformation of measuring elements; *b* – electrical diagram of connection of load cells

When beam II is deformed under the action of only the lifting force, no change in resistance is observed in strain gauges 13–16, designed to measure the pitching moment. Therefore, the influence of the lifting force on the pitching moment is absent.

Since the design of the scale does not allow electrical separation of the Y and M_z components, the influence of the pitching moment on the magnitude of the lift force is determined during the calibration process and is assessed using a special influence graph constructed based on the results of the calibration data.

In strain gauge measurements, the output values of forces and moments acting on the test model are obtained in the form of corresponding readings of the device measuring electrical signals proportional to the applied forces. To convert instrument data into values of forces and moments, it is necessary to calibrate the scales and devices together in order to obtain the so-called calibration coefficients k_x, k_y, k_{mz}.

The calibration coefficients represent the value of one division of the instrument scale in newtons when measuring forces or in newton-meters when measuring moments. By multiplying the data obtained in the experiment by the corresponding calibration coefficient, taking into account the influence of the supporting devices, we obtain the values of forces in newtons and moments in newton-meters. In this case, additional components of aerodynamic forces and moments created by the holder and determined by blowing it in the presence of the model are subtracted with their signs from the instrument data [13–15].

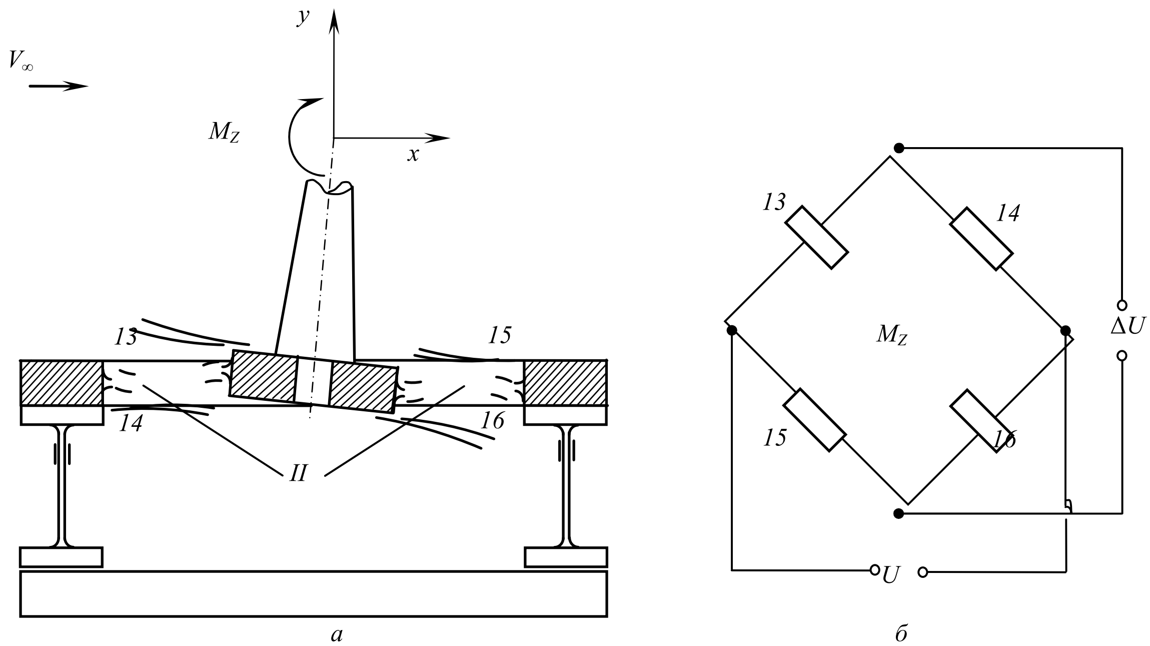


Рис. 4. Измерение момента тангажа:
а – схема деформации измерительных элементов; *б* – электрическая схема соединения тензодатчиков

Fig. 4. Pitch moment measurement:
a – diagram of the deformation of the measuring elements; *b* – electrical diagram for connecting strain gauges

The magnitudes of the forces acting on the model can be represented as

$$X_{\mathrm{mod}} = X_{instr} - X_{holder}$$
$$Y_{\mathrm{mod}} = Y_{instr} - Y_{holder} - \Delta Y_{M_z}$$

where X_{instr}, Y_{instr} are the instrument readings during the blowdown of the model-study system as a whole; X_{holder}, Y_{holder} are the instrument readings during the blowdown of one sting; ΔY_{Mz} is the magnitude of the influence of the pitch moment on the lift force, determined from the influence graph.

The magnitude of the pitching moment acting on the model can be determined by the formula

$$M_{z_{\mathrm{mod}}} = M_{z_{instr}} - M_{z_{holder}}$$

If we know the calibration coefficients k_x, k_y, k_{mz}, the components of the aerodynamic forces and moment acting on the model can be calculated using the formulae

$$X_{[H]} = k_x \cdot X_{\mathrm{mod}},$$
$$Y_{[H]} = k_y \cdot Y_{\mathrm{mod}},$$
$$M_{[Hm]} = k_m \cdot M_{z\mathrm{mod}}$$

To determine the aerodynamic coefficients of forces, it is necessary to relate the dimensional quantities $X_{[H]}$, $Y_{[H]}$ to the dynamic pressure q_∞ and the characteristic area of the model $S_м$.

The drag coefficient is determined as follows:

$$C_x = \frac{X_{[H]}}{q_\infty \cdot S_м} = \frac{X_{[H]}}{\frac{\rho v_\infty^2}{2} \cdot S_м} = \frac{X_{[H]}}{\frac{\rho}{2}\frac{2\varphi\gamma h}{\rho} \cdot S_м} = X_{[H]}\frac{1}{\varphi\gamma h S_м} = C_1 X_{[H]},$$

$$C_1 = \frac{1}{\varphi\gamma H S_м},$$

where φ is the coefficient of the air pressure receiver; γ is the volumetric weight of the liquid poured into the micromanometer, N/m^3; h is the height of the liquid column in the micromanometer, m; $S_м$ is the area of the mid-section of the model.

Similarly for the lift coefficient

$$Cy = C_1 Y_{[H]}.$$

Aerodynamic coefficients C_x, C_y are given in the flow coordinate system, when the OX axis is directed along the flow, the OY axis is perpendicular to it and upwards.

The pitch moment coefficient relative to the center of gravity located on the longitudinal axis of the model can be determined by the formula

$$m_{zt} = C_y\left(\overline{x_t} - C_d\right),$$

where C_d is the coefficient of the center of pressure, determined by the formula

$$C_d = \frac{m_{zt}}{C_y}.$$

Here $\overline{x_t}$ is the relative coordinate of the position of the model's center of gravity, counting from the nose point, in fractions of the model's length:

$$\overline{x_t} = \frac{x_t}{b},$$

where b is the wing chord or the length of the model.

Conclusion

The use of strain gauge scales allows to significantly reduce the time of the experiment and to increase the accuracy of determining the studied quantities. The absence of complex supporting devices in strain gauge scales, typical for mechanical scales, allows reducing the influence of holders on the flow around the studied model and thereby increasing the reliability of the measurement results.

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