Fluid–Structure Interaction Analysis of Number 3 Wood Golf Club with Air Guide

Y. D. Kwon[*1], J. S. Han[#2]

[1]School of Mechanical Engineering and Institute of Engineering Design and Technology, Kyungpook National University, Daegu, 41566, Republic of Korea
[2]Graduate School, Mechanical Engineering Department, Kyungpook National University, Daegu, 41566, Republic of Korea

[1] ydkwon@knu.ac.kr

[2] hjs121987@gmail.com

[*] School of Mechanical Engineering and Institute of Engineering Design and Technology, Kyungpook National University, Daegu, 41566, Republic of Korea

[*] ydkwon@knu.ac.kr

Abstract— **A fluid–structure interaction (FSI) analysis of a no. 3 wood golf club was performed to predict and compensate the downward aerodynamic force that occurs as a result of the club head face's loft angle. In a previous study, we performed an FSI analysis of a no. 1 wood club, wherein most of the deflection induced by aerodynamic forces was eliminated by attaching a flat air guide to the no. 1 wood. In order to eliminate the remaining effect of the aerodynamic forces almost completely, an appropriate modification in the design of the air guide is necessary. A modified air guide was attached to the no. 3 wood club in this study to determine how to increase the performance of the air guide. The golf club's sole deflection could be predicted with respect to certain quantities such as the aerodynamic force and stiffness of the wood head. The stiffness of the shaft was determined using several experiments. The aerodynamic force was obtained using the FSI analysis. We attempted to minimize the deflection induced by the imbalance of the aerodynamic forces, thus allowing a golfer to expect a more consistent and well-balanced shot.**

Keyword-Golf clubs, aerodynamic force, air guide, FSI,

I. INTRODUCTION

In the sport of golf, players use clubs to hit a ball straight to a long distance and into a series of holes, with the goal of finishing the game with the lowest number of strokes. Therefore, good skill in the use of a golf club is needed, and it is usually difficult for beginners, and even low-handicap golfers, to use wood golf clubs accurately. The most-cited reasons for this are the lower stiffness of the club shaft, external disturbances, and the downward aerodynamic force induced by the loft angle of the club head's face.

The project Flogton ("not golf" spelled backward) permits Flogton basic players to use any existing equipment on the market, including nonconforming balls and clubs that are not considered "legal" by the United States Golf Association (USGA). Flogton also encourages engineers to seek innovative designs to help players hit the ball accurately and farther [1]. Currently, to neutralize the downward aerodynamic force, there are several golf clubs that feature an attachment to control the club for better performance [2]-[4].

In this study, a proposed attachment, called an "air guide," was tested to determine how it removed the unwanted deflection induced directly by the downward aerodynamic force. This deflection can be predicted by dividing the downward aerodynamic force by the stiffness of the wood gripped by a golfer [2]. A fluid–structure interaction (FSI) analysis for a no. 1 wood head was performed to determine the downward aerodynamic force induced by particular air currents.

Experiments were conducted to determine the shaft stiffness and stiffness of the entire golf system, which includes a human body and the arm gripping the wood. In the experiments, a weight was suddenly applied to the head, and the dynamic response was captured using a digital camcorder (HDR-FX1, Sony).

The motion of a white dot marked on the head of the wood was followed by a track eye motion analyzer (TEMA) software package to obtain a trajectory map as a function of time. The applied load was divided by the measured dynamic deflection to yield the dynamic stiffness of the head. We were then able to predict the deflection caused by the downward aerodynamic force using the downward force and stiffness of the head.

An attempt was previously made to eliminate inconsistent deflection by adopting an air guide. The air guide was mounted on the no. 1 wood head, and an upward force was induced to compensate for the downward force. A final FSI analysis was performed on the head and non-conforming [4] air guide system to observe the

nullified net aerodynamic force. The deflection induced by the aerodynamic force was minimized using the head and air guide system. Thus, a golfer can expect more consistent and stable shots.

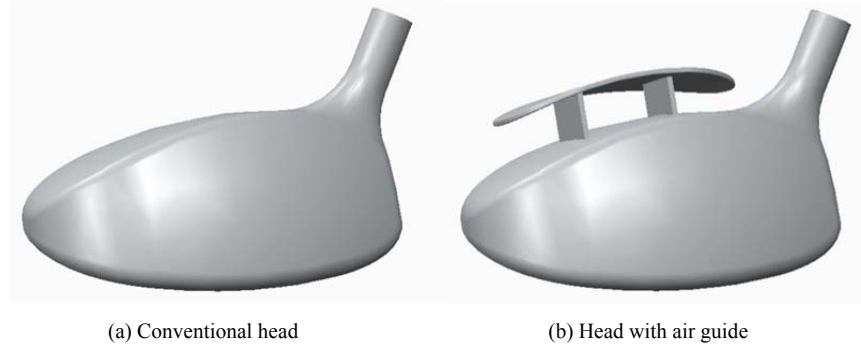(a) Conventional head   (b) Head with air guide

Fig. 1. Conventional head and head with air guide

The relevant analysis of the no. 1 wood was implemented in a previous study [2]. However, the deflection, which was not ideal because of the magnitude of the deflection, was still large. In this study, a compatible air guide was designed that is different from the flat air guide previously attached to the no. 1 wood. The new air guide's wing is curved, and its attack angle is identical to the loft angle of the face of the no. 3 wood (16°). The dimensions of the air guide are as follows: width × length × height = 68.48 × 47.26 × 11.88 mm.

II. FLUID-STRUCTURE INTERACTION INTRODUCTION

In an FSI analysis, fluid forces are applied to a solid, and the solid's deformation changes the fluid domain. For most interaction problems, the computational domain is divided into a fluid domain and solid domain, wherein a fluid model and solid model are defined, respectively, using their material data, boundary conditions, etc. The interaction occurs along the interface of the two domains. By coupling the two models, we can perform simulations and predictions of many physical phenomena. The ADINA FSI software was used, which has a structural analysis capability, as well as a fluid analysis capability. The availability of both capabilities within the same code provides a basis for developing sophisticated FSI tools. Considering a generic domain, a solid structure was placed inside the fluid as schematically shown in Fig. 2. Our objective was to create a mathematical model for the domain, and to solve this model using finite element procedures.

The solid (the golf head and air guide) was mathematically modeled using classical Lagrangian formulations, and the fluid (air) was modeled using an arbitrary Lagrangian–Eulerian (ALE) [5] formulation of the Navier–Stokes equations.

In this study, the solid was an actual three-dimensional (3-D) solid, and the fluid was considered to be a slight compressible medium [6]. The governing equations for the fluid domain were the continuity and Navier–Stokes equations, with the assumptions of a homogenous and slightly compressible fluid, and Newtonian flow. The ALE formulation uses a moving coordinate system to model the deformation of the fluid domain. The momentum and mass conservation equations governing the flow are given by Eqs. (1) and (2) in ALE form as follows:

$$\rho_f \frac{\partial \vec{\mu}_f}{\partial t} + ((\vec{\mu}_f - \vec{\mu}_M) \cdot \nabla)\vec{\mu}_f = \nabla \tau_f + f_f{}^B \tag{1}$$

$$\nabla \cdot \vec{\mu}_f = 0 \tag{2}$$

where ρ_f is the fluid density, $\vec{\mu}_f$ is the fluid velocity vector, $\vec{\mu}_M$ is the moving coordinate velocity, τ_f is the fluid stress tensor, and $f_f{}^B$ is the fluid body force per unit volume. In the ALE formulation, $\vec{\mu}_f - \vec{\mu}_M$ is the relative velocity of the fluid with respect to the moving coordinate velocity. The governing equation for the solid domain is the momentum conservation equation given by Eq. (3). In contrast to the ALE formulations of the fluid equations, a Lagrangian coordinate system was adopted for the solid:

$$\rho_s \frac{\partial^2 \vec{\mu}_s}{dt^2} = \nabla \cdot \tau_s + f_s{}^B \tag{3}$$

where ρ_s is the solid density, $\vec{\mu}_s$ is the solid displacement vector, τ_s is the solid stress tensor, and $f_s{}^B$ is the body force vector. At the fluid–structure interface, the displacements, velocities, and accelerations of the fluid (and fluid mesh) and solid are forced to be identical, thereby enforcing a no-slip/no-penetration condition on the flow field. The boundary conditions applied to the fluid–structure interface represent the kinematic condition:
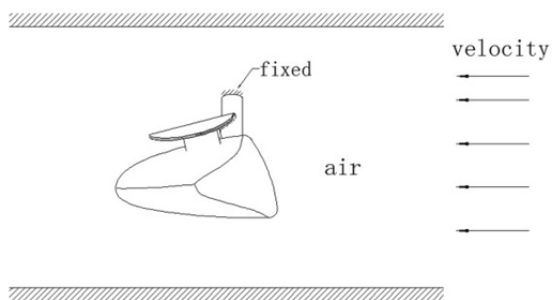
Fig. 2. Schematic of FSI problem

$$\underline{\mu}_f = \underline{\mu}_s \tag{4}$$

and the dynamic condition

$$n \cdot \underline{\tau}_f = n \cdot \underline{\tau}_s \tag{5}$$

Here, $\underline{\mu}_f$ and $\underline{\mu}_s$ are the fluid and solid displacements, respectively; and $\underline{\tau}_f$ and $\underline{\tau}_s$ are the fluid and solid stresses, respectively. The underlining denotes that the values are only defined on the fluid–structure interface. The fluid velocity condition results from the kinematic condition.

If a no-slip condition is applied, we have

$$\underline{v} = \frac{\partial \underline{\mu}_s}{\partial t} \tag{6}$$

If a slip condition is applied, we have

$$n \cdot v = n \cdot \frac{\partial \underline{\mu}_s}{\partial t} \tag{7}$$

where v is the fluid velocity, and $\underline{v}$ is the fluid velocity at the fluid–structure interface.

The fluid traction is integrated into the fluid force along the fluid–structure interface and exerted onto the structure node

$$F(t) = \int h^d \tau_f \cdot dS \tag{8}$$

where h^d is the virtual quantity of the solid displacement [7].

III. FLUID-STRUCTURE INTERACTION ANALYSIS OF WOOD HEAD

An FSI analysis of a golf club was performed using the following steps: modeling, meshing, and analysis. We modeled a golf club using PRO/ENGINEER software. Then, using HYPERMESH software, we performed a preprocessing procedure for meshing and creating the element set, which was used to set boundary conditions within the ADINA software. The FSI analysis was implemented using ADINA. The head and shaft materials were titanium and steel [8], respectively.

The wind drag influence was investigated by considering the pressure on the head's windward surface. The average male golfer swings the club between 80 and 90 mph, and the average female golfer swings between 60 and 70 mph [9]. Consequently, a velocity of 70~90 mph was selected for the analysis. The effects of wind drag on the no. 3 wood with and without an air guide were investigated, as shown in Fig. 3.

From the two images in Fig. 3, we note that when the no. 3 wood is swung at a speed of 90 mph, the pressure contours occurring on the wood's windward surface exhibit little difference between a conventional wood and a wood with an air guide.
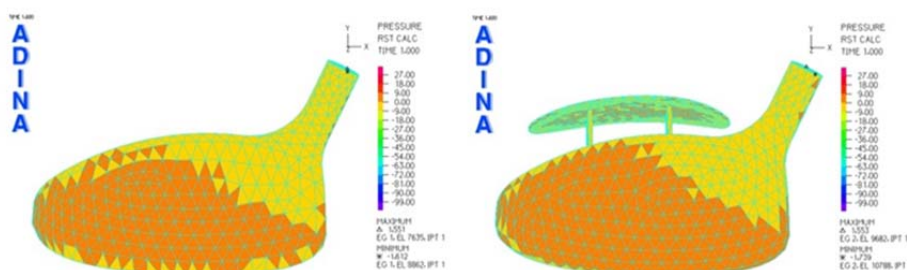

Fig. 3. Pressure distributions on no. 3 wood face (conventional and with air guide)

TABLE I
Downward Force Comparison Between Theoretical and FSI Approaches

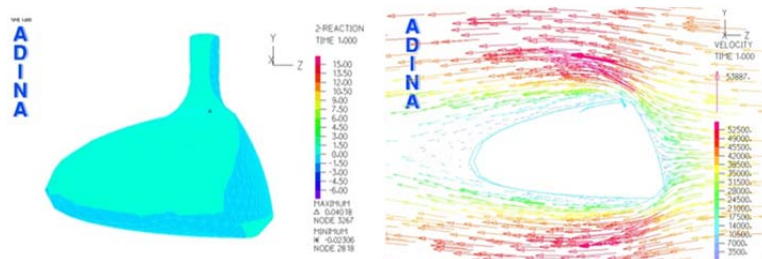| No. 3 Wood	70 mph (N)	80 mph (N)	90 mph (N)
Theoretical	-0.563	-0.735	-0.931
FSI	-0.602	-0.792	-0.982

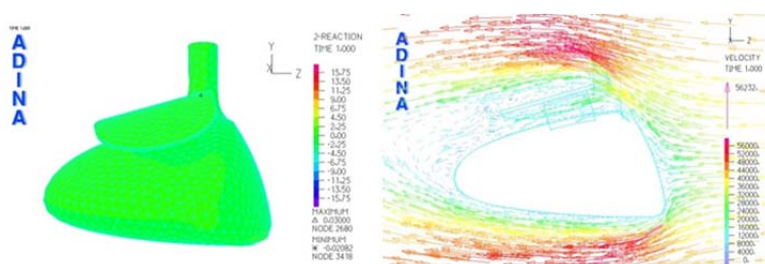Fig. 4. FSI of conventional no. 3 head (head shape and velocity field)

Fig. 5. FSI of no. 3 head with air guide (head shape and velocity field)

We suggest that there is little difference in the wind drag when the no. 3 wood has an air guide. Using swing velocities of 70–90 mph, we performed three FSI analyses of the no. 3 wood head with and without the air guide. Based on our preliminary results, the velocity of flow above the head was retarded by the air guide.

First, to verify the accuracy of the FSI analysis method for the wood club, we compared the results of a theoretical analysis and an FSI analysis of the aerodynamic force on a conventional no. 3 wood. The theoretical aerodynamic force was calculated using Eq. 9 [10].

$$F = \frac{1}{2}\rho V^2 \times H \times W \times \sin\theta \qquad (9)$$

where H is the face height, W is the face width, ρ is the air density, V is the air velocity, and θ is the loft angle.

As listed in Table 1, the theoretical vertical aerodynamic reaction forces are approximately the same as the results obtained by the FSI analysis performed on a conventional wood. Thus, we suggest that using the FSI analysis method for a golf club is reasonable.

Next, the vertical aerodynamic force on the no. 3 wood with an air guide was calculated using the FSI, and a comparison was made to examine the aerodynamic forces for the no. 3 wood with and without an air guide.

In this study, to compensate the downward force more effectively, a modified air guide was attached to the top surface of the head of the no. 3 wood. Formerly, the air guide on the no. 1 wood was flat, and its design looked odd when it was attached to the wood head. Consequently, we designed an air guide with a curved surface so that it appears compatible with the wood head. The surface area was adjusted to obtain the ideal result.

The results listed in Table 2 show that the downward forces exerted on the no. 3 wood were substantially reduced, in each case, by the compatible air guide.

Table 3 lists the vertical aerodynamic forces on a conventional no. 1 wood and a head with the previous air guide.

This flat air guide on a no. 1 wood looked rather odd and resulted in a higher unequilibrated force.

TABLE III
Downward Force on Head of No. 3 Wood (Loft Angle = 16°)

No. 3 Wood	70 mph(N)	80 mph(N)	90 mph(N)
Conventional wood	-0.602	-0.792	-0.982
Wood with compatible air guide	7.01e-3	9.14e-3	1.15e-2

TABLE IIIII
Downward Force on Head of No. 1 Wood (Loft Angle = 10.5°)

No. 1 Wood	70 mph(N)	80 mph(N)	90 mph(N)
Theoretical	-0.403	-0.526	-0.666
Conventional wood	-0.445	-0.582	-0.737
Wood with flat air guide	0.157	0.192	0.227

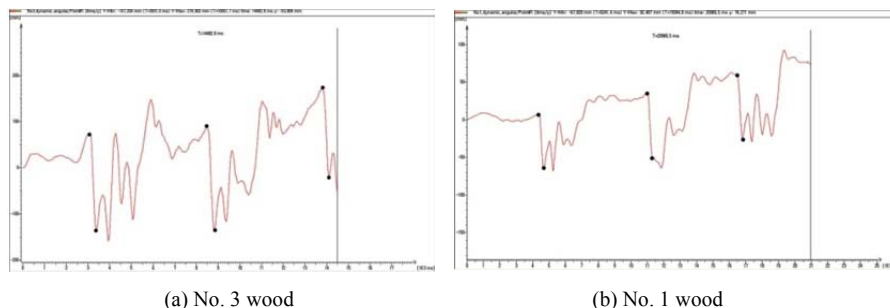(a) No. 3 wood   (b) No. 1 wood

Fig. 6. Deflections of woods gripped by golfer under sudden load

TABLE IVV
KVT: Dynamic Stiffness Values of Wood Gripped by Golfer

	Force (N)	Mean deflection (mm)	K_{VT} (N/mm)
No. 1 wood	4.905	80.414	0.0609
No. 3 wood	4.905	202.00	0.0243

IV. EXPERIMENTAL EVALUATION OF STIFFNESS OF WOOD GRIPPED BY GOLFER

The deflections of the no. 3 and no. 1 woods were obtained as functions of time using the TEMA software package [2]. The deflection data are shown in Fig. 6. The sudden load was 4.905 N, which was applied to the no. 3 and no. 1 woods to obtain the mean deflection and three values that are marked. Lastly, the dynamic stiffness values of the woods were obtained using the load divided by the deflection.

V. PREDICTION OF DYNAMIC DEFLECTIONS OF WOODS WITH AND WITHOUT AIR GUIDE

The deflection of each wood was predicted using the calculated reaction force and experimental dynamic stiffness. Tables 5 and 6 list the deflections of the no. 3 wood and no. 1 wood, with and without the air guide, respectively. The flat air guide mounted on the no. 1 wood resulted in 2.5~3.7 mm uncompensated displacements. However, the new compatible air guide mounted on the no. 3 wood resulted in almost fully compensated displacements of 0.02~0.04 mm.

TABLE V
Downward Force on Head of No. 3 Wood (Loft Angle = 16°)

Velocity (mph)	Deflection (mm)	Deflection (mm) Air guide (compatible)
70	-26.83	0.02885
80	-34.65	0.03760
90	-42.29	0.04749

TABLE VI
Downward Force on Head of No. 1 Wood (Loft Angle = 10.5°)

Velocity (mph)	Deflection (mm)	Deflection (mm) Air guide (flat)
70	-7.307	2.578
80	-9.557	3.152
90	-12.10	3.727

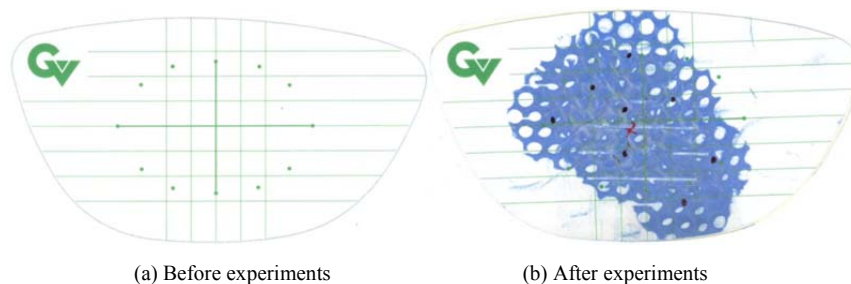(a) Before experiments   (b) After experiments

Fig. 7. Pressure sensitive paper

VI.   RESULTS OF EXPERIMENTS WITH NO. 3 WOOD WITH AND WITHOUT AIR GUIDE

We conducted experiments to verify the effect of the air guide. These experiments were conducted as follows. After attaching pressure sensitive paper, we experimented with a no. 3 wood golf club with and without an air guide. The experiments were carried out by three people, who can be divided into three groups: low handicap, intermediate, and beginner. First, they tried swinging 60%, 70%, 80%, and 90%, two times each, for a total of eight times. Second, they tried swinging 80% eight times. Lastly, after collecting the pressure sensitive paper, an analysis was made of their average points, distance between the average point and center, and distance between the standard deviation and center.
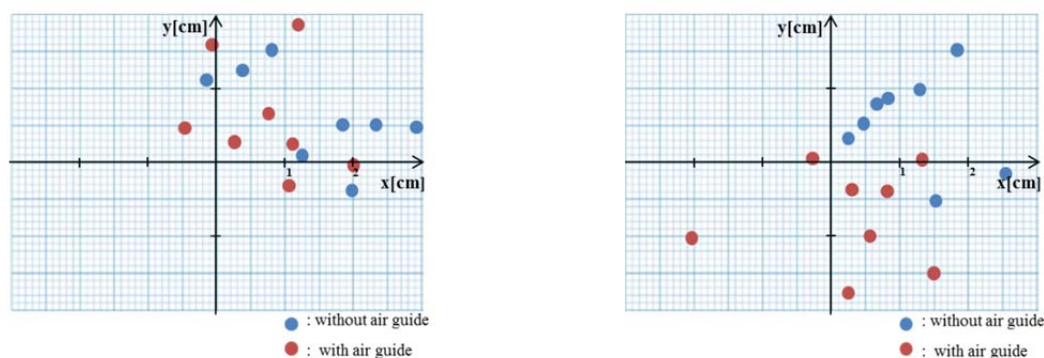
The results were as follows.
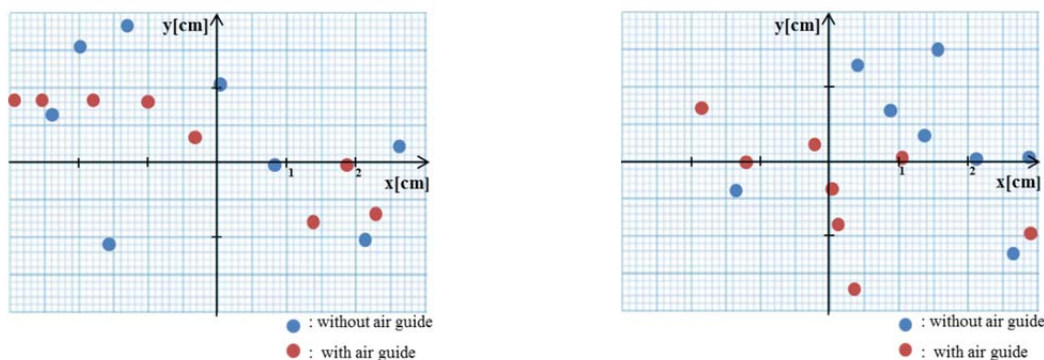
(a) 1st experimental conditions (60%, 70%, 80%, and 90% swinging)   (b) 2nd experimental conditions (80% swinging).
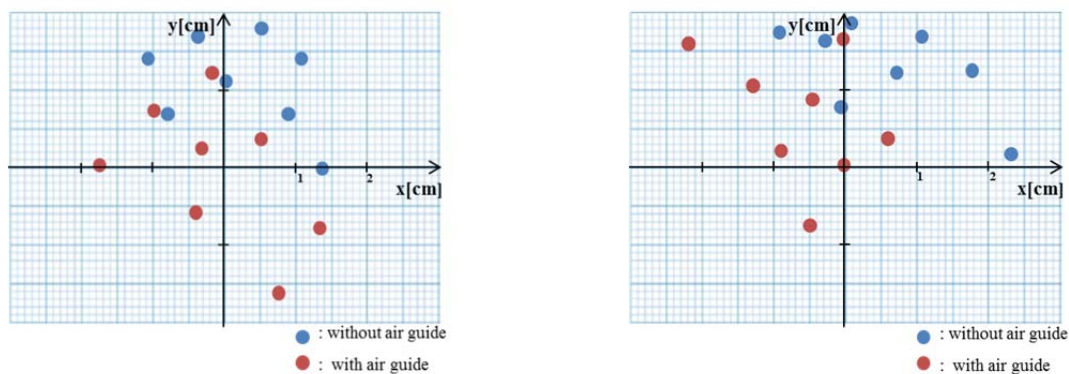
Fig. 8. The result by beginner

(a) 1st experimental conditions (60%, 70%, 80%, and 90% swinging)   (b) 2nd experimental conditions (80% swinging).

Fig. 9. The result by intermediate

(a) 1st experimental conditions (60%, 70%, 80%, and 90% swinging)   (b) 2nd experimental conditions (80% swinging).

Fig. 10. The result by low handicap

TABLE VII
Analysis of Experiments–Average Points

Group	Air Guide	1st experimental conditions Average point (mm)	2nd experimental conditions Average point (mm)
Beginner	X	(-03.86 , 03.94)	(13.54 , 02.84)
	O	(-04.44 , 01.71)	(02.60 , -03.78)
Intermediate	X	(14.86 , 06.40)	(11.99 , 05.19)
	O	(07.68 , 06.03)	(03.19 , -07.70)
Low handicap	X	(02.29 , 11.09)	(06.14 , 13.26)
	O	(-01.35 , -00.31)	(-06.40 , 06.73)

TABLE VIII
Analysis of Experiments–Distance Between Average Point and Center

Group	Air Guide	1st experimental conditions Distance between average point and center (mm)	2nd experimental conditions Distance between average point and center (mm)
Beginner	X	05.52	13.83
	O	04.76	04.59
Intermediate	X	16.18	13.07
	O	09.76	08.33
Low handicap	X	11.32	14.61
	O	01.39	09.29

TABLE IX
Analysis of Experiments–Distance Between Standard Deviation and Center

Group	Air Guide	1st experimental conditions Distance between standard deviation and center (mm)	2nd experimental conditions Distance between standard deviation and center (mm)
Beginner	X	19.85	17.03
	O	22.44	16.05
Intermediate	X	12.38	10.57
	O	11.31	13.45
Low handicap	X	11.61	12.67
	O	09.25	12.24

The above results show that regardless of ability, when the air guide was attached, the coordinates of the hitting spots moved downward on the y axis. In addition, in a comparison of the distances between the average point and center, when the air guide was attached, the distances were closer to the center than without the air guide. However, the distances between the standard deviation and center were similar with and without the air guide.

Consequently, we verified that there is a downward aerodynamic force effect when the air guide is attached.

VII. CONCLUSION

We calculated the aerodynamic force of a no. 3 wood head without an air guide using theoretical and FSI analysis methods. The accuracy of the FSI analysis of a no. 3 wood was verified by checking two aerodynamic force values that were obtained using different methods.

Furthermore, the deflection of the no. 3 wood with a modified air guide was calculated using the FSI analysis method, and the no. 3 wood's deflection magnitude is listed in Table 5. The no. 1 wood's deflections with and without the former air guide are listed in Table 6. We showed that the deflection of the no. 3 wood with a modified air guide could be reduced from 26–42 mm to nearly zero.

As a result, we conclude that the use of the compatible air guide on the no. 3 wood club can reduce the deflection induced by the aerodynamic force almost completely, thus helping a golfer accurately control the shot and more consistently hit with the sweet spot.

ACKNOWLEDGMENT

REFERENCES

[1]   (2015) The Flogton website. [Online]. Available: http://altgolf.org/philosophy
[2]   Y. D. Kwon, S. B. Kwon, J. H. Doh, and H. K. Kim, "FLUID-STRUCTURE-INTERACTION ANALYSIS OF GOLF CLUBS COMPRISING AIR GUIDES," *International Journal of Modern Physics B*, vol. 25 (31), pp. 4289-4293, Dec. 2011.
[3]   K. W. Lee, "Wood type golf club head," U.S. Patent 6 773 359, Apr. 23, 2004.
[4]   Y. D. Kwon, "Golf club," U.S. Patent 7 390 266, Jun. 19, 2006.
[5]   J. Donea, A. Huerta, J. P. Ponthot, and A. Rodriguez-Ferran, "Arbitrary Lagrangian-Eulerian Methods," *Encyclopedia of computational mechanics*, vol. 1 (14), Nov. 2004.
[6]   K. J. Bathe, H. Zhang, and X. Zhang, "Some advances in the analysis of fluid flows," *Computers & Structures*, vol. 64 (5), pp. 909-930, Sep. 1997.
[7]   *ADINA R&D Inc. (ARD 10-9)*, ADINA-F Theory an-d Modeling Guide, 2010.
[8]   M. J. Suk, Y.D. Kim, and Y. S. Kwon, "Fabrication of Golf Club Head and Materials," *Journal of Korea Foundry Society*, vol. 23 (3), pp. 114-121, 2003.
[9]   (2015) The Livestrong website. [Online]. Available: http://www.livestrong.com/article/462901-the-average-womens-golf-swing-speeds/
[10] C. H. Kim, and C. B. Youn, "Aerodynamic effect of roof-fairing system on a heavy-duty truck," *International journal of automotive technology*, vol. 6 (3), pp. 221-227, Jun. 2005.

AUTHOR PROFILE

Author1 Young-Doo Kwon Ph.D. Dept. of Mechanical Engineering & IEDT, Kyungpook National University, KOREA.

Author2 Jin-Sik Han A graduate School student, Mechanical Engineering Department, Kyungpook National University, KOREA.