571. Experimental Modal Analysis of a Golf Clubface: Investigation of Trampoline Effect

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Abstract. A complete modal analysis of a golf clubface has been presented in order to investigate the 'trampoline effect'. The availability of titanium golf drivers with thin, flexible faces opens up the opportunity to design the club so that it works together with the elasticity of the ball to provide the 'trampoline effect' or 'spring' from the clubface. Enhancement of coefficient of restitution results from a close match of the fundamental flexing frequency of vibration of the clubface to a natural frequency for the compressive mode of oscillation. Experimental modal analyses were performed on a driver clubface to determine the frequencies and vibration modes. For the fundamental flexing mode, good agreement is found between the results of experimental modal analyses and the theory.

Keywords: modal analysis, Trampoline effect, golf clubface, clubhead, flexing frequency, vibration.

1. Introduction

The clubface flexibility is of much concern to the golf club manufacturer due to the 'trampoline effect' it can impose on the golf ball. If the *fundamental flexing frequency* of the clubface matches that of the ball during impact, the flexibility of the clubface can add a maximum push on the ball during launching, thus taking the ball farther. This results in an enhancement of the coefficient of restitution (COR) due to the close match between the fundamental frequency of vibration of the clubface and that of the ball. Many scientific papers report the 'trampoline effect' that increases the COR of a golf ball after being hit by a golf club [1-3].

The aim of this study is to determine the fundamental flexing mode of the face of a hollow golf-club. First, theoretical calculations for the natural frequencies of a clubface are presented. Next, experimental modal analyses are performed on the clubface. A detailed analysis on the experimental results is shown in order to deduce the fundamental flexing mode of the golf clubface. Finally, the experimental measurements of the golf clubface are compared to the theoretical calculations for frequencies, where the golf clubface has been modeled as a clamped plate.

2. Natural Frequencies of a Golf Clubface

In this section, the theoretical calculation for natural frequencies of a golf clubface is presented. The clubface can be modeled as a clamped plate. Calculations for stiffness of the face k_p based on theory for a clamped edge circular plate [4] of radius R is given as,

$$k_p = \frac{16\pi D}{R^2} \tag{1}$$

where plate bending stiffness $D = Eh^3/12(1-\upsilon^2)$. Natural frequencies of modal vibrations ω_{mn} for the clamped circular plate [4] can be calculated for various modes where *m* is the number of radial node lines and *n* is the number of nodal circles.

$$\omega_{mn} = \frac{\lambda_{mn}^2}{R^2}\sqrt{\frac{D}{\rho h}}\ , \tag{2}$$

where $\lambda_{01} = 3.196,\ \lambda_{02} = 6.306,\ \lambda_{03} = 9.439,\ \lambda_{11} = 4.611,\ \lambda_{12} = 7.799, ...$

3. Experimental Modal Analysis

Experimental modal analyses were conducted on the face of a titanium driver golf clubhead with free or fixed support conditions. The latter support condition is achieved by clamping the hosel (part of the clubhead to which the shaft attaches). The experiments were performed to determine natural frequencies and corresponding mode shapes. A non-contacting, laser vibrometer was used to measure the natural frequencies of vibration and obtain the corresponding mode shapes. A grid pattern of 27 nodes was set up on the clubface using reflective tapes so the nodal displacements could be measured. A titanium cup face of 11° loft angle-tour cavity forged was used in this experiment.

To obtain calculated estimates of the properties of a driver, measurements of properties were obtained from this driver with 11° loft angle. These properties are listed in Table 1.

Table 1: Properties of a Ti driver head

Mass clubhead (g)	Material density (kg/m^3)	Elastic modulus (GPa)	Face maximum dimension (mm × mm)	Estimated face thickness (mm)
250	4430	114	67 × 90	2.6 – 3.0

4. Discussion: frequency response and mode shape

Figs. 1-2 illustrate the frequency response of a golf clubhead up to 5 kHz for the *free* and *fixed* supports respectively. Inspection on the fixed support case (see Table 2 and Fig. 3) gives the 1st resonant peak at 1852 Hz (peaks below this number are rigid body modes due to the support). At this frequency, the clubface vibrates as part of the rigid body motion of the clubhead. This mode is similar to the one reported by Penner [3]. He reported in the review of literature that the 1st mode of a 250-300cc titanium clubhead is about 1200 Hz, while a 150 cc stainless steel clubhead had a fundamental natural frequency at 1800 Hz. However, these frequencies have been obtained without proper consideration of displacement constraints acting during the experimental measurements.

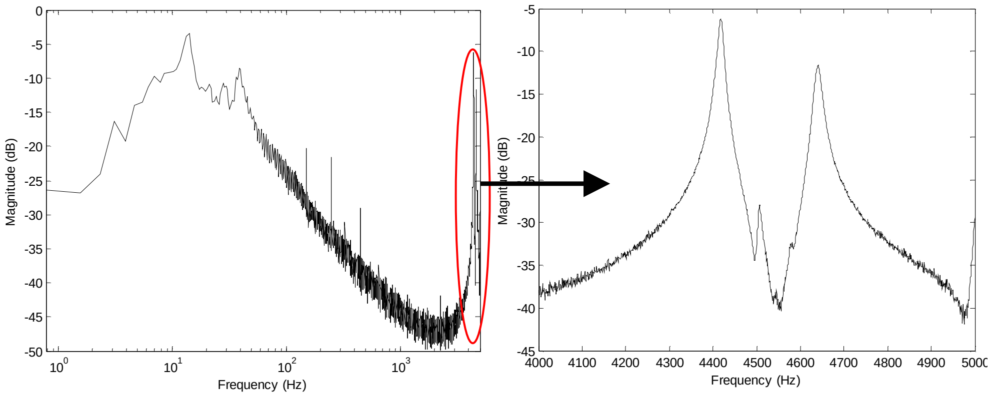

Fig. 1. Frequency response of a free support golf clubhead

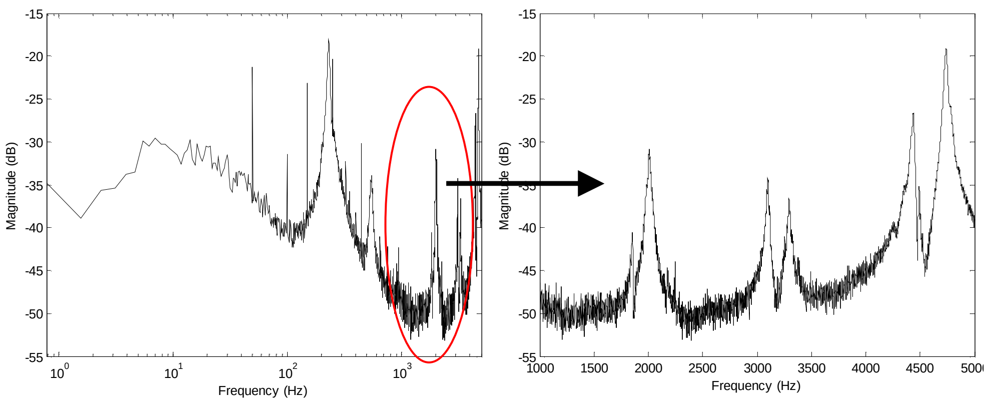

Fig. 2. Frequency response of a fixed support golf clubhead

Table 2. Comparison of frequencies for free and fixed supports of a Ti golf clubhead

Frequency of vibration for *free support* (Hz)	Frequency of vibration for *fixed support* (Hz)	% Difference
	232.03	
	325.78	
	550.00	
	1851.56 (Fig. 3)	
	2009.38	
	2174.22	
	3100.00	
	3294.53	
4417.97 (Fig. 5)	4438.28 (Fig. 4)	0.46
4506.25 (Fig. 6)	4492.19	-0.31
4640.63 (Fig. 7)	4741.41	2.13

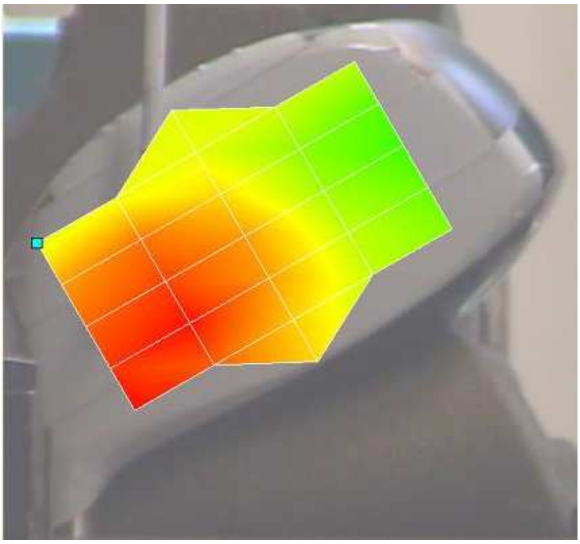

Fig. 3. Fixed support – 1852 Hz. The deformation is maximum at the bottom left side (near hosel)

Comparison of the resonant frequencies between the free and fixed supports (Table 2) gives the fundamental flexing frequency of the clubface at around 4.4 kHz. This is further confirmed by the mode shapes in Figs 4-5 for the fixed and free support cases respectively: in fact they indicate that the fundamental flexing frequency of the clubface has an antinode (displacement peak) at the centre. Below this fundamental flexing frequency (i.e. below 4.4 kHz), the vibrations are dominated by the rigid body modes due to the coupling of many sections (i.e. face, sole, bowl crown and hosel that makes the clubhead) and maybe some other vibration modes as well e.g. torsional. Furthermore, the 1st, 2nd and 3rd mode observed in the free support case (i.e. Figs. 5, 6 & 7) agree with the results reported by Hocknell et al. [5], where the modes of the clubface have a single antinode in the region around the centre.

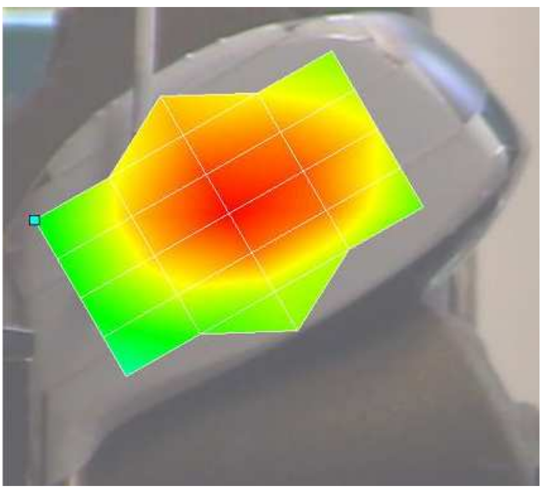

Fig. 4. Fixed support – 4438 Hz[*]

[*] The maximum deformation occurs around the centre of the clubface for Figures 4, 5, 6 and 7.

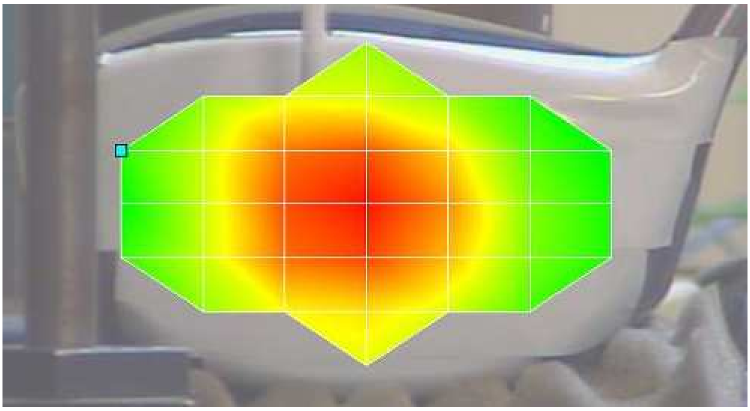

Fig. 5. Free support – 4418 Hz

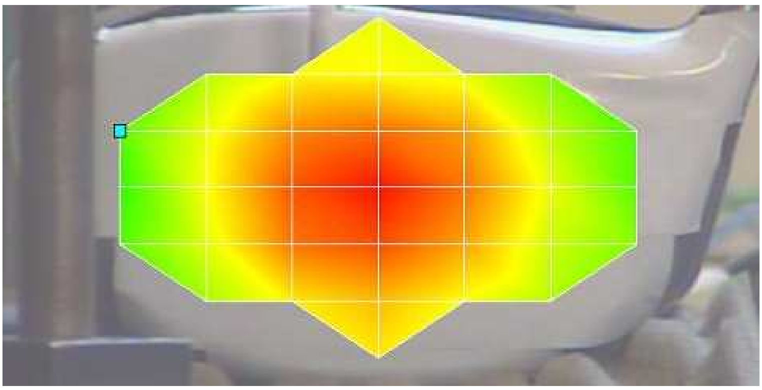

Fig. 6. Free support – 4506 Hz

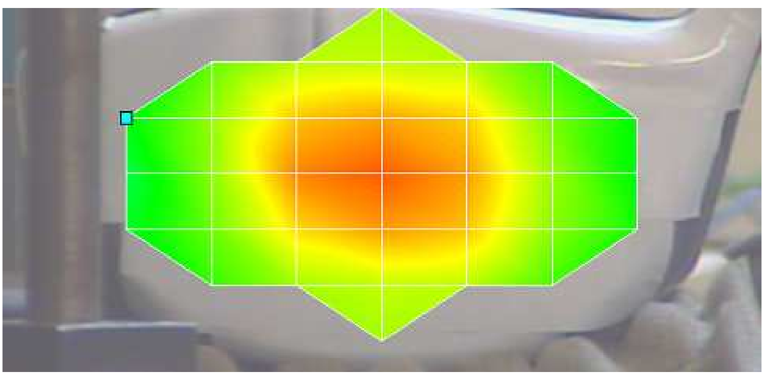

Fig. 7. Free support – 4641 Hz

The clubface can be modeled approximately as a clamped plate. The fundamental flexing mode of the clubface thus should have an antinode at the centre. This is the mode of vibration that can add a maximum push during launching of a golf ball; the mode that provides 'trampoline effect' that increases the coefficient of restitution.

Table 3: Calculated stiffness from uniformly loaded plate and fundamental natural frequency f_{01} (where $\omega_{01}=2\pi f_{01}$) for Ti driver (radius R= 0.040 m)

Face thickness, h (mm)	Plate stiffness, k_p (N/m)	Calculated frequency, f_{01}(Hz)	Experimental frequency, f_{01}(Hz)
2.6	5.76×10^6	4055	4428
2.8	7.20×10^6	4367	
3.0	8.85×10^6	4679	

Table 3 gives the calculated fundamental frequency for the clubface (using Eqs. (1) and (2)). We estimated the face thickness of 2.6 to 3.0 mm. The calculated frequency agrees within 8.5% compared to the experimental measurement at this range of thickness. If we assume the average face thickness of 2.8 mm as a representative of the clubface, the difference between calculated frequency to that of the experimental constitutes just 1.4%.

5. Concluding remarks

The results proved that the fundamental flexing mode (around 4.4 kHz in this case) of the clubface is much higher than the frequency of impact between a golf ball and a golf club (between 800 Hz to 1300 Hz; see Penner [3]). In addition, the results demonstrate good agreement with the theory for calculating the fundamental flexing frequency by assuming the clubface as a clamped plate. The measurement of frequency response needs to be accompanied with the modal analysis so that the correct mode of vibration is determined. This is important for the maximum 'trampoline effect' study, where the flexing mode is the one that provides a maximum push on the golf ball during launching.

6. Reference

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