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Modelling the acoustics of a golf ball impacting a titanium plate

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Abstract

Finite element techniques are often applied to the design and development of golf clubs. While distance and accuracy are the primary design characteristics, the acoustics of the ball/club impact play an important role in player perception. Previous work has applied finite element techniques to predict the sound of a golf ball/club impact. This research helps to lay the foundations for implementing finite element techniques into the process of developing golf clubs which produce a perceived 'desirable' sound upon impact. This study investigates the application of Ansys/LS-Dyna to predict the frequency response of a golf ball impacting three cylindrical titanium plates of varying thickness. A golf ball was fired against each plate at 41 m/s and the sound was recorded using a microphone. Fast Fourier transformations were applied to the sound recordings to obtain the frequency modes. A finite element model was developed for each plate and acoustic simulations for ball/plate impacts were run using the Rayleigh method. Averaged across all three plates, the mean frequencies obtained from the impact simulations for the first two modes were within 3% of those measured experimentally. Further research could work towards applying the techniques presented here to a golf ball/club impact.

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1. Introduction

It has been identified that the impression or 'feel' of sporting equipment has a clear effect on a consumer's perception of its quality (Roberts et al., 2006). Overall performance may be negatively affected if a player's

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equipment makes them feel uncomfortable, either physically or psychologically (Roberts et al., 2001). In sports where an implement is used to strike a ball, the concept of feel can be attributed to a combination of the vibrations felt by the hand/s at impact (Roberts et al., 2005a) and the sound generated (Roberts et al., 2005b; Hocknell et al., 1996). In golf, the acoustic response of a club has been identified as a key factor in how a player perceives the feel of a shot (Roberts et al., 2005a; Hocknell et al., 1996). It is therefore important to consider acoustics when developing equipment, rather than focusing solely on improving physical performance factors.

Increasingly, sports equipment developers are using high performance computing (HPC) and computer aided engineering (CAE) to model and test their products. Finite element (FE) modelling has been applied to golf clubs for optimising outbound ball velocity (Peterson and McPhee, 2009; Nakai, 2004). Mase et al. (2012) explored the ability of FE analysis to predict the acoustic response of a golf ball impacting both a USGA Coefficient of Restitution (CoR) plate (USGA, 1999) and a golf club head. They used both the exact Boundary Element Method (BEM) and the Rayleigh method in LS-DYNA for their acoustic simulations. Mase and colleagues recommend the Rayleigh method over the exact BEM, for running acoustic simulations on golf clubs, as equivalent frequencies are obtained at lower computational requirements. The FE simulations were validated against a modal hammer tap test at the centre of the plate and club face. The frequencies obtained from the plate simulations were in good agreement with their experimental data. However, simplification of the club head geometry (to reduce computational requirements) caused a reduction in its stiffness, resulting in the model significantly under-predicting frequency modes below 6,000 Hz.

This study takes the findings of Mase et al.'s (2012) CoR plate study a step further by modelling the impact of a golf ball on different thicknesses of plate. An imperative first step is to explore changes in geometry before creating a full, comprehensive golf club model. The aim of this paper, therefore, is to validate the frequencies obtained from FE simulations - using the recommended Rayleigh method - for a golf ball impacting three cylindrical titanium plates of varying thickness.

2. Methods

2.1. Experimental methods

Three cylindrical titanium plates, with a centered reduced section, were used in this study (Table 1, Figure 1a). The standard plate corresponds approximately to the USGA CoR plate. Two experimental methods were used to characterise the acoustics of the plates; i) a low-speed tap test and ii) a high-speed ball impact. For both tests the sound generated from impact was recorded using a microphone (Behringer 140 ECM8000) sampling at 44,100 Hz.

Table 1 Dimensions of the three plates used in this study and the plate used by Mase et al. (2012).

Plate	Diameter (mm)	Reduced section diameter (mm)	Thickness (mm)	Reduced section thickness (mm)
Thin	102	76	6.37	2.43
Standard	102	76	9.11	2.92
Thick	102	76	9.55	3.44
Mase et al. (2012)	102 ± 0.127	76 ± 0.127	9.07	2.92

For the tap test the plates were freely suspended from a long string and lightly struck with a handheld golf ball (Titleist Pro V1x). Each plate was struck both at the centre and off-centre, with each experiment repeated four times. Background noise - recorded in the laboratory prior to testing - was subtracted from the signal using Matlab (MathWorks, MATLAB R2012b). The Fast Fourier Transform (FFT) function was then used to convert the signal to the frequency domain, at a resolution of 1 Hz, to obtain the peak frequencies.

For the high-speed impact test, a golf ball was fired without spin - perpendicular to the face of each plate - from a modified pitching machine (BOLA, UK) at a mean velocity of 41 ms⁻¹ (standard deviation = 1.5 m/s) (Figure 1b). The plate rested on a horizontal support and was assumed to be free-free impact. Foam sheets were used to

prevent unwanted noise from secondary impacts between the plate and testing enclosure. Each plate was impacted three times, with the ball targeted at the centre. A thin layer of ink was applied to the front face of the plate, so the impact location could be easily identified. The impact location ranged from 7 to 34 mm from the centre of the plate.

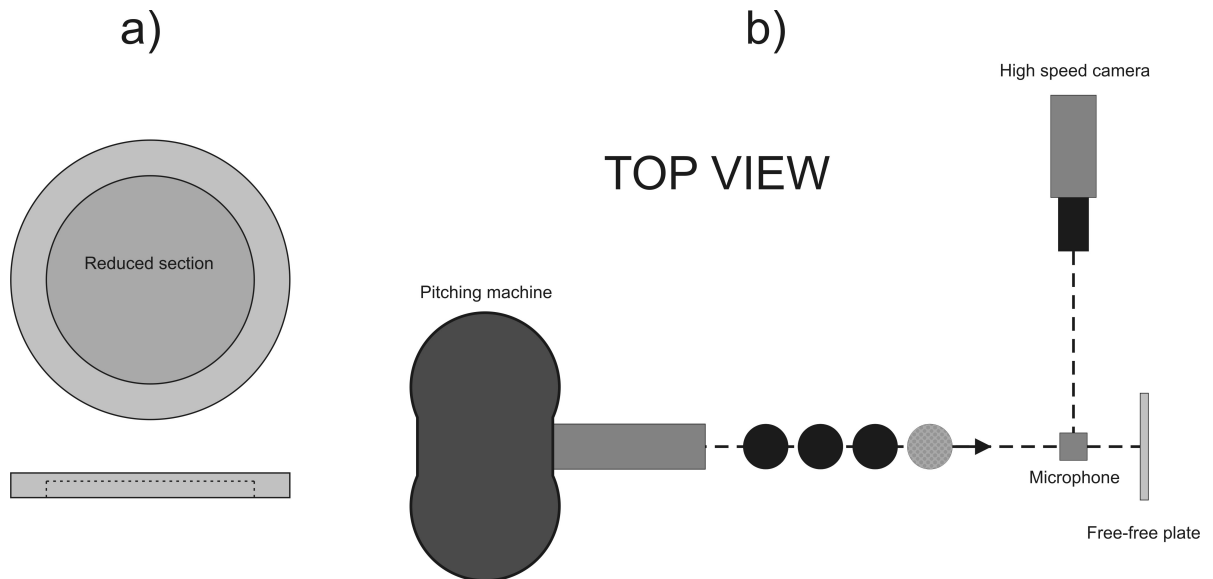


Figure 1 a) Cylindrical titanium plate and b) Experimental setup for high-speed impact testing. The microphone was located 0.13 m in front and 0.83 m above the plate.

Impacts were filmed using a high-speed camera (Phantom v4.3, Vision research) operating at 800 Hz. The video footage was manually digitised using in-house software (Check2D) to obtain the inbound velocity of the ball. The microphone was surrounded by anechoic foam and positioned 0.13 m in front and 0.83 m above the centre of the plate. The audio recordings were cropped to contain only the sound of the ball/plate impact. As per the tap test, background noise - recorded in the laboratory with the pitching machine running - was subtracted using Matlab. The signal was then converted to the frequency domain, at a resolution up to 2.5 Hz, to obtain the peak frequencies.

2.2. Finite element models

Finite element models were developed for each plate using ANSYS/LS-DYNA (solver version R4.2.1). A linear elastic (MAT_ELASTIC (LSTC, 2012)) material model was applied to the plates, which were meshed with 8-node brick elements. The plates were modelled as a homogeneous titanium alloy Ti-6Al-4V (Matweb) ($E = 116 \text{ GPa}$; $\nu = 0.34$; $\rho = 4500 \text{ kgm}^{-3}$). The dimensions and material properties of the golf ball model were taken from Allen et al. (2012).

Modal analysis simulations were used to obtain the frequency modes for each plate. The acoustic simulations were run using the Rayleigh method, as recommended by Mase et al., (2012). The exterior nodes of the plate were selected to create the boundary layer for computing the acoustic response. The ball was set to impact the free-free plate at 41 m/s to correspond to the laboratory experiment. Impacts were simulated at both the centre of the plate and 8.5 mm off-centre.

A massless acoustic node was placed 0.13 m in front and 0.83 m above the centre of the plate, to correspond to the microphone position in the experiment. The node acted as the microphone and measured the sound pressure wave generated from impact. An analysed frequency range of 20-20,000 Hz was set, to correspond with the

audible range of human hearing (Smith, 2006). The acceleration boundary condition for the FFT was used to compute the acoustic response of each impact, at a resolution of 4.0 Hz. The simulations used settings for air at standard temperature and pressure ($\rho = 1.21 \text{ kgm}^{-3}$, $v = 340 \text{ m/s}$, $P = 20 \text{ }\mu\text{Pa}$).

3. Results

Only the lowest two frequency modes were consistently excited in the experimental tests. Therefore, the results focus on a comparison of the 1st and 2nd frequency mode for the different methods. Figure 2 shows a comparison of the results for the 1st frequency mode. The experimental tap tests and impact simulations at the centre of the plate did not excite the 1st frequency mode. Therefore, only the off-centre simulations were compared to the other methods. The experimental results obtained for the off-centre low-speed tap test and high-speed impact test were in strong agreement, with a maximum difference of 14 Hz (0.5%) between both methods. The experimental results show an increase in frequency with plate thickness. The results from the FE modal analysis and off-centre impact simulations were within 2 Hz (0.1%), although both simulation methods slightly under-predicted the experimental results. Averaged across all three plates, the mean difference between the impact simulations and high-speed impact experiments was 63 Hz (2%) for the 1st mode.

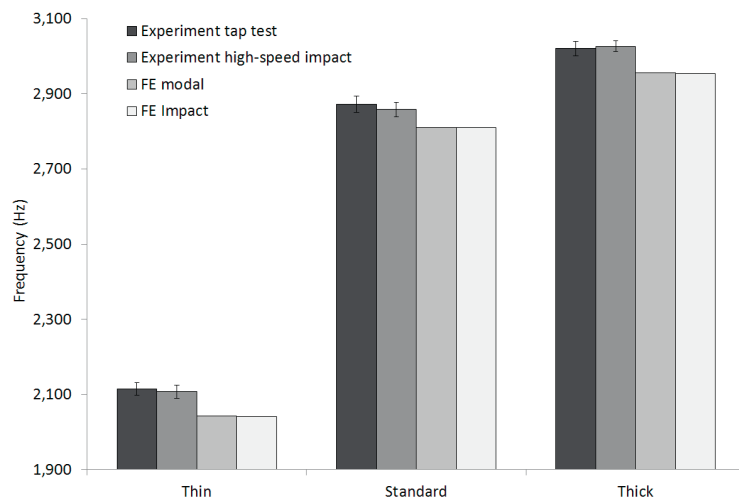


Figure 2 Comparison of results for 1st frequency mode. Experiment tap test shows results for the off-centre impacts. Error bars correspond to one standard deviation either side.

Figure 3 shows a comparison of the results for the 2nd frequency mode. The value from the experimental tap test (at the centre of the plate) and corresponding modal simulation frequency from Mase et al. (2012) was also included for comparison with the standard plate. The frequencies obtained from the experimental low-speed tap tests and high-speed impacts were in strong agreement, with a maximum difference of 10 Hz (0.2%). The frequency obtained from the experimental tap test on the standard plate was 363 Hz (9%) higher than the value reported by Mase et al. (2012). As per the 1st mode, frequency increased with plate thickness. The modal and impact simulations were in strong agreement, with a maximum difference of 17 Hz (0.4%). The simulations under-predicted the experimental results. Averaged across all three plates, the mean difference between the impact simulations and high-speed impact experiments was 136 Hz (3%) for the 2nd mode.

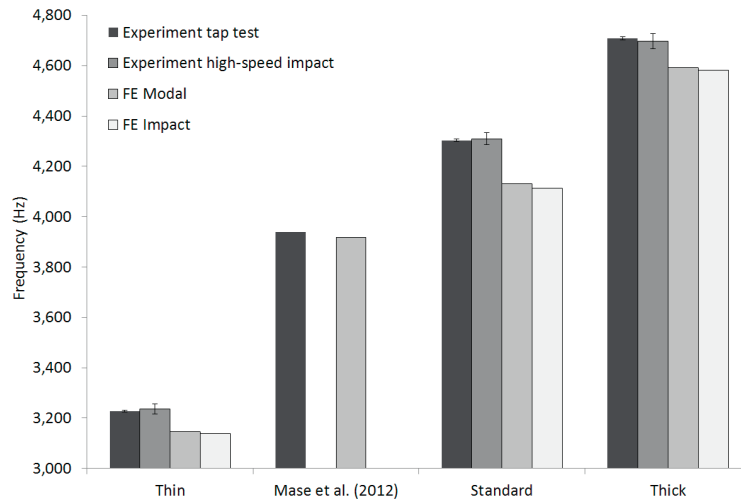


Figure 3 Comparison of results for 2nd frequency mode. Experiment tap test shows combined results for the centre and off-centre impacts. Error bars correspond to one standard deviation either side.

4. Discussion

Finite element acoustic simulations - using the Rayleigh method - were able to predict the frequency response of high-speed ball/plate impacts with reasonable accuracy. The impact simulation results also closely matched those obtained from modal simulations, while the experimental high-speed impact results corresponded to those for a low-speed tap test. The simulations slightly under-predicted the frequencies measured experimentally. The frequencies from the modal simulations were 62 to 72 Hz lower than the experimental tap tests for the 1st mode and 83 - 173 Hz lower for the 2nd mode. This systematic error is likely to be due to the material properties assigned to the plate in the model (Ti-6Al-4V). More representative material properties would likely result in better agreement between model and experiment.

Experimental tap tests and impact simulations at the centre of the plate did not excite the 1st frequency mode. The difference in thickness between the two sections of the plate was sufficiently low for it to behave as though it had uniform thickness (Duan et al. 2008). Figure 4 shows the 1st frequency mode took the form of a twisting mode with two nodal diameters, while the 2nd frequency mode took an axisymmetric shape with a nodal circle. Central impacts failed to excite the 1st frequency mode as the centre of the plate corresponded to a node for this mode. Off-centre impacts (experimental and simulation) excited both the 1st and 2nd frequency modes, as the contact point was located away from any corresponding nodes. The frequency of the lowest mode obtained from the central tap test (on the standard plate) was 357 Hz (9%) higher than the lowest value reported by Mase et al. (2012) for a central tap test, which may be due to differences in plate material (mass and stiffness).

Modal simulations cannot be applied directly to investigate the effect of impact location on acoustics. However, modal simulations can be used to determine mode shapes and help explain the results of high-speed impact simulations or experiments. As the frequencies measured in the off-centre tap test corresponded to those from the high-speed impact experiment, a low-speed impact test may be more appropriate for further testing. A low-speed tap test would allow the effect of impact location to be investigated more easily, which is particularly important if the techniques were applied to the head of a golf club.

Rayleigh simulations were able to accurately predict changes in frequency response - of the lowest two modes - with plate thickness. Validation of the FE modelling techniques presented here is however limited to the lowest two frequency modes. Higher frequency modes were inconsistent in the experimental tests, which is likely to be due to variations in impact location on the plate. Further work could investigate the ability of the FE modelling

techniques to predict higher frequency modes. The ability of the techniques to accurately predict amplitude levels, as well as more complex changes in geometry and material properties would also be of interest.

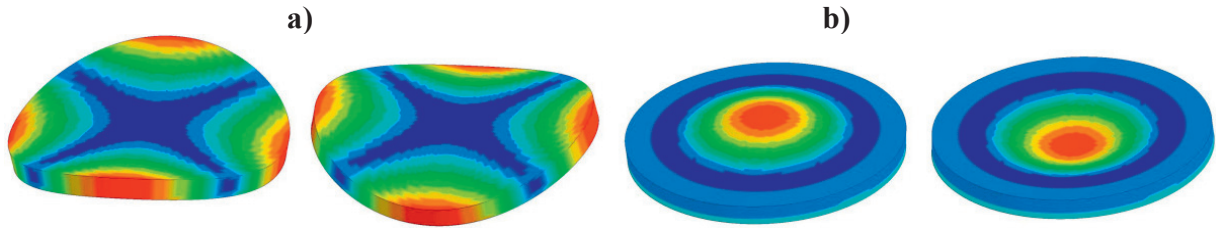


Figure 4 Mode shape of the CoR plate, a) 1st mode with 2 nodal diameters and b) 2nd mode with a nodal circle.

5. Conclusion

Acoustic simulations were able to predict the frequency response of a ball striking a cylindrical titanium plate, with reasonable accuracy. The FE techniques were able to predict the differences in frequency response with plate thickness. Controlled low-speed impact experiments are appropriate for validating impact simulations, while computationally efficient modal simulations can help explain the results. Further research could work towards validating amplitude and applying the techniques to the development of golf clubs with the capacity to incorporate both physical and psychological measures of quality.

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