20th IMEKO TC10 Conference
"Measurement for Diagnostics, Optimization and Control to Support Competitiveness and Innovation"
Lisbon, Portugal, September 28–29, 2026

Vibration Characterization of Gamepad Haptic Actuators: A Multi-Axis Measurement Approach with Spectral and Thermal Investigation

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Abstract **– This paper presents an extended investigation building upon a previously validated compact multi-axis vibration measurement platform for the characterization of haptic actuators in consumer gamepad controllers. Three MPU-6500 MEMS accelerometers interfaced to an RP2040 microcontroller via SPI enable synchronized tri-axial acceleration acquisition at up to 2 kHz across spatially distributed measurement points. Three controllers representing distinct actuator technologies were characterized: the Xbox One S using eccentric rotating mass actuators, and the Sony DualSense and GameSir Nova HD Rumble, both employing voice coil actuators. A custom Python-based spectral analysis tool implementing the Discrete Fourier Transform with automatic and manual window selection was developed for frequency feature extraction. VCA-based controllers exhibited fixed dominant frequencies invariant to commanded intensity, while ERM actuator frequency increased progressively with drive level. Thermal characterization comprised direct thermal imaging of an opened ERM controller under sustained operation, and pre- and post-heating vibration measurements across all three controllers. Thermal imaging revealed no motor heating detectable within camera accuracy, while vibration measurements yielded inconclusive results for most controllers, with a frequency shift observed in one ERM actuator following thermal loading.**

Keywords – Vibration Measurement, Accelerometer, Haptic Feedback, Gamepad Controller, Industry, Innovation and Infrastructure

I. INTRODUCTION

Haptic feedback has become a standard feature of consumer gaming peripherals, providing a tactile communication channel that complements visual and auditory outputs. Despite its widespread deployment, the physical vibration profiles produced by gamepad actuators remain insufficiently characterized in quantitative terms, and objective, repeatable measurement is a prerequisite for correlating haptic signal structure with user experience and for enabling principled actuator selection and design.

This work presents an extension of previously established research involving a compact multi-axis vibration measurement platform intended for characterization of gamepad haptic systems [1]. Earlier development stages demonstrated the feasibility of simultaneous multi-point vibration measurements on controllers employing both eccentric rotating mass (ERM) and voice-coil-based haptic actuators. Previous investigations confirmed that the measured vibration profiles exhibit clear spatial differentiation depending on actuator placement and excitation conditions, while the RMS-derived vibration magnitude provides a robust, orientation-independent metric for comparative analysis. The present work builds directly on this validated foundation, extending the scope of investigation to thermal operating conditions and frequency-domain characterization of the acquired signals.

II. RELATED RESULTS IN THE LITERATURE

Haptic feedback in gaming peripherals has been approached from a number of different angles in the existing literature. The perceptual and communicative dimensions of gamepad vibration have been explored in [2], where an structured typology of rumble as a medium of expression in gaming contexts is provided, though without quantifying the underlying physical actuator parameters. On the measurement side, [3] examines human exposure to vibration from video game controllers, however the results are reported in relative, comparison-based terms rather than absolute physical quantities, and certain methodological aspects are not fully specified, which limits repeatability and quantitative interpretation.

The sensor employed in the present platform (MPU family) has been comparatively evaluated against alternative low-cost accelerometers under random vibration inputs in [4], demonstrating superior inter-axis uniformity and smaller reading deviations, supporting its suitability for vibration characterization applications. While alternative approaches exist, the combination of spatially distributed multi-axis sensing, controlled excitation, and absolute physical measurement adopted in this work provide a repeatable and hardware-accessible foundation for thorough, quantitative measurement.

III. DESCRIPTION OF THE METHOD

A. System implementation

The measurement platform is built around a Raspberry Pi Pico board (RP2040 dual-core Arm Cortex-M0+, 133 MHz, 264 kB SRAM) interfacing two MPU-6500 three-axis inertial measurement units via a shared SPI bus. The MPU-6500 integrates a MEMS capacitive accelerometer with a 16-bit ADC providing simultaneous sampling across all three axes, configured to a ±4 g measurement range, selected experimentally to preserve full dynamic range while avoiding register overflow at actuator saturation.

The firmware for the original prototype was initially implemented in MicroPython, which proved insufficient for deterministic acquisition due to interpreter scheduling overhead. The implementation was migrated to C using the RP2040 SDK, achieving a sustained 2 kHz sampling rate with deterministic interrupt-driven timing, a rate motivated by the Nyquist criterion applied to the harmonic content of the actuator types under investigation.

B. Controller excitation and measurement configuration

Measurements were conducted on three gamepad controllers, each employing a different haptic actuator technology: the Xbox One S controller, which uses eccentric rotating mass actuators (ERM); the Sony DualSense controller, which uses broadband voice coil actuators (VCA); and the GameSir Nova HD Rumble controller, which utilizes a different model of linear broadband Voice Coil Actuator (VCA). The GameSir Nova HD Rumble was selected as a controller marketed as a device designed to be compatible with the Nintendo Switch platform, which at the same time also supports connection to a computer in a separate mode where it is recognized as a standard PC controller.

These three controllers were selected to cover the main actuator technologies currently used in consumer gaming peripherals, enabling comparison of their vibration characteristics under identical measurement conditions.

The sensors are mounted at the left grip and right grip, enabling spatially resolved simultaneous measurement of vibrations generated by each actuator. Physical attachment uses elastic bands rather than rigid adhesive fixings, minimizing mechanical damping (Fig. 1).

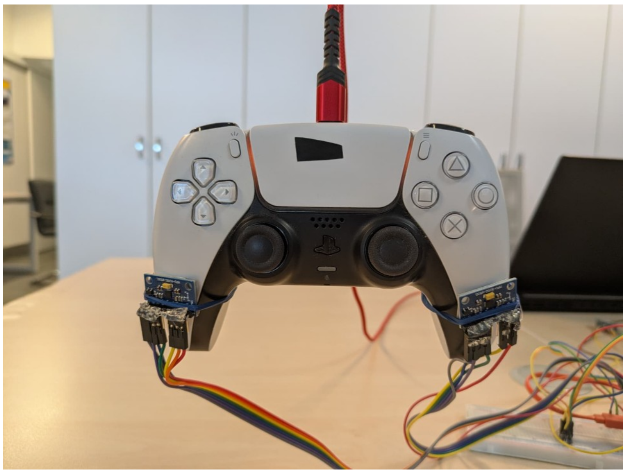

Fig. 1. Sensor placement of the measurement system shown on the Sony DualSense controller.

Measurements are conducted with the controller in a free-hanging suspended configuration, secured at a fixed distance of 10 cm from the suspension point along the cable. Although the controllers use different connectors (USB-C for the Sony DualSense and GameSir Nova HD Rumble; and micro-USB for the Xbox One S), cables of the same model and manufacturer were used throughout, differing only in connector type. This ensured consistent mechanical suspension properties across all measurements. A static bias calibration is performed at startup by averaging 50 samples per axis per sensor, with element-wise subtraction applied to all subsequent samples, removing both gravity projection due to imperfect sensor orientation and any static zero-g offset.

Controlled haptic stimuli are delivered via a custom Unity editor tool [5], enabling definition of time-varying motor speed profiles with independent intensity control per actuator and configurable stimulus duration, compatible with all three types of analysed controllers.

Measurement repeatability was verified through repeated sensor remounting trials, and a noise baseline was established prior to each session with no motor activity, confirming that recorded vibration signatures are well above the ambient noise floor and attributable solely to actuator operation. Each measurement followed a fixed 4-second temporal structure with a standardized trigger burst, stimulus window, and decay period, applied consistently across all tested controllers.

C. Stimulus conditions

Table 1 summarizes the stimulus conditions measured for each controller. Constant-intensity stimuli were applied across six intensity levels to characterize the relationship between commanded intensity and the resulting vibration frequency and amplitude. Each stimulus was applied to the left actuator alone, the right actuator alone, and both actuators simultaneously. In addition to the constant-intensity conditions, measurements were also performed using linearly increasing and decreasing amplitude profiles, as well as sinusoidally modulated stimuli. However, as frequency extraction via the DFT requires a stationary signal, spectral analysis is only applicable to the steady-state portions of constant-intensity recordings, and the present analysis is therefore restricted to those conditions.

Table 1. Stimulus conditions used for measurements on each controller

Stimulus type	*Description*	*Motor conditions*	*Intensity levels*	*Stimulus duration*
Constant	*Fixed intensity held throughout stimulus*	*Left, Right, Both*	*0.1, 0.3, 0.5, 0.7, 0.9, 1.0*	*2 seconds*

Prior to spectral analysis, the raw acceleration signals are acquired and visualized using a custom Python-based desktop application developed alongside the measurement platform. The application operates through three concurrent threads: one responsible for serial data collection from the RP2040 microcontroller, one for writing the acquired samples to persistent storage, and one for real-time graphical rendering of the incoming signal. For each sensor, the application displays the three individual acceleration axes as well as the computed scalar RMS value, allowing immediate visual inspection of the vibration response during and after each measurement session. An example of the application output is shown in Fig. 2, illustrating a dual-motor constant-intensity measurement acquired from an Xbox controller.

D. Signal post-processing and feature extraction

Frequency extraction via the Discrete Fourier Transform was applied only to signals recorded under constant intensity stimulation. For each recording, the stationary interval of the signal was isolated by excluding the actuator ramp-up and ramp-down transients.

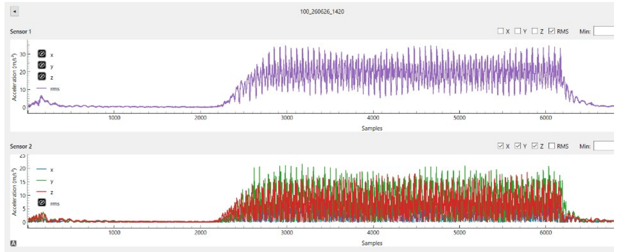

Fig. 2. Dual-Motor Constant Vibration Response of an Xbox One S Controller

The user can manually specify the start and end timestamps of the analysis window, allowing the desired portion of the signal to be selected based on the measurement visualization. The discrete Fourier transform (DFT) was then computed using all samples contained within the selected window. Unlike the fast Fourier transform (FFT), which is computationally most efficient when the number of samples is a power of two, the DFT imposes no such constraint. This allows the analysis window to be of arbitrary length, providing greater flexibility and eliminating the need for the user to adjust the window length solely to satisfy the FFT's computational requirements.

The pipeline was implemented in Python using NumPy for numerical computation and the discrete Fourier transform (numpy.fft), SciPy for envelope filtering and spectral peak detection, pandas for data loading, and Matplotlib for visualization and window verification.

IV. RESULTS AND DISCUSSIONS

The frequency analysis of the Sony DualSense controller is illustrated in Fig. 3, which shows a representative measurement obtained during the mounting repeatability test. This recording incidentally produced one of the clearest examples of spatial vibration dispersion across the device body, and was selected for that reason. Spectral analysis confirms that the left actuator operates at a fixed dominant frequency of 60 Hz, while the right actuator operates at 120 Hz. These frequencies remain constant across all tested intensity levels, with commanded intensity affecting only the vibration amplitude and not the actuation frequency.

Fig. 4 shows the spectral analysis results for the GameSir Nova HD Rumble controller under simultaneous dual-motor excitation at maximum drive intensity. The dominant frequency of the left actuator is identified at 80 Hz, while the right actuator produces a dominant frequency of 135 Hz. As with the Sony controller, both frequencies remain stable across all tested intensity levels.

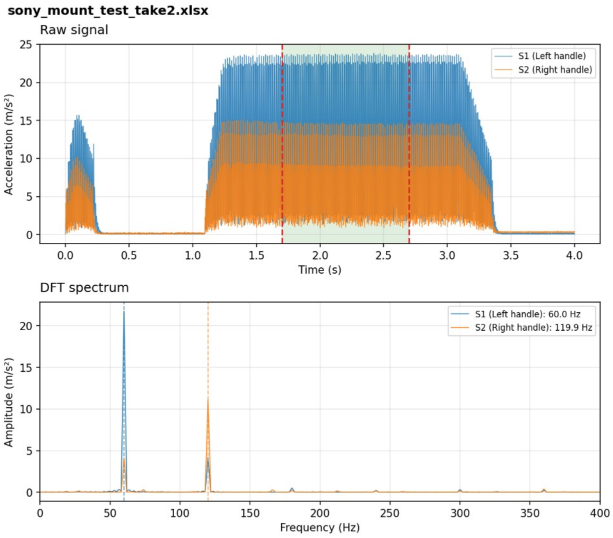

Fig. 3. Spectral Analysis of Sony DualSense Controller

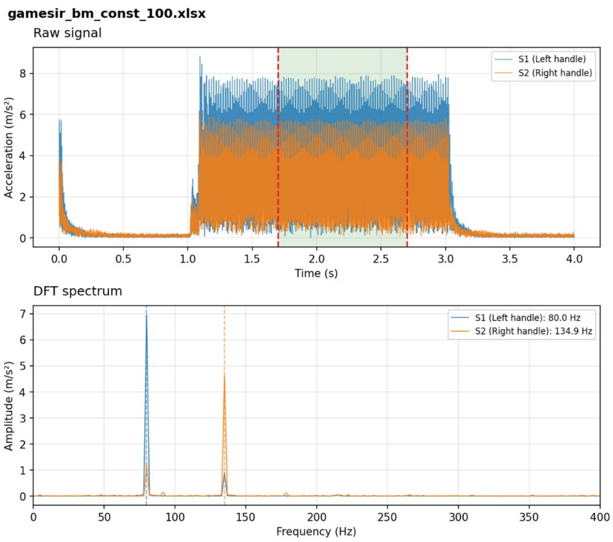

Fig. 4. Spectral Analysis of GameSir Nova HD Rumble Controller

Unlike the VCA-based controllers, the ERM motors of the Xbox controller exhibit a clear dependence of dominant vibration frequency on commanded drive intensity. Fig. 5 summarizes the extracted dominant frequencies across all six tested intensity levels for both the left and right actuators. As drive intensity increases, the dominant frequency of both motors rises progressively, consistent with the speed-torque characteristics of brushed DC motors operating under increasing drive voltage. This behavior distinguishes ERM actuators fundamentally from VCA-based designs.

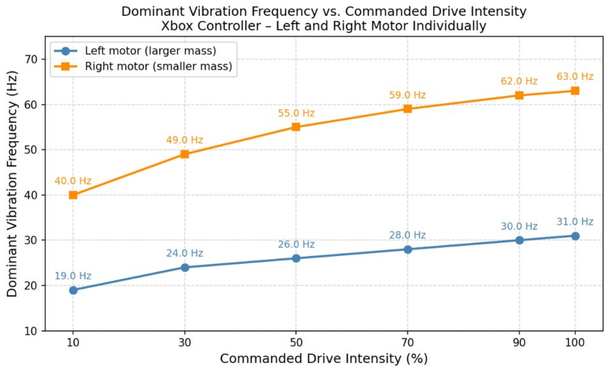

Fig. 5. Dominant Vibration Frequency as a Function of Commanded Drive Intensity

B. *Thermal characterization and analysis*

Thermal characterization comprised two complementary experiments: direct thermal imaging of an opened ERM controller during sustained operation, and pre- and post-heating vibration measurements on the three intact controllers.

A separate Xbox 360 controller, also employing ERM actuators, was used for the opened-controller thermal measurement to avoid disassembling the devices used in the primary characterization. The back side of the case was removed and the actuators secured with zip ties to prevent displacement while allowing unobstructed motor operation (Fig. 6). The controller was then suspended under the same conditions described previously, continuous vibration at maximum intensity was applied to both motors for 3 minutes, and actuator heating was monitored throughout using the FLIR ONE thermal camera [6].

Fig. 6. Xbox 360 controller used for thermal camera monitoring

The opened-controller experiment was conducted on an eccentric rotating mass device, as this actuator technology is usually more mechanically susceptible to heating due to friction in the bearings and continuous rotation of the eccentric mass. Prior to the sustained vibration test, thermal imaging of the ERM-equipped controller was performed while the motors were in a fully quiescent state, establishing a cold baseline thermal profile of the device (Fig. 7).

Fig. 7. Xbox 360 controller thermal image prior to the sustained vibration

Following three minutes of continuous operation at maximum drive intensity, a second thermal image was acquired under otherwise identical conditions. Comparison of the two images revealed no discernible temperature increase in the vicinity of the motor housings. The observed difference of approximately 0.2 °C at the left, larger ERM motor falls well below the measurement uncertainty of the FLIR ONE thermal camera used, which carries an accuracy specification of ±3 °C or ±5% of the full measurement range, whichever is greater. As such, no meaningful thermal loading of the motors can be confirmed from the imaging data alone. The most notable temperature elevation was instead localized to the power regulation circuitry and the main processing unit on the controller board, consistent with resistive losses in the drive electronics rather than in the actuators themselves (Fig. 8).

Subsequently, three controllers used in the main experimental procedure were not opened. Instead, a pre- and post-heating vibration measurement was conducted. The heating stress test between measurements was conducted by constantly vibrating the actuator at maximum intensity for two minutes. This procedure was performed separately for the left and right actuators.

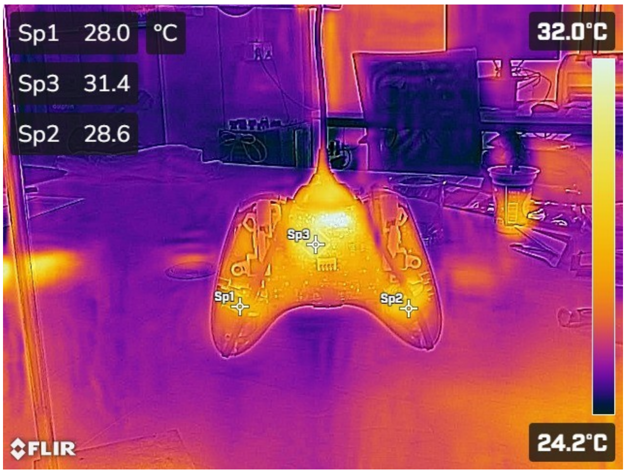

Fig. 8. Xbox 360 controller thermal image following three minutes of continuous operation

For the Sony DualSense, no measurable difference in vibration frequency or amplitude was observed between the cold and post-heating measurements. For the GameSir Nova, the thermal loading protocol could not be completed as intended, as the controller's internal firmware triggered an automatic override that interrupted sustained motor operation after approximately 20 seconds of continuous activity, preventing sufficient thermal loading of the actuators.

For the Xbox One controller, a discernible increase in the dominant vibration frequency was observed in the right motor following the heating period, while the left motor showed no measurable change between the cold and post-heating conditions. The observed frequency shift is documented in the figures below (Fig. 9, Fig. 10) and is noted as a subject for further investigation.

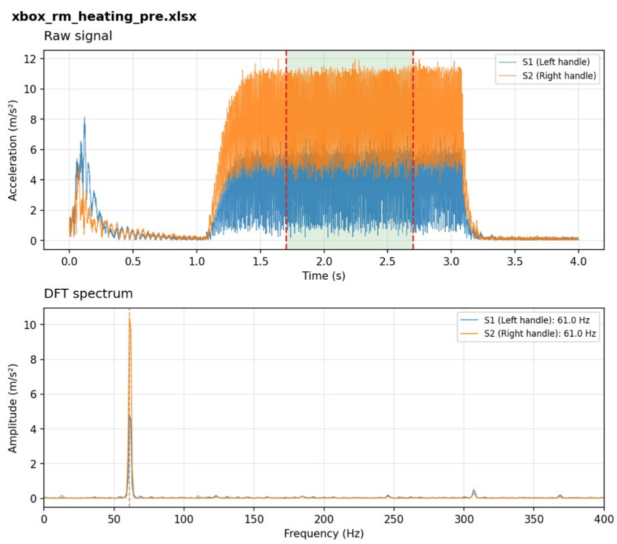

Fig. 9. Xbox One frequency analysis before sustained vibration

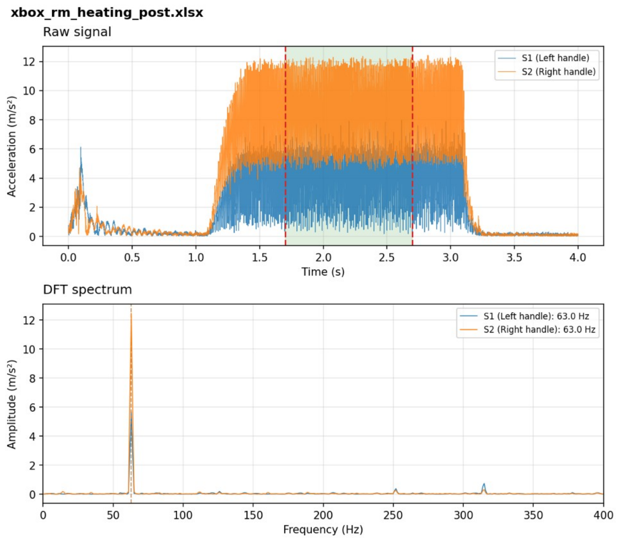

Fig. 10. Xbox One frequency analysis following sustained vibration

V. CONCLUSIONS AND OUTLOOK

This work presented an extension of a previously validated multi-axis vibration measurement platform applied to the characterization of haptic actuators in consumer gamepad controllers. The system demonstrated reliable signal acquisition across actuator types, and the developed post-processing tooling enabled structured spectral feature extraction from the collected signals.

For ERM actuators, both frequency and amplitude increased with commanded intensity, as both are directly coupled to motor speed. The left actuator, carrying a larger eccentric mass, produced greater amplitude but lower rotational speeds; the smaller right actuator reached higher frequencies at equivalent drive levels.

For both VCA controllers, dominant frequency was invariant to commanded intensity, with amplitude alone scaling with drive level. The two actuators within each controller exhibited distinct fixed frequencies. Comparing the Sony DualSense against the GameSir Nova HD Rumble revealed clear differences: the DualSense produced substantially greater amplitude at a lower dominant frequency, while the GameSir exhibited weaker vibrations at a higher dominant frequency.

This study has several limitations that should be considered when interpreting the findings. Firstly, the full capability of the voice coil actuators could not be exploited, as amplitude and frequency could not be controlled independently. Game consoles communicate with their proprietary controllers through dedicated interfaces that permit direct specification of amplitude and frequency, enabling the rich haptic effects these actuators are designed to produce. Such higher-level control over these actuators is available to licensed developers through platform-specific software development kits and console-specific game engine packages. On general-purpose PCs, however, the command path from the game engine through the driver to the controller permits only a single normalized value between 0 and 1 per motor, which can be varied over time, meaning the measurements reflect the constrained PC interface rather than the actuator's full physical capability.
However, since most PC gaming operates through exactly this constrained path, the results accurately characterize what PC users actually experience. This makes the findings particularly relevant for PC gaming contexts, and motivated the inclusion of both VCA controllers despite the interface limitations.

VI. ACKNOWLEDGMENTS

This research has been supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-34/2026-03/200156) and the Faculty of Technical Sciences, University of Novi Sad through the project "Scientific and Artistic Research Work of Researchers in Teaching and Associate Positions at the Faculty of Technical Sciences, University of Novi Sad 2026" (No. 01-3609/1).

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