Feel & Control in Tennis: Modal Analysis of Tennis Rackets

System Tailoring for 'Feel and Control'

Tennis • Feel • Experimental Modal Analysis

Fall 2023

Ray Ewry Sports Engineering Center

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Abstract

Feel and control for a tennis racket are incredibly important to a tennis player as the racket acts as an extension of the player's hand. While important, feel and control are largely subjective parameters making design criteria difficult to satisfy. This project aims to quantify feel and control, bridging the gap between the subjective player experience and racket engineering while understanding the racket components that constitute feel. The prior year's literature review identified the parameters of feel in tennis rackets to be nervousness, shock, plow-through, and soundwave properties. These feel components are further manipulated in racket construction through stiffness, mass distribution, and damping. This semester, an apparatus consisting of an impact hammer and uniaxial accelerometer was constructed to perform experimental modal analysis on different rackets to draw conclusions on how these racket properties relate to the identified feel parameters. From this setup, shock and nervousness were able to quantified, while modal analysis provided the natural frequencies, damping, and mode shapes of the structure, enabling comparison. The validity of the results was ensured through a repeatability assessment. Figure 1 is an example of how the repeatability was evaluated by observing the distribution and the repeatability coefficient with the natural frequency parameter.

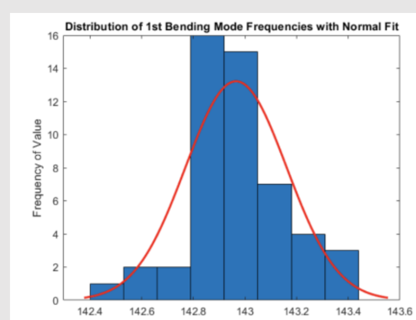

Fig. 1: Example of Repeatability Assessment

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Project Overview

The objective of this project is to build a bridge between the theoretical work developed with the literature review to experimental results. This semester's goals were to design an apparatus to conduct experimental modal analysis. This procedure would generate experimental data in characterizing the natural characteristics of rackets (such as natural frequency) and allow for calculations for the parameters of feel introduced in the literature review.

This semester, the team worked to establish a standardized testing procedure that is conducive to consistent and accurate results. Additionally, in supporting the user-friendly nature of handling multiple and large data sets, a GUI was designed. Currently, the team is conducting tests to observe the overall dynamic characteristics of rackets and ensuring the natural characteristics are consistent with reported values (such as natural frequency) to make sense of the values retrieved in the experimental setup.

The target goal overall of the project is to be able to test and compare multiple rackets with the testing procedure. Additionally, the team plans to integrate with the team designing unique dampers to understand how the dampers affect the racket dynamics. In the future, the team would like to make sense of the quantitative data to qualitative data shared by tennis players according to what they 'feel' with various racket constructions.

Project Method and Results

The experimental testing apparatus consisted of a force transducer tipped hammer, uniaxial accelerometer, two rubber bands freely suspending a racket, NI DAQ, and a computer running DAQ Express (Fig. 2). From this setup, a roving impact experimental modal analysis procedure was implemented, impacting rackets at 19 and 23 different locations for 16x19 and 18x20 string patterns, respectively. Each location was recorded 3 times, ensuring a single impact and proper force were used for each impact.
The force vs time and acceleration vs time signals from each recording were then exported as CSV files from DAQ Express into MATLAB for postprocessing. A MATLAB GUI was created to take the three CSV files from each location and output the associated and average Fourier response functions (FRFs), using the modalfrf function in MATLAB (Fig. 3). The MATLAB modalfrf and modalfit functions generated calculations for the natural frequencies, damping ratios, and mode shape vectors. Additional parameters in this study that are under investigation, such as shock, nervousness, and damping rate, required functions to be individually coded.

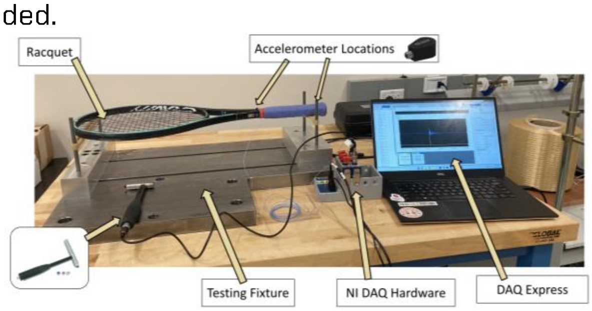


Fig. 2: Experimental testing setup

Project Method and Results (cont.)

Shock was calculated by identifying the peak acceleration point from impact and multiplying it by mass to observe the quantity as a unit of force in newtons. Because the hammer cannot be controlled to induce precise levels of excitation, a shock ratio calculation was created to have a measurement comparing the level of shock experienced relative to the force exerted by the hammer. The next parameter, nervousness, was assessed by calculating the area under the acceleration response post-impact until the 2% settling time. The damping rate is computed from understood dynamics as function of the damping ratio and modal frequency.

Three different rackets were tested, and their results were recorded from the handle accelerometer location. This location was chosen since it is where tennis players hold the racket and ultimately feel the vibrations of the racket. The three rackets were the Head Gravity Pro, Head Protect, and Wood All Pro. The natural frequency of the Head Gravity Pro was available to the team, allowing for the results to be verified by observing the frequency of the first bending mode from the averaged frequency response.

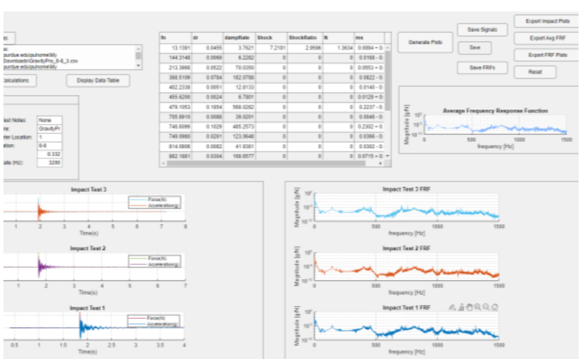


Fig. 3: MATLAB GUI results for Head Gravity Pro at Impact Location 6-8

Additionally, the Head Gravity Pro was tested with 5 different silicone handle damper inserts (1 made from DS10, 2 from DS20, and 2 from DS30). These dampers targeted the 2nd bending mode for the Gravity found from the setup and were created by the handle design team.

From these tests, the unmodified Head Gravity Pro recorded the greatest shock and shock ratio values of 38.15 N and 4.00 respectively at location 10-18. The Wood All Pro racket recorded the greatest nervousness measurement of 2.68 N*s at location 6-20.

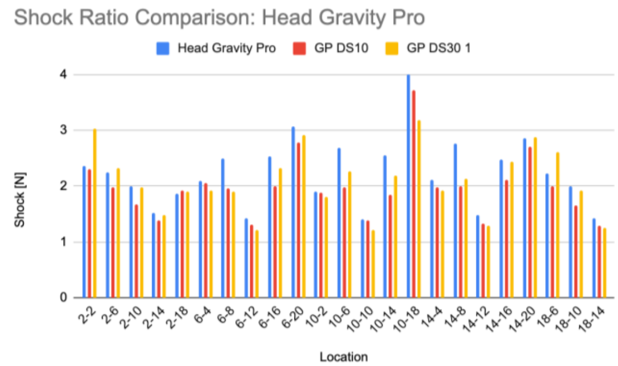


Fig. 4: Average recorded shock levels at each location for the Gravity Pro, DS 10, and GP DS 30 1

While the DS10 and DS30 1 dampers were found to effectively decrease the overall average recorded shock levels by 16.45% and 40.66% respectively, seen further in Figure 4. The significance of this data is still being evaluated as the team creates a better way to normalize inconsistent force inputs across locations.

Conclusions and Future Work

- This project aims to quantify feel and control, bridging the gap between the subjective player experience and racket engineering. Parameters of feel in tennis rackets include nervousness, shock, plow-through, and soundwave properties. These are further manipulated in racket construction through stiffness, mass distribution, and damping.
- Experimental modal analysis is an approach used to identify the dynamic properties of structures using decoupled modes consisting of natural frequency, damping, and mode shapes. This study includes additional individualized functions to calculate a full-encompassing list of 'feel' parameters.
- Future work entails expanding testing to additional racket models to evaluate trends across advertised benefits and draw conclusions on how different materials, technologies, and physical properties affect vibrational response.

Ray Ewry
Sports Engineering Center

About RESEC

The Ray Ewry Sports Engineering Center (RESEC) is named in honor of a record-setting Olympian and College of Engineering graduate, Ray Ewry. As a joint effort between Purdue College of Engineering and Intercollegiate Athletics, the center reflects Ewry's passion for both sports and engineering and creates research and learning opportunities to athletes and students alike.

What is Sports Engineering?

Sports Engineering is a multidisciplinary field that uses engineering principles to create solutions to the greatest challenges and opportunities facing sports today. The field utilizes scientific theory, practical application, and technical knowledge to address sports-related challenges through data-driven insights and a results-oriented approach. To contribute to this field RESEC aligns it's investigations with the following priorities

EXCITEMENT
Smart Performance & Fan Experience

How can we use the latest sensors, signal processing, and analytics to improve athlete performance and improve engagement with fans?

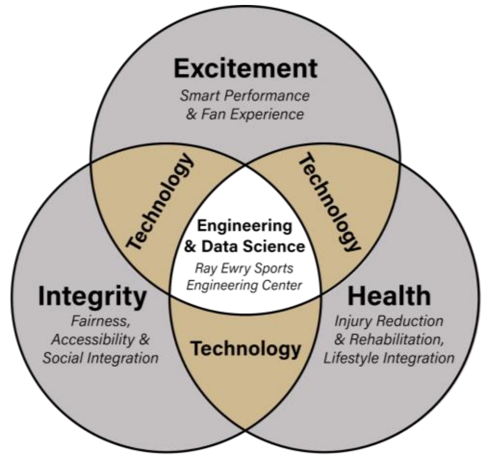
INTEGRITY
Fairness, Accessibility & Social Integration

As technology in sports grows, what are the limits of human judgement, and how do we develop technology to ensure a level playing field?

HEALTH
Injury Reduction & Rehab, Lifestyle Integration

What aspects of advanced healthcare and science can be engineered into solutions for sports rehabilitation and performance?

Every sport must balance these priorities to create the best experience for all. RESEC searches for the technology to fill the gaps between each priority and facilitates collaborative research across Purdue through the application of engineering and data science



Research Technology Platforms

RESEC categorizes industry partners and academic affiliates into the following technology platforms for scaling and implementation to streamline collaboration.

- **Smart Materials for Performance and Safety**
- **Accessible Technology for Societal Integration**
- **Equipment Design for Athlete Feel and Control**
- **Intelligent Prototyping for Rapid Development**
- **Digitalization of Sports Ecosystems**
- **Spectator Experience and Fan Engagement**

When ideas arise from industrial partners or internal faculty affiliates, RESEC facilitates the operations necessary turn opportunities into action.

Education Offerings

Purdue's academic prowess offers a unique opportunity to engage talented students, staff and faculty members with sports engineering. In addition to research opportunities for undergraduate and graduate students, RESEC is proud to offer the first comprehensive Professional Masters Concentration in Sports Engineering in the United States. With these capabilities, we are equipping the next generation of sports engineers to redefine what's possible.

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