

DEVELOPMENT OF 3-COMPONENT FORCE-MOMENT BALANCE FOR LOW SPEED WATER TUNNEL

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An effort is made to develop a new 3-component force-moment balance, which is capable of measuring lift force, drag force and pitching moment of a model mounted in the water tunnel. The concept used in the balance design is the bending- beam principle. The forces acting on the spring element cause strains on its surface, which are measured by strain gauges. Since strain yielded by the axial force is usually very small, therefore it is not practical to measure axial force using strain gauge directly to sense the strain in axial direction. The main idea of the new balance design is to translate all desired forces (lift and drag) in such a way that they yield bending strain at selected strain-gauge station. This is done by using a bending balance geometry. Under this apparatus, the model wing is mounted at one of its end to the bending balance. The corresponding Lift, Drag forces and Pitching moment are translated into moments at the other end of the balance, and can be measured from sets of strain gauges in bending mode (twisting mode for pitching moment). Example readings are presented in this paper.

Keywords: 3 component force-moment balance; strain-gauge; bending balance; water tunnel.

1. Introduction

Water tunnel has always been known for its exceptional ability to perform flow visualization. However, it is extremely difficult to obtain accurate and reliable force and moment data using typical strain-gauge balance. The model loads encountered in water tunnel are usually quite small. The problem is further magnified when dealing with very low Reynolds number tests. The balance needs to be sensitive enough to detect very small forces, yet stiff enough to avoid vibration induced by high-density water flow.

The water tunnel, in the Nanyang Technological University (NTU) shown in Figure 1, is a closed-loop type water tunnel with range of flow speed, 0 – 30 cm/s. The speed range results in a maximum testing Reynolds number of approximately 50,000. Thus, the expected force range measurable by the balance is 0–2 N. The new balance should comply with existing model mounting device, shown in Figure 2. This means that the balance should be attached at the end part of the rotating arm (angle-of-attack, AoA)

mechanism, can only be a sting type balance and must immerse under water during operation, i.e. it must be water-proof.

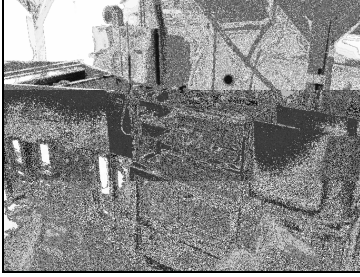


Fig. 1 (left): NTU water tunnel, note the model mounting device (black colour).

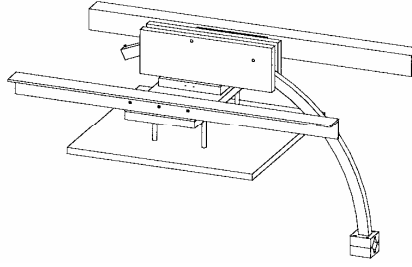


Fig. 2 (right): Model mounting device, with rotational arm that changes angle of attack of the model.

2. Balance Design Concept

The concept used in the balance design is the so-called bending-beam principle, as shown in Figure 3. The forces acting on the spring element cause strains on its surface, which are measured by strain-gauges. Strain-gauges are connected in a Wheatstone bridge where the change in strain will result in corresponding change in strain-gauge resistance thus producing a certain amount of voltage difference from the bridge. The voltage will be amplified and fed into the data acquisition system.

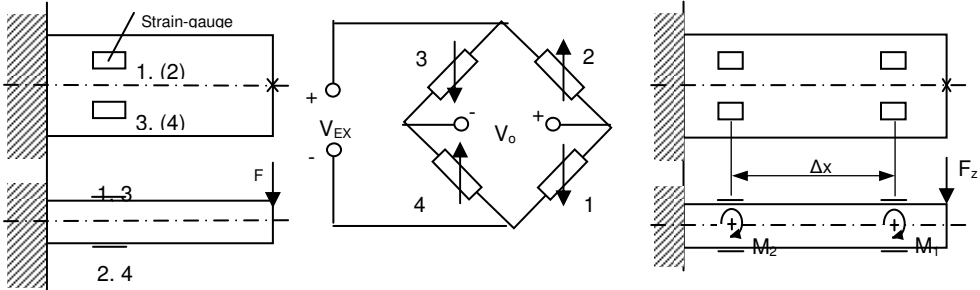


Fig. 3 (left, center): Simple beam-bending principle and strain-gauges connection in Wheatstone bridge.

Fig. 4 (right): Two strain-gauge station to measure normal force.

The gauge factor, GF , of a strain-gauge, relates the change in resistance (ΔR) to the change in length (ΔL). The GF is constant for a given strain-gauge, and R is the nominal (non-deformed) resistance of the strain-gauge, so

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\epsilon} \quad ; \text{ where } \epsilon \text{ is the strain} \quad (1)$$

With the full-bridge configuration of strain-gauge in the circuit, the output voltage, V_o is directly proportional to the additional strain at the gauge station:

$$V_o = \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_{EX} = \left(\frac{R + \Delta R}{2R} - \frac{R - \Delta R}{2R} \right) V_{EX} = \left(\frac{\Delta R}{R} \right) V_{EX}$$

$$V_o = GF \cdot \epsilon \cdot V_{EX} \quad ; \text{ where } V_{EX} \text{ is the excitation voltage} \quad (2)$$

Since bending strain is proportional to the moment or force acting on the beam, we can relate V_o to the external loading linearly. Furthermore, such connection also provides

thermal compensation since temperature-induced strain of equal magnitude and sign in the adjacent arm of Wheatstone bridge will be cancelled off. The bridge would be insensitive to the strain induced by axial force by the same argument.

To measure the normal force, F_z , we simply measure pitching moment at two different gauge stations with the known distance between them, Δx . F_z can be calculated using the following equation:

$$F_z = \frac{M_2 - M_1}{\Delta x} \quad (3)$$

Since strain yielded by the axial force is usually very small, therefore it is not practical to measure axial force directly using strain-gauge to sense the strain in axial direction. This will lead to data which is low in accuracy and sensitivity. In most cases, the data will lay within the electrical noise region. Therefore, to avoid the necessity to measure axial force component in the balance. The main idea of the balance design is to translate all desired forces (lift and drag) in such a way that they yield bending strain at selected strain-gauge station on the spring element. This is done by using a bending balance geometry, as shown in Figure 4.

3. Actual Balance Design

From the main problem with sting type balance, the solution is sought in a simple Bending cantilever beam. The overall view of the balance attached to the model mounting device is shown in Figures 5 and 6, note that the AoA rotational arm is moved to the left side in order to maximize the moment arm. The wing model is attached to point A of the balance at quarter-chord location. With proper selection of the strain-gauge (SG) stations, lift (L), drag (D) and pitching moment at quarter-chord ($M_{c/4}$) can be reduced from force-moment analysis as follows.

As shown in Figure 6, the lift, drag and pitching moment at the wing model is transferred to point A with M_L and M_D being the corresponding moment result from L and D . Point 1 and 2 denote the strain-gauge station.

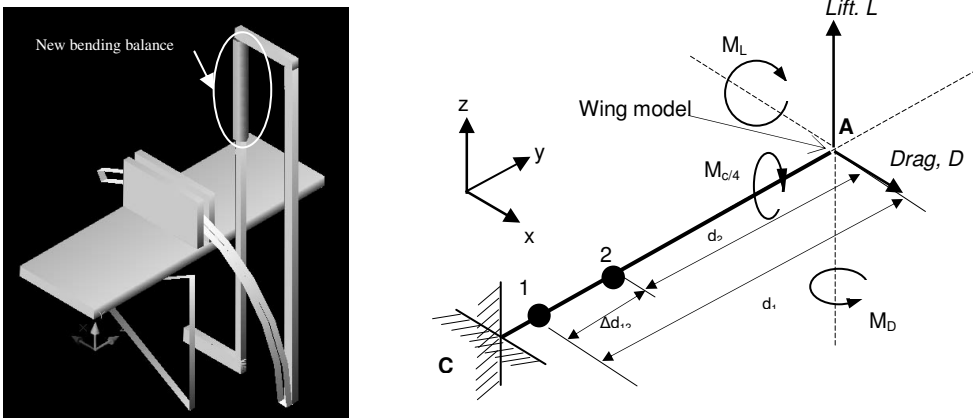


Figure 5 (left): 3D rendered drawing of the overall configuration of the new balance.

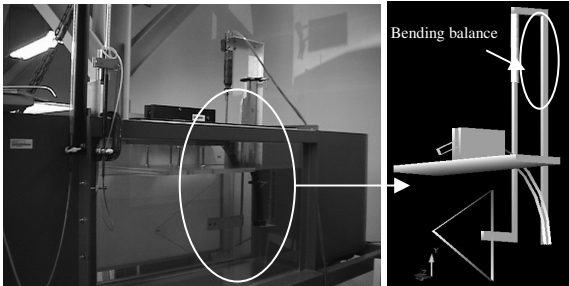
Figure 6 (right): Free body diagram of the balance.

By this setup, the L and D are producing bending strain at SG stations 1 and 2 where the strain can be measured with adequate accuracy. Their value can be calculated using the equations (8) and (9). The pitching moment can be obtained from equation (10).

$$D = \frac{M_{z1} - M_{z2}}{\Delta d_{12}} \quad \text{and} \quad L = \frac{M_{x1} - M_{x2}}{\Delta d_{12}} \quad (8),(9)$$

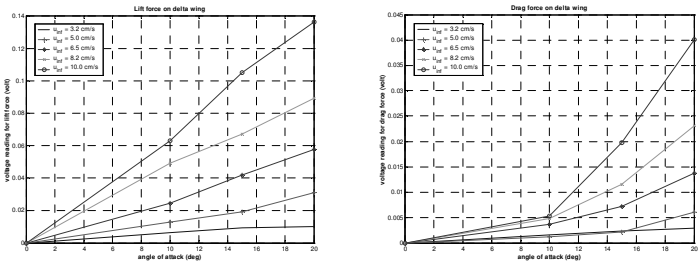
$$M_{c/4} = M_{y1} = M_{y2} \quad (\text{Twisting moment}) \quad (10)$$

4. New Bending Balance and Initial Force Measurement Result



Figures 7 and 8: The new bending balance at NTU water tunnel facility and the 3D rendered drawing.

The new bending balance has been built as shown in figure 7. A 3D model is shown in figure 8. The tested model was a 65° swept angle delta wing with 30 cm chord, 5 cm/s freestream velocity (i.e. $Re_C = 15000$) at $0^\circ - 20^\circ$ AoA. The expected lift and drag forces are in the order of milli-Newton (mN). The readings can be presented in terms of voltage outputs, which can be converted to lift and drag forces, as shown in figures 9 and 10.



Figures 9 and 10: Lift and Drag force (voltage outputs) v.s. AoA of 65° swept delta wing at $Re_C = 15000$.

5. Conclusions

The new force probe for NTU water tunnel has been built in-house, based on the bending moment balance principle. It has been used for testing the force on delta wing at low Reynolds number of 15000. The distinctive voltage output for both lift and drag forces in order of milli-Newton can be read.

References

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