**Abstract:** Using the world’s largest magnetic suspension and balance system (MSBS) and a low-turbulence wind tunnel, we successfully measured the aerodynamic forces acting on a non-spinning women’s javelin. It was found that the drag and the lift increased as the angle of attack was increased up to 18°. The pitching moment increased for angles of attack up to about 9°, and then decreased, becoming negative above 12°, indicating nose-down rotation. We used a pseudo supporting rod to simulate a javelin attached to a support, as used in a conventional setup, and confirmed that this interferes with the javelin by creating differences between the aerodynamics forces acting on the javelin with and without the pseudo supporting rod.

**Keywords:** MSBS; javelin; aerodynamic forces; wind tunnel test

1. Introduction

When estimating the distance a javelin can be thrown, accurate measurements of the aerodynamic forces acting on the javelin are needed. The conventional wind tunnel test is performed by fixing the javelin to a supporting rod. This rod disturbs the flow, an effect called support interference. In particular, for a long and narrow object like the javelin, interference by the support becomes significant because the diameter of the supporting rod is comparable to that of the javelin, making it difficult to measure the aerodynamic forces accurately.

In this study, we used the world’s largest magnetic suspension and balance system (MSBS) at Tohoku University to measure the aerodynamic forces acting on a full-size women’s javelin, thereby avoiding the use of a support [1]. The MSBS can levitate an object containing neodymium magnets. There are four parts to the system; these are the object with the neodymium magnets, a coil system for magnetically supporting the object, a control system for levitating the object by supplying appropriate currents to the coils, and a position-sensing system to determine the position of the object.
2. MSBS Experiment

2.1. Javelin

A full-size women’s javelin was employed for the wind tunnel tests. The length of the javelin used was 2213 mm, and the center of gravity was at 920 mm from the tip. Most of the surface of the javelin was painted white by a spray, as shown in Figure 1. This was for detecting the position, the details of which are described in the next section. For the same reason, a 15-mm-long collar was attached to the javelin at the center of gravity, and a 5-mm-wide black tape was wrapped around the javelin at the center of gravity.

Neodymium magnets were inserted along the longitudinal axis, as shown in Figure 1. Two types of magnet with diameters of 19 mm and 20 mm were used, and the total length of the assembly was 495 mm. Grip strings were wound around the javelin both on the upstream and downstream sides of the collar.

![Figure 1. Neodymium magnets were inserted along the longitudinal axis.](image)

2.2. Position-Sensing System

A schematic of the position-sensing system is shown in Figure 2. The coordinate system is also shown in Figure 2. The origin was at the center of gravity of the javelin, with the positive x-axis in the horizontal forward direction, the y-axis was also horizontal and orthogonal to the x-axis. The positive z-axis was vertically upward.

![Figure 2. Schematic illustration of the sensor system.](image)

The optical position-sensing system comprised a convex lens (focal length 125 mm), dichroic color filters (red and blue), a half mirror, red and blue LED lights (MSPP-CB74, Moritex), and a CCD (Charge-Coupled Device) line sensor (TL7450S, Takenaka system equipment).

Side camera X, shown in Figure 2, was used to detect the x-position of the javelin. The color filter meant the camera detected only the blue light reflected from the javelin. A schematic illustration around the collar is shown in Figure 3. Side camera X was an optical line sensor with a row of 7450 CCD elements. The boxes inside the circle in Figure 3 show the CCD elements. The blue and gray elements indicate those elements detecting and those not detecting blue light reflected from the javelin, respectively. The output signal from Side camera X is shown by the pink line in Figure 4. The
abscissa is the CCD element number, and the ordinate is the brightness. The white part of the collar corresponds to high brightness, while the black part corresponds to low brightness. In order to define the edges between the white and black lines on the collar, the pink line was binarized, as shown by the green line in Figure 4.

![Figure 3. Schematic illustrations of the collar with blue light and the line sensor of Side camera X.](image)

Figure 3. Schematic illustrations of the collar with blue light and the line sensor of Side camera X.

![Figure 4. The output signal from Side camera X.](image)

Figure 4. The output signal from Side camera X.

2.3. Coil System

Figure 5 shows a schematic diagram of the coil system, in which the coils are numbered from 0 to 9. The model can be levitated by the magnetic forces generated by the coils. Ten coils were used in this experimental setup to control the position and the attitude of the javelin. For example, coils #0 and #9 worked in the x-direction. The current in the coils controlling the javelin in the x-direction, $I_x$, is obtained from Equation (1), which gives the average value of the currents in coils #0 ($I_{00}$) and #9 ($I_{99}$). The current values for the other axes are defined in the same way.

![Figure 5. Coil system.](image)

Figure 5. Coil system.

$$I_x = \frac{I_{00} + I_{99}}{2}$$ (1)
2.4. Control System

A block diagram of the control system is shown in Figure 6. The signal from the position sensor passed through two filters, which delayed the signal. This time delay was compensated for by a double-phase advancer. In order to reduce the difference between the measured position and the set position, the currents to each of the ten coils were determined by PI (Proportional Integral) control [2].

![Figure 6. Block diagram of the control system.](image)

2.5. Calibration

2.5.1. Position-Sensing System

The javelin was fixed on a calibration stage, as shown in Figure 7, and was moved in each direction using the calibration stage. The position of the javelin in the x-direction was determined by the number of the CCD element aligned with the center of gravity. Figure 8 shows the calibration results when the javelin was moved ±2 mm in the x-direction. The abscissa is the actual x position, while the ordinate is the corresponding number of the CCD element, xc. Figure 8 shows that xc is linearly proportional to x. The element number at the center of gravity gives the actual position of the javelin. Each axis was calibrated in the same way.

2.5.2. Force Calibration

It was also necessary to do calibrations for the aerodynamic forces acting on the javelin. The drag calibration system is shown in Figure 9. A plastic jig with 2 mm aluminum rods on either side was attached around the center of gravity of the javelin. The drag was simulated by applying a force in the negative x-direction using a system of weights and pulleys attached to the aluminum rods, while the current required to keep the javelin in the home position was measured. The lift and the pitching moment were calibrated in the same way. These calibrations were then used to calculate the aerodynamic forces acting on the javelin.

2.6. Filtering the Resonance Frequency

Our first trial to levitate the javelin failed, as we were unable to control the javelin in the MSBS. Temporal variations in the y-direction are shown in Figure 10. The green line shows the result of our first trial. It can be seen that this was unstable, and diverged after 0.25 s. The frequency components were 22 Hz and 55 Hz. The frequency of 22 Hz corresponded to the resonant frequency of the javelin [3], and this led to us being unable to control it. Therefore, a notch filter was employed in order to cut out the resonant frequency. As can be seen by the blue line in Figure 10, the notch filter stabilized the javelin, allowing us to levitate the javelin in the MSBS.

Moreover, the orange line denotes the temporal variation of y with a weak notch filter, i.e., a filter with decreased intensity. The orange line oscillates with time. By decreasing the intensity of the notch filter, oscillation of the javelin, as in real flight, was realized. The frequency of the oscillation was 22 Hz, and the javelin was still under control.
2.7. Experimental Conditions

The aerodynamic forces acting on the non-spinning javelin were measured at 25 m/s. The angle of attack, \( \text{AoA} \), was varied from \(-1^\circ\) to \(18^\circ\). The sampling rate was 1250 Hz, and the longest sampling time was 6.6 s.

Moreover, the influence of support interference was investigated at \( \text{AoA} \) of \(0^\circ\), with the wind speed varied from 20 m/s to 30 m/s. A schematic diagram of the setup is shown Figure 11. Although
the javelin was supported by magnetic force, a pseudo supporting rod with a diameter of 20 mm was set 2 mm away from the surface of the javelin. The thickness of the boundary layer around the center of gravity was estimated to be about 4 mm. Therefore, the tip of the pseudo supporting rod penetrated the boundary layer. Although the pseudo supporting rod did not touch the javelin, it was considered to interfere with the measurements, as in a conventional wind tunnel test.

![Figure 11. Experimental setup with a pseudo supporting rod.](image)

3. Measurement of Aerodynamic Forces Acting on the Javelin

3.1. Aerodynamic Forces Acting on the Javelin

It is strictly necessary to measure aerodynamic forces acting on the “real” javelin in the real situation. The “real” means that the javelin flies without the supporting rod. Moreover, it vibrates during the flight. In this study, aerodynamic forces acting on the “real” javelin were measured using an MSBS.

The aerodynamic forces acting on the javelin are depicted in Figure 12. The angle of attack is denoted by \( \text{AoA} \), the drag by \( D \), the lift by \( L \), and the pitching moment by \( M \). The time-averaged aerodynamic force coefficients as a function of the angle of attack are shown in Figure 13. The drag coefficient, \( C_D \), is given by Equation (2), where \( \rho \) is the air density, \( U \) is the wind speed, and \( A \) is the maximum cross-sectional area. The lift coefficient, \( C_L \), is given by a similar equation. The pitching moment coefficient, \( C_M \), is given by Equation (3), where \( l \) is the length of the javelin. The aerodynamic force coefficients measured with the notch filter (static case) are shown by the closed circles ●, those with the weak notch filter (oscillating case) are shown by the triangles ▲.

\[
C_D = \frac{D}{0.5\rho U^2 A},
\]

\[
C_L = \frac{L}{0.5\rho U^2 A l},
\]

\[
C_M = \frac{M}{0.5\rho U^2 A l}.
\]

![Figure 12. Depiction of the aerodynamic forces acting on the javelin and the angle of attack (AoA).](image)
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Figure 13. Aerodynamic force coefficients as a function of the angle of attack at $U = 25$ m/s. (a) The drag coefficient. (b) The lift coefficient. (c) The pitching moment coefficient.

It was found that the differences between the static case and oscillating case for $C_D$ and $C_L$ were negligibly small. However, the difference in $C_M$ became significant above $10^\circ$. The pitching moment, $C_M$, for the oscillating case became negative above $10^\circ$, and above $12^\circ$ for the static case. It can be seen that $C_D$ and $C_L$ increased with increasing the angle of attack up to $18^\circ$, whereas $C_M$ increased for several degrees, and then decreased.

3.2. Interference by the Supporting Rod

The aerodynamic comparisons between $D$, $L$, $M$ with the supporting rod and without the supporting rod as a function of wind speed are shown in Figure 14. The aerodynamic forces measured with the rod are shown by squares ■, those without the rod are shown by the closed circles ●.

There were some differences in $D$, $L$, and $M$ with and without the supporting rod. In other words, there was interference from the supporting rod. It was found that the drag without the rod was smaller than that with the rod. Although $L$ and $M$ without the rod were almost $0$ with $AoA = 0^\circ$, $L$ and $M$ with the rod were non-zero. At $25$ m/s, $L$ with the rod was equal to the value of $L$ without the rod at $AoA = 7^\circ$. Therefore, it can be concluded that the effect of the supporting rod was to make the angle of attack positive.

Figure 14. Aerodynamic comparisons between $D$, $L$, and $M$ with the pseudo supporting rod and without it as a function of wind speed. $AoA = 0^\circ$. (a) The drag. (b) The lift. (c) The pitching moment.

4. Summary

The aerodynamic forces acting on the full-size javelin were measured utilizing an MSBS. We reached the following conclusions.

- The effect of the resonant frequency of the javelin was nullified by using a notch filter, which allowed the javelin to be levitated stably in the MSBS.
- The drag and the lift coefficients increased with increasing the angle of attack up to $18^\circ$.
- The pitching moment coefficient increased with increasing the angle of attack up to about $9^\circ$, and then decreased, becoming negative above $12^\circ$.
- The drag and the lift coefficients of a javelin oscillating at its resonant frequency were comparable to those of a static javelin.
- The difference in the pitching moment coefficient between the oscillating javelin and the static javelin became significant for angles of attack above $10^\circ$. 
• There were differences between the drag, the lift, and the pitching moment whether the supporting rod was used or not.

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