Improvement of a sensitivity-adjustable three component force balance and its application to supersonic wind tunnel testing

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Received 24 March 2014

Abstract
The objective of this study is to improve the performance of the sensitivity-adjustable three component force balance developed in the previous study for the usage of various experimental conditions. In the present study, balance shape is modified from the previous oval-shape to hexagonal-shape. First, the strain distribution for three kinds of balance shapes is deduced by FEM analysis to decide the strain gauge paste positions and the validity is confirmed by force balance calibration. Then, the characteristics of the sensitivity adjustability are investigated by FEM analysis and force balance calibration for various kinds of balance shapes. Finally, a hexagonal force balance is designed and applied to the wind tunnel experiment in a supersonic flow condition which is one of the severe experimental conditions. As a result, the use of hexagonal-shape enables us to improve the measurement accuracy because to paste strain gauges on appropriate positions is much easier for hexagonal-shape than for oval-shape. In addition, we can adjust the sensitivity ratio more extensively for hexagonal-shape than for oval-shape. The designed hexagonal force balance can measure aerodynamic forces in a supersonic flow condition. In conclusion, we can improve the performance of the sensitivity-adjustable three component force balance by the use of hexagonal-shape and apply to a supersonic wind tunnel experiment. In future, force balance calibration to investigate dynamic characteristics is required for a supersonic wind tunnel experiment.

Keywords: Force balance, Sensitivity-adjustable, Hexagonal-shape, Supersonic wind tunnel testing

1. Introduction

Aerodynamic force measurements have been conducted using a force balance in wind tunnel experiments (Minato, et al., 2010). Most force balances used in the experiments are expensive and complex in structure. In addition, it can be broken in severe experimental conditions such as supersonic regime due to the unexpected forces. This fact limits experimental conditions and model scales in wind tunnel experiments. Therefore, it is desirable to develop the method of designing the force balance which can be utilized in various experimental conditions. Kawazoe et al. (1999); Kawazoe and Morita (2003); Kawazoe and Kato (2006) developed the circle-shape force balance which could measure longitudinal three components of forces and moment, namely lift, drag, and pitching moment and applied to some wind tunnel experiments. The force balance can be easily manufactured at a low price because the structure is very simple. Tanno et al. (2005) designed the strain gauge force balance for aerodynamic force measurements with short test duration and its performance was evaluated by a hypersonic wind tunnel experiment. However, the application of these force balances is limited because the sensitivity cannot be adjusted to correspond to several experimental conditions. To solve this problem, Yamada et al. (2013) developed the method of designing and manufacturing a sensitivity-adjustable three component force balance. In the work, oval shape was newly introduced for the balance shape and the sensitivity ratio for loaded
forces was adjusted by changing the balance shape. The validity of the force balance was examined in a low speed wind tunnel experiment, showing that the force balance had enough performance for aerodynamic force measurements. However, it is difficult for oval-shape to paste strain gauges on appropriate positions, degrading the measurement accuracy for aerodynamic force measurements. In addition, the sensitivity ratio should be more adjustable to apply to the wind tunnel experiment in a wide range of experimental conditions.

The objective of this study is to improve the performance of the sensitivity-adjustable three component force balance developed in the previous study for the usage of various experimental conditions. In this study, balance shape is modified from the previous oval-shape to hexagonal-shape. First, the strain distribution for three kinds of balance shapes is deduced by FEM analysis to decide the strain gauge paste positions and the validity is confirmed by force balance calibration. Then, the characteristics of the sensitivity adjustability are investigated by FEM analysis and force balance calibration for various kinds of balance shapes. Finally, a hexagonal force balance is designed and applied to the wind tunnel experiment in a supersonic flow condition which is one of the severe experimental conditions. As a result, the use of hexagonal-shape enables us to improve the measurement accuracy because to paste strain gauges on appropriate positions is much easier for hexagonal-shape than for oval-shape. In addition, we can adjust the sensitivity ratio more extensively for hexagonal-shape than for oval-shape. The designed hexagonal force balance can measure aerodynamic forces in a supersonic flow condition. In conclusion, we can improve the performance of the sensitivity-adjustable three component force balance by the use of hexagonal-shape and apply to a supersonic wind tunnel experiment.

In the following, experimental and numerical methods are described in Section 2. Then, results and discussion are shown in Section 3. Finally, the conclusion of this study is shown in Section 4.

2. Method

In this study, the shape of three-component force balance is modified from the previous oval-shape to hexagonal-shape. Figure 1 shows a schematic drawing of the three-component hexagonal force balance. In this figure, C is the parameter to represent the difference of the aspect ratio for the hexagonal force balance. Strain gauges are glued at L, D, M to measure lift, drag, and pitching moment. Strains of these positions occur independently for loaded forces and moments. The strain gauge paste positions are decided by the FEM analysis described in the following Section 2.1.

![Fig. 1 A schematic drawing of the hexagonal force balance](image)

2.1 FEM analysis

To decide the strain gauge paste positions and investigate the sensitivity adjustability, FEM analysis is performed using the software, SolidWorks by changing the aspect ratio C. Figure 2 shows an example of the numerical models used in the FEM analysis. The model has 55490 elements and 85685 nodes with the element size of 0.703456 mm. In this analysis, the bottom part of the model is fixed and calculations are conducted for vertical and horizontal loads, respectively.
2.2 Force balance calibration

Figure 3 shows the experimental setup for force balance calibration. The calibration device is newly developed in this study and enables us to load six component forces on a force balance independently by means of the calibration body. Figure 4 shows the detail of the calibration body. A force balance is attached inside the calibration body and loaded by stringing weighs through the steel wire connected to the calibration body. In this study, force balance calibration is conducted for three component forces, lift, drag, and pitching moment. To obtain output voltages from strain gauges on the force balance, the four active gauge method is applied for the wheatstone bridge circuit. Output signals from the force balance are amplified using signal conditioners (KYOWA CDV-700) and stored in PC via a 12 bit A/D converter.

Fig. 2 Numerical models for FEM analysis

Fig. 3 Experimental setup for force balance calibration

Fig. 4 A detail of the calibration body
2.3 Supersonic wind tunnel experiment

In order to investigate the validity of the designed hexagonal force balance, a supersonic wind tunnel experiment is carried out. Figure 5 shows a schematic drawing of the experimental setup for the supersonic wind tunnel experiment. In this study, a shock tunnel is used to generate a supersonic airflow. The shock tunnel is composed of a reservoir, low pressure tube, supersonic nozzle, test section, and vacuum tank. Figure 6 shows the test model used in the wind tunnel experiment. A wedge model with the angle of 20 deg is attached to the supporting rod by means of the hexagonal force balance. The force balance is covered with a stainless cover to avoid the influence of flows on the output signals. Experimental conditions are shown in Table 1. The total pressure is 0.35 MPa and the total temperature is 570 K. The supersonic nozzle with the throat diameter of 30 mm and exit diameter of 150 mm is used to generate the supersonic airflow at the Mach number of 3.8 in the test section. The angle of the attack of the model is fixed at 0 degree.

<table>
<thead>
<tr>
<th>Table 1 Experimental conditions</th>
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<tr>
<td>Mach number</td>
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<tr>
<td>Total pressure, MPa</td>
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<td>Total temperature, K</td>
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<td>Attack angle, deg</td>
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2.4 Estimation of Starting loads

Whenever a supersonic wind tunnel is being started or stopped, the normal shock system passes through the test section and large normal forces are imposed on the test model. The forces called starting loads are larger than those imposed on the model during steady flow in the same tunnel and may destroy the force balance used in the experiment. To design the force balance for a supersonic wind tunnel experiment, starting loads should be estimated in advance. In this study, starting loads are estimated based on the Normal shock theory (Pope and Goin, 1965). Starting loads are considered to be caused by the unsteady shock wave at the starting of a wind tunnel. Here, assume that a normal shock wave is generated on the one side and that the upstream static pressure acts on the opposite side. The pressure ratio across a normal shock wave is given by the following Eq. (1) (Liepmann. and Roshko., 1965).

\[
\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1} \left( M^2 - 1 \right)
\]

where \( P_1 \) is the upstream static pressure acting on the one side. \( P_2 \) is the static pressure behind the shock wave acting on the other side. \( \gamma \) is the specific heat ratio for air. \( M \) is the design Mach number of the nozzle. Starting loads \( F_{SL} \) are generated by the pressure difference between the one side and the other side, representing Eq. (2)

\[
F_{SL} = (P_2 - P_1) S_a = \frac{2\gamma(M^2 - 1)}{\gamma + 1} \frac{P_f S_a}{\left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{\gamma - 1}}
\]

where \( P_f \) is the total pressure of tunnel flow. \( S_a \) is the lifting surface planform area. From Eq.(2), it is found that starting loads are proportional to \( P_f \) and \( S_a \).

3. Results and Discussion

3.1 Characteristics of strain distribution

Figures 7 and 8 show the calculated strain distributions when \( F_x \) and \( F_y \) are loaded on each force balance, respectively. The position D has large strain for \( F_x \) and small strain for \( F_y \). On the contrary, the position L has small strain for \( F_x \) and large strain for \( F_y \). The result shows that the strains on the positions D and L occur independently for loaded forces \( F_x \) and \( F_y \). From these results, D is determined to be the strain gauge paste position to measure \( F_x \) while L is determined to be the strain gauge paste position to measure \( F_y \). The strain gauge paste positions for each force balance are found to be slightly different, depending on the balance shape. However, these positions are located on a flat surface for all balance shapes. To paste strain gauges on appropriate positions is much easier for hexagonal-shape than for oval-shape.

To investigate the validity of the calculated results, output characteristics are investigated for three component forces by force balance calibration. Figure 9 shows the output characteristics of the force balance for \( C = 0.6 \). It can be seen that an effect of \( F_y \) on the output of \( F_x \) is small in Fig.9 (a) and vice versa in Fig.9 (b). Pitching moment \( M_z \) also has small effect on the outputs of \( F_x \) and \( F_y \). Furthermore, the effects of \( F_x \) and \( F_y \) on the output of \( M_z \) are small in Fig.9 (c). To estimate the errors for \( F_x \), \( F_y \) and \( M_z \), output strains are obtained by loading three components of forces and moment on the force balance at the same time. The output strains are converted into forces and moment by using the calibrated result in Fig.9. Then, the errors are obtained from the comparison of the obtained forces and moment with the loaded three component of forces and moment which are known values. Finally, the errors for \( F_x \), \( F_y \) and \( M_z \) are deduced to be 0.89, 3.27 and 4.59 %, respectively. Concerning the oval-shape force balance in the previous study, the maximum error for loaded forces is more than 10 % (Yamada, et al., 2013). The present result shows that the strain gauge paste positions deduced by the FEM analysis are appropriate for three component force measurements. In addition, the use of hexagonal shape enables us to improve the measurement accuracy.
Fig. 7 Strain distributions for $F_x$

(a) $C = 0.4$  
(b) $C = 0.6$  
(c) $C = 0.8$

Fig. 8 Strain distributions for $F_y$

(a) $C = 0.4$  
(b) $C = 0.6$  
(c) $C = 0.8$
3.2 Characteristics of output sensitivity

Force balance calibration and FEM analysis are carried out by changing the aspect ratio C to investigate the characteristics of output sensitivity. Figures 10 (a) and (b) show the dependence of the balance shape on the output strains for $F_x$ and $F_y$, respectively. In these figures, the output strain for $F_x$ increases with increasing C while the output strain for $F_y$ decreases with increasing C. The result shows the hexagonal-shape with larger C is more sensitive to $F_x$. On the other hand, the hexagonal-shape with smaller C is more sensitive to $F_y$. Here, the gradients of the output strains for $F_x$...
and F_y are defined as S_x and S_y, respectively. The sensitivity ratio represented by S_y/S_x is deduced from the result in Figs. 10(a) and (b) for C = 0.4, 0.6, and 0.8. In addition, the sensitivity ratio is calculated by FEM analysis for a wide range of C.

Figure 11 shows the sensitivity ratio S_y/S_x as a function of C. The measured and calculated sensitivity ratios agree well each other and show the same tendency for the variation of C. The sensitivity ratio drastically varies from 1.4 to 51.4, depending on C. The previous study shows that the sensitivity ratio can only vary from 2.0 to 8.0 by the use of oval-shape (Yamada, et al., 2013). Therefore, the use of hexagonal-shape enables us to adjust the sensitivity ratio more extensively than that of oval-shape.

3.3 Application to a supersonic wind tunnel experiment

To design the hexagonal force balance for the usage of a supersonic wind tunnel experiment, the starting load acting on the wedge model is estimated using Eq. (2). Figure 12 shows the calculated starting load as a function of Mach number of tunnel flow. It is found that the starting load depends on Mach number and show the maximum value of 250 N at the Mach number of 1.8. From this result, the hexagonal force balance which can endure the starting load of 250 N is designed. Figure 13 shows the designed force balance used in the supersonic wind tunnel experiment. The force balance is made of stainless steel with the aspect ratio of 0.8. Figures 14 (a) and (b) show the measured aerodynamic forces as a function of time. In Fig. 14 (a), the vertical load rapidly increases and reach the maximum value of 36.8 N. After the maximum value, the vertical load rapidly decreases to a plateau within 50 ms. The maximum load is the starting load acting on the model. The starting load under the test condition can be estimated to be 75.8 N from Eq. (2). The calculated
starting load is about two times higher than the measured one. The result is consistent with the fact that the normal shock theory assumes the condition to produce the maximum starting load. In Fig. 14 (b), the horizontal load rapidly increases at the instance of starting the wind tunnel and reaches a plateau. The plateau is considered to last until 70 ms followed by a slight decrease. Considering the duration time of the starting load, steady flow is estimated to be produced between 50 and 70 ms, providing the effective aerodynamic force acting on the model. However, an oscillation appears in both output signals until 160 ms and hinder the accurate value of aerodynamic forces. The oscillation is considered to be caused by the vibration of the force balance component, such as model, force balance, and sting. In future, the vibration mode of the force balance component should be made clear by the dynamic calibration to remove the oscillation in raw data.

![Fig.12 Estimation of starting load](image)

![Fig.13 Hexagonal force balance for the supersonic wind tunnel testing](image)
4. Conclusion

In this study, balance shape is modified from the previous oval-shape to hexagonal-shape. First, the strain distribution for three kinds of balance shapes is deduced by FEM analysis to decide the strain gauge paste positions and the validity is confirmed by force balance calibration. Then, the characteristics of the sensitivity adjustability are investigated by FEM analysis and force balance calibration for various kinds of balance shapes. Finally, a hexagonal force balance is designed and applied to a supersonic wind tunnel experiment. The use of hexagonal-shape enables us to improve the measurement accuracy because to paste strain gauges on appropriate positions is much easier for hexagonal-shape than for oval-shape. The investigation for the sensitivity adjustability shows that we can adjust the sensitivity ratio more extensively for hexagonal-shape than for oval-shape. From the supersonic wind tunnel experiment, the designed hexagonal force balance can measure aerodynamic forces in a supersonic flow condition. In conclusion, we can improve the performance of the sensitivity-adjustable three component force balance by the use of hexagonal-shape and apply to a supersonic wind tunnel experiment. In future, force balance calibration to investigate dynamic characteristics is required for a supersonic wind tunnel experiment.

Acknowledgment

This work was carried out under the Collaborative Research Project of the Institute of Fluid Science, Tohoku University.

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