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Modelling the sound of a golf ball impacting a titanium plate

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Abstract

A model was developed to predict the sound of a ball impacting a USGA CoR plate, as a first step towards simulating the acoustics of a ball/driver impact. A ball was dropped from 2.5 m onto a free-free plate with the impact sound recorded with a microphone. The experiment was replicated in Ansys/LS-DYNA, with both the exact Boundary Element Method and the Rayleigh method applied to predict the sound. The Rayleigh method predicted lower acoustic pressure than the Boundary Element Method, and was less accurate at predicting relative amplitudes of the frequency spectrum. The models under-predicted decay time, although, increasing mesh density improved agreement with the experiment. Further work should look to improve agreement between model and experiment for decay time, while investigating the effect of impact speed for a range of plate thicknesses.

Keywords: Sound; feel; performance; finite element; sporting equipment; perception

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1. Introduction

The ‘feel’ of sports equipment can influence the user’s perception of its quality [1, 2] and any physical or psychological discomfort can decrease performance [1]. While the feel of a golf stroke with a driver is a combination of vibrations felt at the hand and the impact sound [3, 4], it is dominated by the acoustic response of the club [5]. Sound is a subjective characteristic, but golfers tend to differentiate drivers in terms of perceived loudness and sharpness [2]. Computer simulation represents an alternative to physical testing, with Finite Element (FE) based structural analysis used for club design [6, 7]. As highlighted by Roberts et al. [4], if impact sound could be predicted using modelling techniques, it would be possible to manipulate the acoustics of a club earlier in the design process.

Several simulation methods are available for solving vibroacoustic problems. The FE method requires discretisation of the entire acoustic domain, while the Boundary Element Method (BEM) only requires the surface of the vibrating structure to be meshed. LS-DYNA (Livermore Software Technology Corporation) couples an FE solver with a BEM solver [8, 9]. The structural response of the object is computed in the time domain, and then transformed into the frequency domain via a Fast Fourier Transform (FFT) as a boundary condition for the BEM solver. The Rayleigh method is a similar alternative to the BEM, in which each element of the vibrating surface is assimilated to a plane surface mounted on a rigid baffle and vibrates independently, it is more efficient but less reliable at predicting acoustic pressure, particularly for curved surfaces [10, 11].

LS-Dyna has been used to model the sound of a golf ball impacting a circular titanium plate with a reduced central section (CoR plate, United States Golf Association [12]). Mase et al. [13] used the BEM to predict the plate frequencies excited by impact, while Allen et al. [14] (2014) applied the Rayleigh method to plates of varying thickness. Mase et al. [13] also simulated a ball/driver impact using the BEM and Rayleigh method, although some frequencies did not match the experiment as the geometry in the model was simplified. It is important to ensure the capabilities of LS-DYNA at predicting the acoustic response of a ball impacting a

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simple plate, before developing a ball/club impact model. This investigation, therefore, explored the time and frequency dimensions for ball/plate impact models.

2. Methods

A ball (Titleist ProV1x) was dropped 2.5 m onto the CoR plate placed face up on anechoic foam, to give an impact speed of 7 ms^{-1}. The drop test overcame issues of obtaining consistent impact velocity and location, as encountered when using a high-speed projectile device [14]. The plate was impacted three times at both the centre and 20 mm off-centre, with the sound recorded at 44,100 Hz with a microphone (Behringer 140 ECM 8000) located 2.5 m away. Matlab (Version R2014a) was used to subtract background noise and convert the signal to the frequency domain via an FFT at a resolution of 1 Hz. The drop test was replicated numerically and solved using both the exact BEM and approximate Rayleigh method in Ansys/LS-Dyna.

The ball and plate were modelled in ANSYS 15.0, following the methods of Allen et al. [14], and the simulations were run using the LS-DYNA solver (version R7.0.0). The ball diameter was 42.7 mm, with 22,736 8-node constant stress brick elements. The same elements were used for the plate, with an aspect ratio of four. Modal simulations were used to identify plate frequency modes, which showed low dependency to mesh density when there were at least four elements through the reduced section. Two meshes were selected for the acoustic simulations with, i) 4 elements through the reduced section and 5,040 in total (coarse) and ii) 8 elements through the reduced section and 36,192 in total (fine). The material properties assigned to the plate were modified slightly from those used by Allen et al. [14], to improve agreement between model and experiment ($E = 117$ GPa, $\nu = 0.34$, $\rho = 4{,}388$ kg.m^{-3}). Density was reduced by 112 kg.m^{-3} to match the mass of the plate in the model with that of the actual plate and Young's modulus was increased by 1 GPa to improve agreement between simulation and experiment for modal frequencies.

For the acoustic simulations, the ball was set to impact the free-free plate at 7 ms^{-1} at both centre and off-centre locations. A massless acoustic node was set 2.5 m away, corresponding to the microphone position. Acceleration was written from the structural response every 5 μs, and converted to the frequency domain via an FFT with a raised cosine window, to serve as the boundary condition for the BEM solver. The simulation time was set to 0.15 s for the coarse plate according to a time domain preliminary study and to 0.25 s for the fine plate following the work of Volkoff-Shoemaker [15]. The acoustic medium was air at room temperature with a density of 1.21 kgm^{-3}, a speed of sound of 340 ms^{-1} and a reference pressure of 20 μPa.

LS-DYNA computes the acoustic pressure in the frequency domain as a complex variable, containing magnitude and phase information for each frequency. Output frequencies were set to range from 20 to 20,000 Hz, corresponding to the human ear audible range [16], at a resolution of 5 Hz. The microphone used in the experiment was not calibrated for acoustic pressure so the relative amplitudes of excited modes were investigated, which represents the sound timbre [16]. The time domain was also explored, which informs us about the sound behaviour over time [17]. The simulations provided the magnitude of the complex acoustic pressure in the time domain, which does not represent sound as recorded by the microphone as the phase delay is missing.

To obtain the actual time domain representation of the sound, Matlab was used to apply an Inverse Fast Fourier Transform (IFFT) to the complex pressure computed by the solver in the frequency domain. The real and imaginary parts of the complex acoustic pressure were provided. The frequency range was set to 0 to 9,000,000 Hz. After applying the IFFT the resulting sampling frequency was 54,613 Hz which is in accordance with the Nyquist theorem [16] to prevent aliasing when frequencies up to 20,000 Hz need to be discerned. The time domain was investigated for a centre impact with the computationally efficient coarse Rayleigh model.

3. Results

Table 1 compares frequencies from experimental impacts and a modal simulation of the plate, up to the 6th mode. The model tended to slightly under-predict experimental frequencies. The 1st, 3rd and 6th mode were not excited for a centre impact, and the 3rd mode was not excited for an off-centre impact, as the impact location corresponded to nodes for these modes. A few experimental frequencies did not match any mode of vibration from the modal simulation and were attributed to noise. One of these modes had a frequency of 3,570 to 3,735 Hz, which was likely to correspond to the ball as a frequency of 3,415 Hz was identified in a modal simulation of the ball. In addition, Hocknell et al. [18] attributed frequencies recorded from ball/club impact up to 3,500 Hz to vibrations of the ball.