Aerodynamic characteristics and PIV analyses concerning tennis balls

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Abstract. The structure of the current tennis ball is covered with a uniform felt fabric on the outer surface made of hard rubber. As the ball continues to hit, the surface felt wears. Also, air leaks out through the structure inside. These factors cause a difference in the aerodynamic characteristics of new and used balls. In this research, the aerodynamic characteristics of the old and new tennis balls rotating were investigated and the PIV results of the flow around the ball due to the wear of the felt producing these characteristics were showed. For the four types of tennis balls tested, used balls showed higher in drag coefficient than new balls, and new balls tended to be higher than used ball in lift coefficient. It is believed that deformation due to deterioration of ball rubber brings about a change in drag coefficient, which causes a change in lift coefficient due to wear of the surface felt. In the new ball, felt fluff stands, which indicates that the wake flow is large and inclined diagonally backward compared to the used ball, and the air around the ball is found to be caught by the felt fluff.

1. Introduction
The origin of tennis was born in France around the 12th century and was called Jeu de paume. At that time a ball was struck with the palm of the hand [1]. Various shapes and sizes of rackets were introduced since the 16th century to the mid 18th century. The origin of the modern tennis was invented by Major Walter Wingfield, an army officer of Wales in 1873. The structure of the current tennis ball is covered with a uniform felt fabric on the outer surface made of rubber and the inside of the ball is filled with gas above 1.8 atm. This is called as pressured ball. The rotational speed of the tennis ball is up to 5,500 rpm in serve and 4,700 rpm in stroke. In order to achieve such a high rotational speed, balls are struck strongly by gut and this repeatedly strike on ball cause the wear of the outer felt fabric and pressure decreasing of the ball. The surface texture of the felt fabric and internal pressure are the most significant factors related with the aerodynamics drag and lift force of the tennis ball which is closely linked with the trajectory of the ball [2, 3]. In addition, the pressured ball is usually enclosed in a pressured can before use. After the can opened, the air in the ball escapes through the ball's core structure and the pressure decrease slowly. These factors make differences of the aerodynamic properties and trajectory of the ball between the new and the used ball. In the professional matches, the balls are replaced every nine games after the seven games from the beginning. However, in the ordinary practice, such a frequent replacement of balls is difficult because of the cost. The difference of the trajectory between new ball and old ball are known by players sensuously, but from the scientific point of view it is not well understood. The understandings of the aerodynamics characteristics of new and old used ball are significant for the accurate ball controlling for the players and the development of new tennis ball. Therefore, in this research, we compared new
balls and old used balls from a scientific / hydrodynamic point of view by fluid force and PIV measurement.

2. Experimental setup
To understand the effect of the felt wear of the ball on the fluid force and flow, we performed force measurement and PIV measurement in the wind tunnel on the four types of balls. Figure 1 shows the four types of balls measured in this study, new and old used DUNLOP FORT ball, new and old used BRIDGESTON XT8. The used balls were actually used balls about 50 hours in competitions. The balls were rotated by the mortar in the range of 3700 ~ 4000 rpm. The rotation axis passes through the center of the ball. To remove the effect of the shape change of the ball on the measured fluid force caused by the pressure decreasing and ball rotation, we also measured the additional four types of the balls filled with urethane inside.

2.1. Fluid force measurement
In order to measure the fluid force on the rotating ball, measurements were made using a wind tunnel experimental device and a three components force detector. For each experimental condition, the wind speed is 14, 18, 20, 22, 24, 26, 28, 29, 30 m/s, the ball rotational speed was 4000 rpm. The drag coefficient and the lift coefficient were calculated from the averaged value of the three times measurement for each balls.

2.2. 2D-PIV measurement
PIV measurement was performed to visualize the flow around each ball as shown in Figure 2. The wind speed was 29 m/s and the ball rotation speed was 3700 rpm. The rotation direction was both of the forward rotation and the reverse rotation. The frequency of the high speed camera was 2000 Hz.

3. Results and discussion
3.1. Fluid force measurement
The results of the drag coefficient and the lift coefficient of the fluid force measurement in this experiment are shown in Figure 3 to Figure 6. In the both FORT and XT8 balls, the drag coefficients in the used balls were larger than that in the new balls. On the other hand the lift force in the used balls tended to lower than that in new balls. The possible causes of these differences of the aerodynamic characteristics are changes of the internal pressure and fluffing of the felt fabric. In case of the FORT, the differences of the drag coefficient and the lift coefficient in each ball were smaller than these of XT8. The felt fabric of the FORT is prepared by woven felt and the condition of the felt did not change so much between new and old one. Woven felt is made by a special method called satin weave, which is considered to have the effect of improving durability and reducing felt fluff. On the other had, since the felt of XT 8 stands long upright, both the drag and lift are considered to have increased.
From this result indicates that the felt fluff stand affected aerodynamic characteristics of the ball significantly.

3.2. 2D-PIV measurement
The images of the averaged flow velocity of PIV measurement are shown in Figure 7, Figure 8. There is a difference in the wake flow between the new balls and the used balls, which is related with the difference of the lift force and the drag force shown in Figure 3 to Figure 6. In the new ball, felt fluff stands, which indicates that the wake flow is large and inclined diagonally backward compared to the
used ball, and the air around the ball is found to be caught by the felt fluff. Although the flow around
the balls and the weak flow were visualized, the flow on the ball surface was not measured clearly.
This difficulty of the observation of the flow was caused by the felt fluffing. In the PIV
measurement, if the surface of the object is smooth, the reflected laser light is easily removed and can
be measured accurately. However, the surface of the tennis ball is covered with felt and it scattered
the reflected laser. In addition, the color of the surface of the tennis ball is yellow and the reflected light
showed haloation. These characteristics of the tennis ball made the accurate measurement of the flow
on the surface of the tennis ball difficult. The PIV measurement with the color changed tennis ball is
future work for more accurate measurement of the surface velocity distribution of the tennis ball.

4. Conclusion
We performed fluid force and PIV measurement of the rotating new and used tennis balls to reveal the
effect of the surface texture on the aerodynamics characters. The following results were obtained.
1. The effect of wear of the surface felt on the flow field and lift / drag force was measured by
   comparing the new and used balls. The angle change of the flow filed caused by the ball rotation
   and wake flow in case of the used balls were smaller than that of the new ball. This difference of
   the flow was reflected in the larger drag and smaller lift force of the used ball.
2. The impact of wear on the aerodynamic characteristics was depending on the surface felt types
   covering the ball, especially for the fluff. In case of the ball type FORT, which is covered by the
   woven felt, the changes of the aerodynamics performance by the wear is smaller than the other
   types. The felt type of the ball is significant on the changes of the aerodynamic characters during
   the wearing process.

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