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ANALYSIS OF GOLF BALL SPIN MECHANISM AT IMPACT BY FEM

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Abstract

It is important to improve the initial launch conditions of golf ball at impact between golf club and ball to get a long flight distance. The flight distance is greatly influenced by the initial launch conditions such as ball speed, launch angle and back spin rate. It is also important to analyze the mechanism of ball spin to improve the initial conditions of golf ball. Back spin rate is created by the contact time and force.

Previous studies showed that the contact force is determined as the resultant force of the reaction forces normal and tangential to the club face at the contact point. The normal force causes the compression and restitution of ball, and the tangential force creates the spin. Especially, the tangential force is known to take either positive or negative values as the ball rolls and slides along the club face during impact. Although the positive and negative tangential forces are known to create and reduce the back spin rate, respectively, the mechanism of ball spin creation has not yet been discussed in detail in the literature.

In this paper, the influence of the contact force between golf club and ball is investigated to analyze the mechanism of impact. For this purpose, the contact force and the time at impact between golf club head and ball are computed using finite element method (FEM) and compared with previous results. In addition, we investigate the impact phenomenon between golf club head and ball by FEM and clarify the mechanism of ball spin creation accurately, particularly focusing on the effect of negative tangential force on ball spin rate.

1. INTRODUCTION

The velocity of a human nerve is approximately 130 m/s. If the distance of a nerve is 1 m, the time to reach the end is 7 ms. However, the impact time between the golf club, usually a #1 wood, and ball is 400~600 ms depending on the club's initial velocity and the material of ball. Because of the impact moment, the ball has the initial velocity and spin after it flies away similar to a parabola.

A primary factor that affects the ball's release velocity is the club's initial velocity before impact. For example, the ball's release velocity is 50m/s when the club's initial velocity is 35m/s. The larger the club's initial velocity is, the larger the ball's release velocity becomes. On the other hand, as the ball back spin rate, important factors are the club's loft angle and initial velocity. The larger the club's loft angle and initial velocity are, the larger the ball back spin rate becomes. The golf ball is crushed by the force that is transferred from the club head during impact after it slips or rolls along the club face and finally it takes off the golf club. These initial conditions are generated by short time impact moment when a golfer hits a golf ball, and then the ball flies in the air, so finally the distance and trajectory of ball are created through such complex mechanism.

The impact problem of the club and ball was analyzed by previous studies. However, the results of many papers are different each other, so we could not find the accurate mechanism of the impact. Thus, in this study, we analyze the impact of the golf club and ball by using FEM and clarify the mechanism of ball spin creation accurately.

2. PRECEDING WORK

2.1 Assumption for analysis

In this study, the analysis is carried out under the following assumptions:

(1) The impact phenomenon can be described as the collision between the ball and the club head, because it is said that the shaft has negligible effect by Iwatsubo at al [1].
(2) The effect of the dimples on the ball surface is ignored because the flying ball is not analyzed.
(3) The ball cover and club head are made of linear elastic material and the ball core is made of rubber material. This assumption is considered to satisfactorily model the characteristics of the club head.
(4) The club head moves horizontally before impact.
(5) The Augmented Lagrange method and the Coulomb's friction law are valid at the contact surface between the ball and club head.

2.2 Finite element model

Figure 1 shows the cross section of a finite element model of a golf club head and a golf ball. The golf ball is modeled as a two piece ball consisting of a butadiene rubber center and an ionomer resin cover. The two piece ball, with a diameter of 42.8mm, weight of 46g, and cover thickness of 1.8mm, is modeled using solid element with rubber property. A butadiene rubber center is designed with Mooney-Rivlin hyperelastic material model because considerable deformation of the ball happens during impact. The number of elements in the center is 6912 and in the cover it is 2592. The club head (driver) is modeled as an elastic body considering the thickness distribution using 3-D shell elements. The driver head, with a weight of 210g, is modeled using 3264 shell elements with elastic property. The loft angle is 11.5 °, moment of inertia is $1526 gcm^2$, and initial velocity is 35m/s.

The software LS-DYNA, which is transient dynamic code, was used for the analysis of impact between the ball and club head. LS-DYNA was chosen primary for its explicit numerical method, most suitable for short duration contact problems.

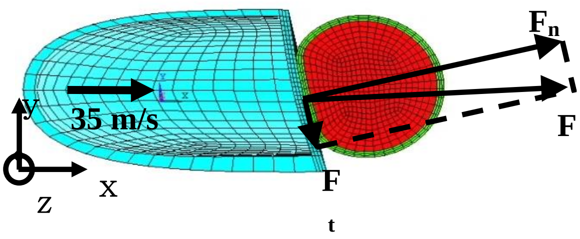

Figure 1. Golf club head and ball model (normal and tangential forces at impact)

2.3 Calculation of release velocity, spin rate, and contact force

The distance and direction of the flying ball are the criteria to judge the performance of the club head. They are influenced by the release velocity and the spin rate of the ball after impact and are defined as follows:

Every node in the ball model has different velocity vectors due to the spin after impact. The release velocity of ball, hence, is defined as the velocity at the average of all nodes after impact. The contact force (F) between a golf club head and a ball is determined as the resultant force of the reaction force normal to the club face at the contact point (F_n) and that along to the club face (F_t) as shown in figure 1. Every node in the contact area has a different force due to the elastic body. Therefore, the normal and tangential forces are calculated as the sum of forces of contact area nodes. It is difficult to determine the back spin rate of the ball after impact geometrically because of the deformation of the ball caused by its vibration. Therefore, the back spin rate is computed by using a nodes set which is located on cross section area including mass center.

3. ANALYSIS OF IMPACT

3.1 Theoretical analysis of impact by T. P. Jorgensen [2]

The impact phenomenon can be analyzed by dynamic theory that expressed by Jorgensen before FEM. Jorgensen suggested to use the compression factor (f) about the deformation of ball.

In the moving frame the ball again approaches the club face with a velocity V at angle φ to the normal N as shown in figure 2. The ball is moving upward along the surface of the club face. If it slides without friction it continues at velocity $V\sin\varphi$, but if the force of friction is large enough, it starts to roll and by the end of the impact may be rolling upward along the club face with a smaller velocity. We may calculate the final velocity of the ball by equating the impulse on the ball from the possibly varying frictional force $F(t)$ opposing the motion of the ball to the decrease in the momentum of the ball along the club face. Therefore, we may write

$$\int F(t)dt = mv_1 - mv_2 \ . \qquad (1)$$

Where v_1 is the initial velocity of the ball, v_2 is it final velocity, and m is the mass of the ball. When the ball is rolling, $v_2=R\omega$, where R is the radius of the ball and ω is the angular velocity of the rolling motion. We assume here that the radius of the ball remains essentially constant throughout.

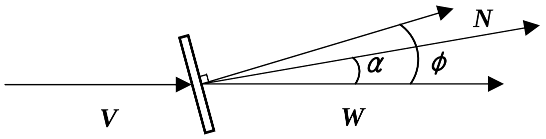

Figure 2. Vector of club and ball at impact

Besides the linear impulse $\int F(t)dt$, a torque impulse $\int F(t)Rdt$ also acts on the ball. This impulse torque is equal to the angular momentum acquired by the ball as it reaches its final velocity v_2. We therefore may write as a good approximation for the ball

$$\int F(t)Rdt = 0.4mR^2\omega = 0.4mRv_2 \,. \tag{2}$$

Here $0.4mR^2\omega$ is the moment of inertia of the ball about an axis through its center. If we regard R as constant, we may combine equations (1) and (2) to obtain

$$\int F(t)Rdt = R\int F(t)dt = Rm(v_1 - v_2) = 0.4mRv_2 \tag{3}$$

and thus

$$v_2 = \frac{5}{7}v_1 \,. \tag{4}$$

The velocity v_2 is less than v_1 because the force of friction acting for the distance the ball slides removes energy from the ball and does work in setting the ball into rotational motion. Since the original velocity of the ball up the club face is $V\sin\varphi$, we may write the velocity with which the golf ball rolls on leaving the club face as $\frac{5}{7}V\sin\varphi$. However, from many photographs in golf literature, we know that the golf ball compresses a significant amount, decreasing the distance from the surface of the ball against the club face to the center of the ball. Equation (3) should be modified using a variable radius *R(t)* to calculate the torque, to read

$$\int F(t)R(t)dt = 0.4mRv_2 < \int F(t)Rdt = R\int F(t)dt = Rm(v_1 - v_2) \,. \tag{5}$$

Equation (5) tells us that the actual velocity of the ball up the club face at the end if the impact is $\frac{5}{7} fV\sin\varphi$, where f is the fraction of the velocity remaining when the compression of the ball is considered. Therefore, final angular velocity is calculated by $v_2 = R\omega$.

$$\omega = \frac{5f}{7R}V\sin\varphi \tag{6}$$

Although we do not know the exact value of f, Jorgensen estimated f=0.7.

3.2 Analysis of impact by FEM

Since the contact time is approximately from 400 μs to 600 μs, we analyze the impact problem until 1000μs by LS-DYNA. Figure 3 shows that the launch angle of the ball is 9.8 °, the release velocity of the ball is 50.4m/s, and the velocity of the club after impact is 24m/s when the club initial velocity is 35m/s. These results are similar to previous results from related papers.

The contact force is determined as the resultant force of the reaction forces normal and tangential to the club face at the contact point. The normal force causes the compression and restitution of the ball, and the tangential force creates the spin. Especially, the tangential force is known to take either positive or negative values as the ball rolls and slides along the club face during impact. As normal force, the maximum result is 6600N at 280 μs as shown in figure 4. On the other hand, the tangential force until 320 μs is the positive tangential force that directs the spin downward along to the club face, but the negative tangential force that directs the spin upperward along to the club face is represented after 320 μs. Although the negative tangential force is very important to create spin, it was not mentioned in previous studies.

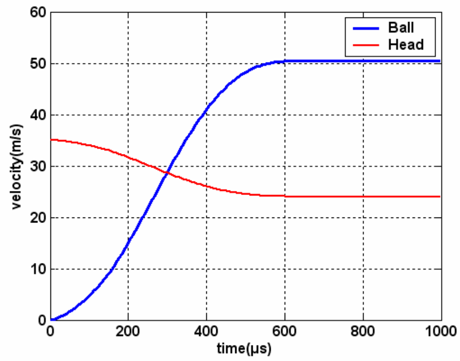

Figure 3. Ball and head velocity at impact

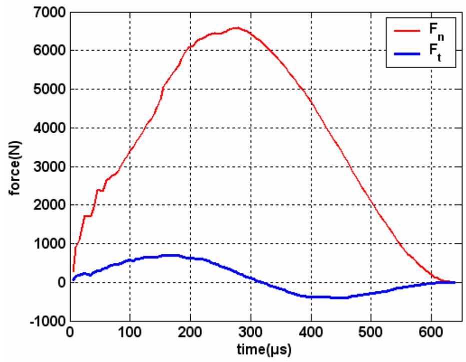

Figure 4. Normal and tangential forces

To find out more, the normal and tangential forces by several elements of contact area are computed every 120 μs as shown in figure 5. As the normal force that is only positive, the results of the center part are bigger than other the results of other sections because the deformation of the ball center is severe. On the other hand, as the tangential force, the only positive results are generated at the beginning of impact, but the negative results, as shown at 120 μs, are generated from the upper side of ball as time goes on. Henceforth, the area of negative tangential force is gradually increased and finally spread out all over the ball. As shown in figure 4, the negative tangential force appears after 320 μs because the sum of the tangential force by several elements of contact area is negative. The negative tangential force is created because of the force of restitution due to the elasticity of ball. The force of restitution is increasing when the ball is compressing, and it is maximized by the maximum deformation of ball. After this deformation is released during the expansion stage of impact, then the ball receives the opposite tangential force as cutting the surface of the club face due to increasing the force of restitution. Because the deformation of upper part of ball is smaller than the lower part of ball due to the club loft angle, the first negative tangential force is created on the upper part of ball. Thus, we conclude that the positive tangential force increases the ball spin rate and the negative tangential force decreases the ball spin rate as shown in figure 6.

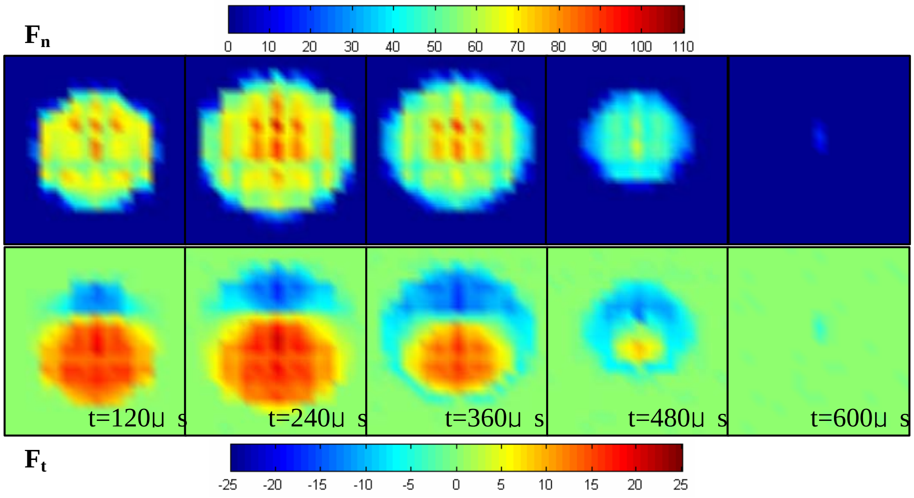

Figure 5. Normal and tangential forces during contact

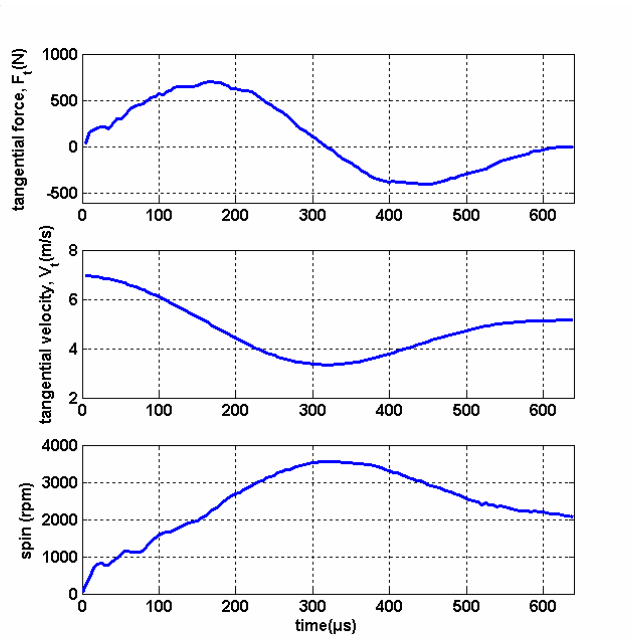

Figure 6. Tangential force, tangential velocity and spin rate at impact

To find the relation between the tangential force and back spin rate, the tangential velocity that is directed along the club face is calculated. As shown in middle of figure 6, the tangential velocity is 7.0m/s at the beginning of impact. This result is equal to $V \sin\varphi$ before mentioned dynamic theory. After the tangential velocity is decreased, the minimum tangential velocity is at 320µs that is equal position to the zero point of the tangential force as shown in the topside of figure 6. After 320µs, the tangential velocity is increased and finally the ball takes off the club head on 5.15m/s. If the ball takes off the club head only roll, the ball spin rate is 2298rpm by $v_2=R\omega$. However, the numerical result of spin rate is 2047rpm as shown in bottom of figure 6. The reason of this difference about two results is that the ball does not only roll at final time of impact. Because the ball takes off the club head by almost roll with a little slip, the back spin rate does not go up 2298rpm, but it stops on 2047rpm. The compression factor is 0.92 when the back spin rate is 2047rpm by equation (7), but this result is quite different compared to 0.7 by Jorgensen [2].

We calculate a variable radius *R(t)* of the ball to find accurate the compression factor. As shown in figure 7, this result is calculated to consider varied mass center. A radius is decreased until 300μs, and the maximum contraction rate is 23% at 300μs. To use this result, we recalculate the compression factor by equation (6). First, equation (6) is arranged to use the varied compression factor (*f'*).

$$\int F(t)R(t)dt = 0.4mRv_2 = f'\int F(t)Rdt = f'R\int F(t)dt = f'Rm(v_1 - v_2) \tag{8}$$

$$f' = \frac{\int F(t)R(t)dt}{R\int F(t)dt} \tag{9}$$

Because we know *F(t)* and *R(t)*, *f'* is 0.8379 by equation (9). To use equation (5), the relation between *f'* and *f* is

$$v_2 = \frac{f'}{0.4 + f'}v_1 = \frac{5f'}{5f'+2}v_1 = \frac{5}{7}fv_1 \tag{10}$$

and

$$f = \frac{7f'}{5f'+2}. \tag{11}$$

Equation (11) tells us that *f* is 0.9476, but this result is quite large compared to 0.7.

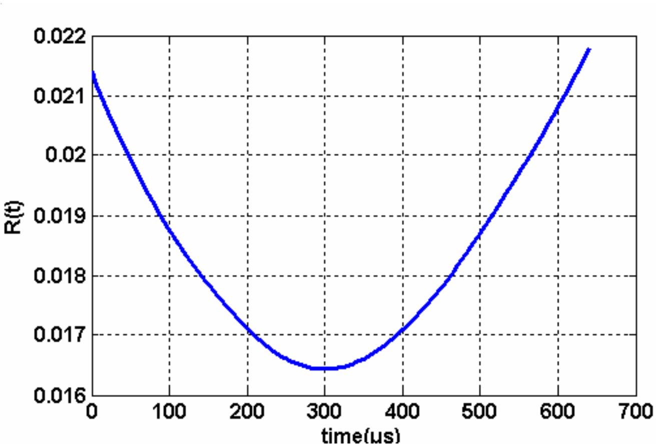

Figure 7. Effective radius of deformed ball at impact

3.2 Effect of varying club initial velocity and loft angle

We used that the initial velocity of the club head is 35m/s, and the loft angle is 11.5° on this study. These values are suitable to a beginner or woman golfer. The initial velocity of professional golfers is higher than 50m/s, as Tiger Woods approximately 60m/s. The loft angle is also various form 8° to 12°. Therefore, we analyze various initial velocities and loft angles. As shown in figure 8, ball velocity, launch angle, spin rate, and compression factor are calculated by varied club initial velocity from 30m/s to 60m/s and loft angle from 8° to 12°. The bigger the club initial velocity and loft angle are, the bigger the ball velocity, launch angle, and spin rate linearly become. On the other hand, the bigger the club initial velocity is, the smaller the compression factor becomes and the bigger the loft angle is, the bigger the compression factor becomes. The minimum compression factor is 0.922 that is also larger than 0.7 by Jorgensen [2].

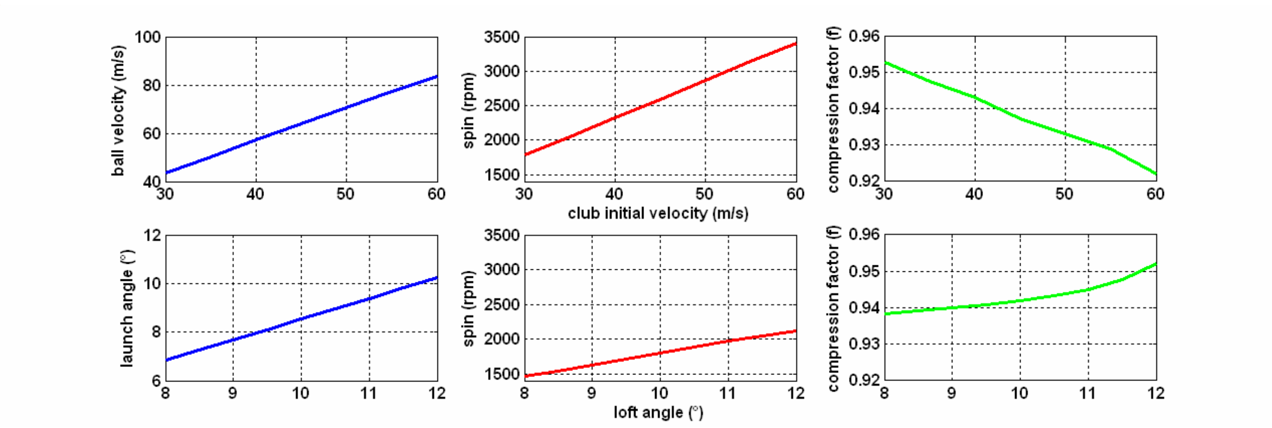

Figure 8. Ball velocity, launch angle, spin rate and compression factor for club initial velocity and loft angle varied

4. CONCLUSIONS

In this paper, we investigate the impact phenomenon between the golf club head and ball by FEM and clarify the mechanism of ball spin creation accurately, particularly focusing on the effect of negative tangential force on the ball spin rate.

The release velocity and launch angle of ball are 50.4m/s and 9.8° when the club initial velocity and loft angle are 35m/s and 11.5°. These results are similar to previous studies. The ball spin rate is 2047rpm that means to include not only roll but also a little slip at final impact time. We estimated that the compression factor is 0.948 and the minimum compression factor is 0.92 when we consider various initial velocities and loft angles.

Although this impact problem completely based on mathematical and mechanical theory, the results of impact problem are very similar to the results of actual impact. It means that to scientific approach is possible about golf and applying to other fields is also possible. Thus, we expect that this impact problem is applied to other impact problems.

ACKNOWLEDGEMENT

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