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Application of sensors to investigate tennis racquet dynamics

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Abstract

The need to understand more about the behaviour of tennis racquet strings beyond initial tensioning and after hammer impacts led to tests being conducted by Cross et al, in 2000, which produced information on single-string dynamic properties. In another study by Cross, the effect of string-bed damping on boules was tested for providing COR data from which a damping coefficient can be approximated. Developing further understanding of the string-bed's dynamic properties through information on an actual response to a ball impact was considered here. A method of measuring the string-bed's full response to a ball impact with a linear variable displacement transducer (LVDT) was investigated. The recordings from an a.c. LVDT and a high-speed camera HSC were compared, and it was found that the LVDT's measurement of overall frequency for the complete oscillations after the ball had left the strings was 98.2% in agreement to that recorded by the HSC.

Keywords: Tennis; racquet; string-bed; sensor

1. Introduction

Over the past 70 years, linear variable displacement transducers (LVDTs) have been adopted by different disciplines, such as aerospace and medical, to provide accurate measurement. Recently 'micro miniature' LVDTs have become available thereby increasing the possibility of positioning more of them over the string-bed to simultaneously record deflections. The aim of this paper is to appraise the ability of a LVDT to record a complete vibrational response of the string-bed from a ball impact. For comparative purposes, a high-speed camera (HSC) is used to simultaneously record the response and provide a separate set of data.

An LVDT is a displacement sensor. It consists of an armature (or core), made of a ferromagnetic material, which moves inside a former. The former is also ferromagnetic and tubular, and has wound onto it a single primary winding and two secondary windings. The primary winding is energised by an a.c. voltage (4 to 6V) at a known frequency (usually 5kHz) inducing voltages, V1 and V2, in the secondary

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windings, but because the secondaries are connected in series opposition the output voltage is V1-V2. When the armature is at the centre of the former this is what is called the null point because V1-V2 equals zero (ideally). When the armature is displaced by a moving element, which in this case is the string-bed, a d.c. signal (converted from the a.c. signal) is output. A phase-sensitive demodulator enables the positions either side of the null point to be distinguished [7].

The reason for investigating how the string-bed responds is to improve on the current understanding and interpretation of how it behaves dynamically. Tennis players use the initial tension at which their rackets are strung as a guide to how it performs during play. However, a newly tensioned string-bed is affected by several factors [5], not least time, which change the tensions held by the strings thereby creating a degree of unpredictability of its dynamic response at the point of play. A method that generates string-bed responses to ball impacts might, for example, assist in identifying different strung racquets with a similar dynamic response for consistent performance in a match.

A method for measuring the initial string deflection used a high-speed camera (HSC) and aluminium rods to track the main string's motion, in experiments by Goodwill and Haake, to verify a spring-dashpot model of a ball and a string-bed [3]. The deflection of tennis strings is relatively small and so when it is viewed from one side, the width of the frame obscures the string-bed's response. The length of the aluminium rods in the experiments was 100mm long enabling the HSC to track the initial deflection from an end view. However, the addition of a mass to the string-bed may affect the dynamic response.

Experimental work by Cross has investigated how tennis string properties affect ball propulsion off the string-bed [2]. The dynamic response of the string-bed may not always have been considered, because the efficiency of the interaction between it and the ball is high. It was established that when dropping a 760g steel ball (a boule) from heights of up to 2.4m on the strings, rebound velocities of 95 ± 2% of incident velocities were achieved deducing that energy loss due to friction between the strings is negligible.

However, by investigating the string-bed's actual response a better understanding of its dynamic behaviour and properties can be gained. The need for more information about strings beyond the initial tensioning has been explored by Cross et al [1] through tests which subjected tensioned strings to hammer impacts. The strings's tensions were calibrated from a load cell within a steel frame, and the results showed that tennis strings can be categorised by dynamic stiffness, tension loss with time, and the coefficient of friction between string and ball.

The dwell time is the duration of contact between the ball and the strings. The subjects of feel and power are of some interest, and knowing the dwell time may help to not only understand how these effects are generated but also explain the change in string-bed stiffness from higher velocity impacts. The length of dwell time has been measured, using a laser beam, from the point where the incoming ball touches the strings to the same point where it is being released from the string-bed [4]. In terms of string deflection, this is the same as moving through the first half period, which could be measured by an LVDT. Dwell times from 6.1 to 6.8 ms were measured for balls impacting racquets at 8.3 m/s.

The availability now of LVDTs and their signal processing allows experiments measuring impacts to be considered. Section 2 describes the experimental setup in which a ball was fired at a racquet with the deflection measured by an LVDT and recorded by a high-speed camera. Section 3 discusses the results obtained and compares the results from the LVDT with the video material. In particular, different forms of attaching the LVDT to the string-bed are explored. Conclusions are presented in Section 4.

2. Experiment

A Prince mid-size graphite racquet was clamped, by two steel bars, across the frame to a rig, which was bolted to a wall. The racquet was strung with 15L nylon at 55 pounds, and a 'used' tennis ball was fired from a BOLA ball launcher at 25 mph. The legs of the machine were modified to bring the height of the machine in-line with the rig. In order to remove the variability in results from the changing properties of a new ball from a pressurised can [6], a several-month old, used ball was launched at the racquet's geometric centre.

An AC25 Solartron LVDT was attached to one of the two central main strings at its mid-point. A high-speed camera (HSC), Photron Fastcam-X 1280 PCI, was positioned in the plane of the string-bed to record the deflections (at 1000 frames per second), and increased light was provided for the camera from two high-intensity lamps. The images, recorded by the HSC, were processed for their deflections using Photron Motion Tools software.

In initial experiments the LVDT was attached to the string-bed by steel wire wound around it. It was found that this was not sufficiently robust – it permitted relative movement between the two. A more rigid solution was later employed consisting of a light collar.

3. Results

In this section there are two sets of results. The first set used a simplistic way of attaching the LVDT to the string-bed, but nonetheless produced a useful result. However, it became apparent that the attachment between the LVDT and the string-bed could be improved. The second set used a stronger attachment, and here the results are compared with a HSC recording.

3.1. Initial experiment

The effectiveness of an LVDT in being able to record the dynamic response of the string-bed to a ball impact rests in not only the sensor and signal processing capabilities, but also in the ability of an attachment to ensure that the armature follows the string-bed's oscillations. The initial attempts at making an attachment between the string-bed and the LVDT were conscious of the effect of mass on the response so methods which incorporated the lowest possible weight were explored. Figure 1 is a plot of an initial experiment where a used Slazenger ball was launched at 30 mph and impacted the racquet at its geometric centre.

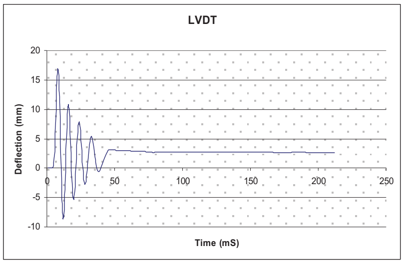

Fig. 1. String-bed response with an early attachment at 30 mph

The plot in Figure 1 shows the effect of an attachment which does not completely secure the armature to the string-bed throughout the duration of a response. The more promising attachments at this stage of testing were wire-based. However, at a velocity of 30 mph it was evident this method was unsuitable.

3.2. Refined experiments

In the following test, simultaneous recordings were made by a HSC and an LVDT of a 25 mph impact. The purpose of this experiment was to achieve a complete string-bed response thereby enabling a comparison of the LVDT results to be made with the recording from the HSC. However, the additional masses of the collar and armature connected to the string-bed have an effect on the frequency of the response.

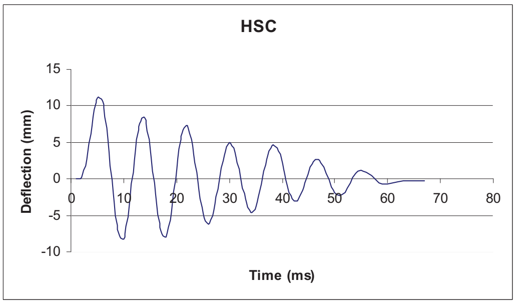

Fig. 2. Camera plot of deflection at the geometric centre

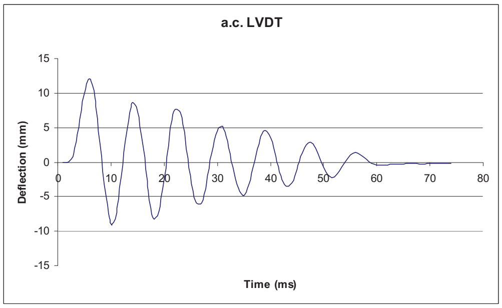

Fig. 3. LVDT plot of deflection at geometric centre

In Figure 2 is a plot of the string-bed's response as recorded by the HSC and processed by Photron Motion Tools software. Figure 3 shows a plot from the a.c. LVDT whose data was processed by LabView software. Both plots show a full string-bed response resulting from a robust attachment. In order to compare the plots with each other, measurements were taken from enlarged prints. The camera recorded an initial deflection by the ball of 11.2mm whereas the LVDT plot was slightly higher at 12.1mm. From the initial point of maximum deflection, the HSC recorded a time of 58.1 milliseconds for the oscillations to come to rest, which compared well to the time measured on the LVDT plot of 56.5 milliseconds.

A further comparison between the plots was made by measuring the time of the oscillations and calculating the percentage error between the LVDT frequencies and those of the HSC. In Table 1 are the effective frequencies for each cycle assuming the response to have remained consistent throughout the duration of the recording.

Table 1. Error (%) between the HSC and LVDT recordings

Cycle	HSC (*Hz*)	LVDT (*Hz*)	Error (*%*)
1	118.4	120	1.3
2	125	120	- 4
3	121.6	122.7	0.7
4	115.4	117.4	2.5
5	121.6	120	- 1.3
6	115.4	110.2	- 4.5

The first cycle starts from where the ball may be considered to have left the strings. So the vibrations after the first half period may be said to be 'free'. The LVDT plot was compared, cycle by cycle, with that from the HSC. There was found to be a good agreement through an error range of 0.7 to 4.5%. The sensitivity of measurements on the HSC plot meant that 0.5mm equated to 3.4 Hz. However, averaging the frequency across all six cycles the difference between the HSC and the LVDT is 1.8 %, which is encouraging for the sensor's ability to record vibrations in racquet experiments.

The responses in Figures 2 and 3 show a lower frequency of oscillation than that of only the string-bed due to the additional masses of the armature and collar of approximately 20g. The average string-bed frequency has been measured to be in the region of 500 Hz, by attaching a piezoelectric transducer to the string-bed with Blu-Tack and tapping the frame [8]. The LVDT method of measuring string position against time is of the contact type and will, therefore, affect the response. By reducing the mass of the attachment a higher frequency can be measured. The Prince racquet used in the experiment has only 14 main strings so using the lower end of Brody's [4] range of values for string-bed stiffness, 2x104 N/m, the theoretical frequency of string-bed, assuming its mass is 15g, is 120 Hz. The experimental results show agreement with this theoretical value. The theoretical frequency of a string-bed with an assumed effective mass of 15g is 183 Hz. If the LVDT method is used to assist in identifying rackets with similar responses for consistent play, some mass might be acceptable provided the tests are consistent.

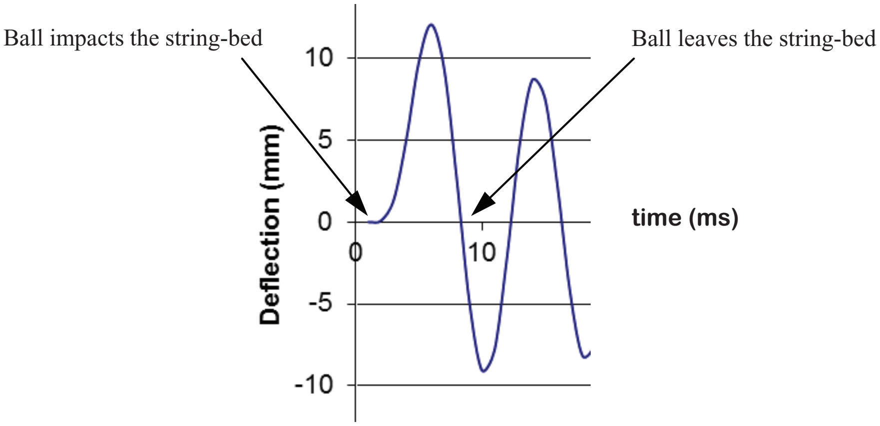

Fig. 4. Initial displacement of string-bed recorded by the LVDT

The plots can be used to estimate the time the ball is in contact with the string-bed. The plot in Figure 4 shows the string-bed moving from rest to the maximum initial deflection where the velocity of the ball is zero. The energy now stored in the string-bed dissipates by accelerating the ball (and strings) up to its exit velocity from the racquet. The plot shows the string-bed passing back through the rest position at which point ball is assumed to be leaving the strings. The dwell time is assumed to be the time from the initial deflection to the point where the plot first intersects the time axis. Brody [4] explained how string tension influences dwell time, and measured times of 6.3 and 6.7 ms for tensions of 70 and 50 lbs, respectively. The HSC plot was measured from the start of the trace to the half period and found to take approximately 6.6 ms. The LVDT trace was measured to be 7.03 ms. According to Brody [5], higher ball velocities reduce the dwell time because the string-bed stiffness increases, so these measured values would reduce with a higher impact velocity.

The string-bed, in Figure 4, deflects from rest by approximately following a parabolic curve mainly from the compliance of the ball. A tennis ball compresses during an impact thereby applying force in a non-linear manner. The nylon string-bed also has a non-linear deflection characteristic as shown in single string experiments by Cross et al [1] as dynamic stiffness. This non-linear string-bed characteristic is described by Brody [4] as an increasing effective k, which affects the prediction of the dwell time (using simple harmonic motion) for larger deflections when the actual displacement will be smaller. The combined mass of the collar and armature may also affect the response but it is not investigated in this paper.

4. Conclusions

Experimental results of how a string-bed responds to a central impact were recorded simultaneously by a linear variable displacement transducer (LVDT) and high-speed camera (HSC), and are shown to have a close agreement. The initial deflection recorded by the LVDT of the string-bed from a ball impact of 25 mph differed by 0.9mm. The difference in frequency for the six cycles after the ball had left the string-bed was 1.8% lower at 117.8 Hz for the LVDT plot. The results show the LVDT capturing actual deflections, which oscillate at a lower frequency than just the string-bed due to an additional mass from the attachment connecting the LVDT to the string-bed. Therefore, the responses are of the string-bed and attachment masses. However, the frequency recorded in the experiments agree with the theoretical value when using a lower stiffness value for the string-bed from a range of values measured by Brody

The ability of the LVDT to produce a complete plot of the string-bed's response was shown to lay in the design of the attachment. The associated mass of the attachment influences the results, and further work in reducing its mass can give more accurate recordings. Nonetheless, the current results show how the deflection varies with time from the ball impact.

The LVDT is now a cost effective means of obtaining data, and multiples can be used in parallel to simultaneously measure more points on the string-bed. The comparison of the LVDT's measurement of the response with the recording by the HSC suggests that the LVDT provided accurate results. The dwell time was estimated by taking measurements from the LVDT plot. The length of time measured by the LVDT is in agreement with Brody's results.

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