

Labview-Based Virtual Instrumentation for Seismic Building Vibration and Structural Damage Monitoring

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Abstract— Continuous structural health monitoring is vital for assessing civil infrastructure integrity under seismic excitations and environmental degradation. Traditional manual visual inspections are periodic, qualitative, and incapable of capturing transient dynamic responses. This paper presents a virtual instrumentation framework developed in LabVIEW for real-time seismic vibration simulation, dynamic response monitoring, and structural damage detection. A base-excited single-degree-of-freedom mass-spring-damper model is implemented to simulate structural dynamics under ambient shaking, resonance, sudden stiffness reduction, structural tilt, and pseudo-random earthquake ground motion. The virtual instrument tracks critical dynamic indicators including fundamental natural frequency, roof-to-base transmissibility ratio, instantaneous roof acceleration, and tilt angle, triggering a multi-criteria threshold alarm logic upon abnormal state detection. Simulation findings demonstrate that a 48.5% loss in lateral stiffness (from 1300 N/m to 670 N/m) induces a 0.51 Hz downward shift in natural frequency (from 1.81 Hz to 1.30 Hz), confirming frequency tracking as a sensitive damage indicator. A proposed hardware acquisition architecture incorporating dual MEMS accelerometers (ADXL345 and MPU6050) interfaced via microcontroller serial streaming to LabVIEW VISA is documented. This prototype provides an educational testbed for structural dynamics and non-destructive damage diagnosis.

Keywords: Virtual instrumentation, LabVIEW, structural health monitoring, seismic vibration, resonance, MEMS accelerometer.

I. INTRODUCTION

Civil engineering structures such as multi-story residential towers, commercial complexes, transportation viaducts, and offshore installations are subjected to continuous dynamic environmental and operational forces throughout their service lives¹. Among these loading regimes, seismic excitations represent the most severe and unpredictable hazard, transmitting substantial kinematic energy through the ground directly into foundation footings³. The resultant physical response within the superstructure is dictated by the distribution of its structural mass, lateral elastic stiffness, and energy dissipation mechanisms, typically represented as equivalent

viscous damping³. When ground excitations possess spectral energy concentrated near the fundamental natural frequency of the structure, resonance occurs, yielding extreme dynamic amplification factors that induce excessive inter-story drift, plastic hinge formation, joint loosening, and catastrophic structural failure³. The maintenance of modern civil infrastructure has historically relied on manual visual inspections conducted at periodic intervals or immediately following major seismic events¹. However, visual evaluations exhibit inherent limitations: they are labor-intensive, hazardous to personnel, qualitative in nature, and incapable of detecting internal material micro-cracking, foundation settlement, or unseen stiffness degradation until macro-scale structural defects manifest on accessible exterior surfaces⁶. Consequently, structural health monitoring (SHM) has emerged as an indispensable paradigm, facilitating non-destructive, continuous, and automated condition

assessment through the tracking of physical and modal parameters over time². A primary challenge in engineering education and prototype validation is the capital expense and operational complexity of dedicated, rack-mounted dynamic signal analyzers and laboratory shake tables⁵. Virtual instrumentation offers an effective solution to this challenge by combining modular computing hardware,

reconfigurable data acquisition interfaces, and graphical software architectures¹⁰. National Instruments LabVIEW provides a dataflow-driven visual programming environment that integrates numerical simulation, hardware interface drivers, real-time signal processing, and customizable graphical user interfaces¹⁰. This paper details the design, numerical formulation, and implementation of a virtual instrument developed in LabVIEW for seismic building vibration analysis and structural damage detection⁵. The framework models a base-excited single-degree-of-freedom (SDOF) mass-spring-damper mechanical oscillator, visualizing structural acceleration responses, estimating modal and orientation parameters, and executing multi-criteria threshold alarm logic across multiple operational regimes⁸. Furthermore, an integration pathway utilizing low-cost micro-electro-mechanical systems (MEMS) accelerometers and embedded microcontrollers is established⁵. It is explicitly emphasized that the current investigation demonstrates a software-based numerical simulation and laboratory instrumentation concept rather than a field-certified commercial SHM deployment⁸.

II. LITERATURE REVIEW

Vibration-based damage identification is founded on the structural dynamics principle that damage-induced modifications to physical properties—specifically lateral stiffness, boundary constraints, or effective mass—manifest directly as observable perturbations in structural modal parameters, including natural frequencies, modal damping ratios, and mode shapes¹⁴. In their seminal survey, Doebling et al. systematically reviewed vibration-based non-destructive damage detection techniques across civil, mechanical, and aerospace infrastructures, classifying methods according to their reliance on modal parameter shifts, frequency response functions, or finite

element model updating¹⁴. Salawu provided a comprehensive analysis of structural damage identification through shifts in natural frequencies, establishing that while natural frequencies can be measured with high experimental repeatability and minimal sensor counts, global frequency tracking exhibits localized spatial insensitivity unless supplemented by spatial curvature or multi-sensor response ratios¹⁶. Farrar and Worden formalized the statistical pattern recognition paradigm for structural health monitoring, defining a four-stage hierarchical process encompassing operational evaluation, data acquisition and cleansing, feature selection and extraction, and statistical model development for feature discrimination¹⁴. Within this paradigm, damage is characterized as an anomaly relative to an established undamaged baseline state⁶. Brownjohn underscored that long-term monitoring of civil infrastructure requires capturing both environmental variability and structural operational profiles, pointing out that temperature fluctuations and foundation adjustments frequently introduce benign natural frequency variations that must be distinguished from permanent structural degradation⁵. Transmissibility functions and roof-to-base response ratios have been widely adopted to evaluate structural amplification without requiring precise measurement of applied seismic input forces¹⁸. Deraemaeker et al. demonstrated that transmissibility functions calculated between operational degrees of freedom provide reliable indicators of localized structural changes under ambient or base-excited conditions, serving as effective non-model-based diagnostic features¹⁸. Concurrently, advancements in micro-electro-mechanical systems (MEMS) technology have transformed structural instrumentation⁹. Lynch and Loh reviewed the integration of wireless and digital MEMS sensors for infrastructure health assessment, emphasizing that miniaturized, low-power capacitive accelerometers offer adequate dynamic range, DC response capability, and noise floors suitable for civil structural monitoring at a fraction of the cost of traditional force-balance accelerometers⁹. Multiple studies have successfully integrated MEMS sensors such as the Analog Devices ADXL345 and InvenSense MPU6050 with embedded microcontrollers to monitor bridge deflections, pipeline leaks, and laboratory scale frames¹². In the domain of virtual instrumentation, LabVIEW has been established as an industry standard

for structural dynamics research and condition monitoring. Researchers have utilized LabVIEW's graphical architecture to execute synchronized multi-channel data acquisition, Fast Fourier Transforms (FFT), digital filtering, and automated threshold alerts for machine tool wear prognostics, drillstring vibration diagnosis, and seismic shake-table control¹⁰. Despite these advances, an educational and experimental research gap persists: conventional commercial monitoring suites operate as proprietary closed systems, separating theoretical equations of motion from real-time visualization and physical sensor hardware⁸. This work addresses that gap by presenting a transparent, modular LabVIEW virtual instrument that bridges continuous numerical dynamic simulation with an embedded MEMS hardware acquisition architecture⁸.

III. THEORETICAL BACKGROUND AND MATHEMATICAL FORMULATION

1. Equation of Motion for Base-Excited Single-Degree-of-Freedom Systems

To capture the fundamental lateral dynamic behavior of a multi-story building subjected to ground shaking, the structure is idealized as a lumped-parameter single-degree-of-freedom (SDOF) mass-spring-damper mechanical oscillator⁸. In this idealization, the building's floor and roof slabs contribute the effective lumped mass, the vertical structural columns and shear walls provide the lateral restoring stiffness, and structural materials along with non-structural partitions provide equivalent viscous energy dissipation⁸. Let denote the absolute displacement of the ground foundation, and let denote the absolute lateral displacement of the lumped roof mass¹⁰. The relative displacement of the roof with respect to the moving ground base is defined as: Differentiating with respect to time yields the relative velocity and relative acceleration ¹⁰. The forces resisting the motion of the roof mass include the internal elastic restoring force and the viscous damping force , where represents the lateral stiffness and denotes the viscous damping coefficient⁸. Applying Newton's second law of motion to the absolute inertial motion of the roof mass yields: Substituting into the dynamic equilibrium equation produces: Rearranging the inertial base acceleration component to the right-hand side establishes the

standard governing differential equation of motion for a base-excited SDOF system⁸: where represents the instantaneous ground acceleration⁸. The effective dynamic excitation force acting on the relative structural degree of freedom is an inertial d'Alembert force proportional to structural mass and base acceleration¹⁰.

2. Modal Parameters and Degradation Modeling

Dividing the equation of motion by the effective mass normalizes the governing dynamic equation into standard modal form¹⁰: where represents the undamped circular natural frequency in radians per second and denotes the dimensionless viscous damping ratio⁸. These modal quantities are mathematically defined as: The nominal baseline parameters selected for the healthy structural model are an effective lumped mass of , a lateral elastic stiffness of , and a viscous damping ratio of , which represents 5% of critical damping typical for reinforced concrete structures⁸.

Evaluating the fundamental natural frequency of the healthy reference state yields: The corresponding equivalent viscous damping coefficient for the undamaged model is: In the event of seismic damage, yielding of reinforcement bars, concrete spalling, or column joint degradation produces a localized loss of lateral load-bearing capacity, modeled as an overall reduction in structural stiffness while the effective structural mass remains constant⁵.

For the simulated damage scenario, the lateral stiffness is reduced to 8. Recalculating the degraded natural frequency: The physical reduction in stiffness induces a downward shift in the fundamental natural frequency: Because , an elastic stiffness loss of 48.46% produces a 28.2% reduction in operational cyclic frequency, providing a measurable dynamic indicator of structural distress⁸. Parameter Notation Healthy Baseline Damaged State Units Physical Interpretation Lumped Mass 10.0 10.0 Effective inertial mass of floor and roof slabs⁸ Lateral Stiffness 1300.0 670.0 Combined restoring stiffness of lateral columns⁸ Damping Ratio 0.05 (5%) 0.05 - Energy dissipation ratio relative to critical⁸ Natural Angular Frequency 11.40 8.19 Circular natural frequency of oscillation⁸ Natural Cyclic Frequency 1.81 1.30 Fundamental cyclic resonance

frequency8 Damping Coefficient 11.40 8.19 Viscous
dissipation coefficient8 Natural Period 0.551 0.768
Fundamental natural period of vibration10

3. Dynamic Amplification and Transmissibility Indicators

Under steady-state harmonic base excitation, the total absolute acceleration experienced at the roof level is 10. The virtual instrument defines the dimensionless response transmissibility indicator as the peak-to-peak ratio between roof acceleration and base excitation8: From steady-state vibration theory, the theoretical absolute acceleration transmissibility for a base-excited linear oscillator is expressed as10: where represents the excitation frequency ratio10. At exact resonance (), this expression simplifies to: For light structural damping (), the term, yielding the dynamic amplification approximation10: This theoretical derivation demonstrates why lightly damped structures exhibit roof accelerations an order of magnitude larger than ground accelerations during resonant seismic excitations8.

4. Gravitational Tilt Estimation

Under static or quasi-static conditions, a triaxial MEMS accelerometer senses the local gravitational acceleration vector projected onto its internal orthogonal sensing axes5. When a building suffers foundation settlement or structural tilting, the orientation of the top-mounted sensor changes relative to the gravitational field8. The resulting inclination angles—roll () and pitch ()—are derived using trigonometric projections8: During dynamic ground motion, lateral inertial accelerations corrupt these static projections; thus, practical tilt estimation requires dedicated low-pass filtering to isolate gravitational components from dynamic vibration8.

IV. SYSTEM ARCHITECTURE AND PROCESSING FRAMEWORK

The system architecture is structured into two complementary operational pipelines: the verified software simulation environment executed within LabVIEW, and a proposed physical hardware data acquisition pipeline designed for scale-model instrumentation8. In the simulation pipeline, operation commences with user selection of an active operating mode via the Front Panel interface8. The software

computes instantaneous ground acceleration profiles, evaluating continuous sinusoidal functions for harmonic excitations or pseudo-random arrays for earthquake ground motions8. These synthetic ground motions drive the numerical integration of the base-excited differential equation of motion, calculating the relative structural response8.

Absolute base and roof accelerations are derived, from which diagnostic indicators—including the operational natural frequency, transmissibility ratio, and inclination angle—are extracted8. These metrics are continuously checked against threshold-based alarm rules, driving graphical waveform charts, numerical indicators, and boolean annunciators on the user interface8. The proposed physical hardware pipeline establishes a transition path from numerical simulation to laboratory experimental testing8.

An Analog Devices ADXL345 triaxial digital accelerometer mounted to the shake-table moving carriage captures base input acceleration, while an InvenSense MPU6050 sensor mounted on the building roof captures the structural response and orientation8. A local microcontroller reads both sensors synchronously across a shared digital bus and formats the readings into structured ASCII records8. These records stream across a USB serial bridge into the host computer, where the LabVIEW Virtual Instrument Software Architecture (VISA) driver parses the incoming data streams, routes acceleration channels to charting and feature extraction routines, evaluates alarm conditions, and archives time-history records to disk8.

The hardware architecture accommodates two alternative microcontroller configurations: an Espressif ESP32 and an Arduino Mega or Uno platform8. Because signal levels, bus peripherals, and timing loops differ between these microcontroller architectures, their pin maps and firmware configurations must be maintained as distinct, non-interchangeable implementations8.

1. System Specification

ESP32 Implementation Variant Arduino Mega / Uno Variant

Units / Standard Core Architecture 32-bit Xtensa Dual-Core LX6 8-bit ATmega328P / ATmega2560 Embedded Microprocessor Operating Voltage

3.3 5.0 (Requires level shifter) Data Line (SDA) GPIO 21 Pin A4 (Uno) / Pin 20 (Mega) Physical Hardware Pin Clock Line (SCL) GPIO 22 Pin A5 (Uno) / Pin 21 (Mega) Physical Hardware Pin Actuator PWM Output GPIO 25 Pin 9 / Pin 10 PWM Digital Output Pin Alarm Relay Trigger GPIO 26 Pin 8 Digital Output Pin Serial Baud Rate 115200 115200 Baud (bps) Firmware Language MicroPython / C++ FreeRTOS Embedded C++ (Arduino IDE) Firmware Environment Sampling Rate Target 100 50–100 () The ESP32 platform natively operates at 3.3V logic levels, permitting direct electrical interfacing with both sensor breakout boards without risk of overvoltage damage⁸. In contrast, the 5V logic employed by standard Arduino platforms necessitates external bidirectional logic level shifters on the clock and data lines to protect sensor input circuitry⁸.

V. VIRTUAL INSTRUMENT SOFTWARE DESIGN IN LABVIEW

1. Front Panel Interface Design

The Front Panel provides an interactive supervisory dashboard designed for real-time observation and parameter adjustment⁸. The operator selects the simulation state via an enumerated control offering choices between Normal, Resonance, Damage, Tilt, and Earthquake modes⁸. Adjacent rotary knobs and numeric controls permit continuous adjustment of excitation frequency across a range of 0.1 to 10.0 Hz and base acceleration amplitude up to 1.5 g⁸. Dynamic behavior is visualized on a dual-trace waveform chart that simultaneously displays base input acceleration and roof response acceleration, making phase relationships and amplitude amplification directly apparent to the user⁸. Digital indicators present real-time numerical estimates of natural frequency, the roof-to-base transmissibility ratio, and structural tilt angle⁸. A high-visibility boolean LED indicator illuminates bright red when any monitored parameter exceeds its safe operating limit, while an adjacent alphanumeric text indicator provides diagnostic context, such as NORMAL, RESONANCE ALERT, STIFFNESS LOSS DETECTED, or EXCESSIVE TILT⁸. A latching emergency stop button ensures clean program termination and deterministic software shutdown⁸.

2. Block Diagram Execution Logic and State Propagation

The Block Diagram provides the computational engine of the virtual instrument, utilizing LabVIEW dataflow execution principles⁸. The primary loop runs continuously under the regulation of a Wait (ms) timing block set to ms, establishing a steady graphical interface refresh rate of 20 Hz⁸. Dynamic continuity across successive loop iterations is maintained using shift registers wired to the loop boundaries⁸. These registers store state variables—including relative structural displacement, relative velocity, and peak response values—ensuring that dynamic history is carried forward into subsequent iterations without numerical discontinuity⁸. To maintain numerical stability during rapid dynamic transients, the software executes ten internal sub-integration steps within each 50 ms execution period, producing an internal integration time increment of 8. Within an embedded Formula Node, relative velocity and relative displacement are updated through finite-difference approximations: A multi-case structure coordinates operational behavior based on the active simulation mode⁸. In Damage mode, lateral stiffness is throttled from 1300 N/m down to 670 N/m⁸. In Resonance mode, excitation frequency is automatically aligned with the fundamental natural frequency⁸. In Tilt mode, an incremental pitch offset is added to simulate foundation settlement⁸. For physical hardware testing, VISA serial read blocks ingest newline-delimited sensor strings, routing parsed acceleration data directly into the display and monitoring subroutines⁸.

3. Monitoring Indicators And Multi-Parameter Alarm Logic

Diagnostic Threshold Criteria

To ensure reliable structural assessment, the virtual instrument evaluates multiple independent physical indicators rather than relying on a single measurement channel⁵. Structural distress can manifest as excessive dynamic deflection, stiffness degradation, foundation settlement, or extreme acceleration bursts⁸. The alarm logic evaluates five condition flags using parallel boolean comparisons: Condition triggers when the estimated tilt angle exceeds a threshold, indicating excessive inclination⁸. Condition activates if the calculated natural frequency shifts more than from the

healthy baseline reference of γ , signaling potential structural softening⁸. Condition monitors the roof-to-base transmissibility ratio, activating when dynamic amplification exceeds 3.58.

Condition guards against severe inertial over-stressing by flagging absolute roof accelerations exceeding 8. Finally, Condition identifies the application of irregular, high-energy earthquake excitation⁸. Diagnostic Criterion Evaluated Parameter Nominal Healthy Value Alarm Threshold Alarm State Evaluation Logic Structural Lean / Tilt Inclination angle Boolean TRUE when Stiffness Degradation Frequency shift () Boolean TRUE when Dynamic Amplification Transmissibility ratio Boolean TRUE when Peak Inertial Response Roof acceleration Boolean TRUE when Seismic Ground Motion Input Excitation Mode Continuous Sine Transient Burst Boolean TRUE in Earthquake mode⁸

2 Decision Logic and Operational Stability

The master alarm state is evaluated using a boolean disjunction that activates when any individual condition flag becomes true: When evaluates to true, the Front Panel alarm LED illuminates and an appropriate descriptive warning message is routed to the status display⁸. Conversely, when all condition flags are false, the master alarm remains inactive and the status indicator displays NORMAL⁸. These threshold values were established specifically for an educational laboratory simulation and physical tabletop scale model⁸.

They do not represent regulatory safety limits for full-scale civil structures⁸. In real-world structures, environmental factors such as diurnal temperature cycles and traffic loading can induce benign natural frequency shifts of up to 5–8%⁵. Operational deployments therefore require statistical data normalization, persistence timers, and noise filtering to prevent false positive alarms⁶.

2. Simulation Results And Comparative Discussion

The virtual instrument was evaluated across its five operational simulation modes to examine dynamic response patterns, indicator tracking, and alarm responsiveness⁸. Simulation Mode Input Excitation Characteristics Structural Parameters Measured Response Indicators Alarm State System Diagnostic

Status Normal Mode Harmonic sine, , , , , Inactive (OFF)
NORMAL: Nominal Operation Frequency Sweep
Stepped sine, , , Peak response at ; Variable SWEEP: Peak
Near Resonance Resonance Mode Harmonic sine, , , ,
, Active (ON) RESONANCE ALERT: High Transmissibility
Damage Mode Harmonic sine, , , , , Active (ON)
DAMAGE ALERT: Frequency Drop Exceeded Tilt Mode
Static / Low-frequency, , , increases to , Active (ON) TILT
ALERT: Lean Exceeds 3.0 Deg Earthquake Mode Multi-
frequency random burst, , , Transient bursts, Active (ON)
EARTHQUAKE: Severe Shaking Detected

3.Steady-State Normal Operation

In Normal mode, the model was excited with a steady harmonic base acceleration at γ and an amplitude of 8. Because the excitation frequency is lower than the natural frequency (γ), the system operates below resonance⁸. The roof waveform exhibited steady sinusoidal oscillations with bounded amplitude⁸. The transmissibility settled at γ , static tilt remained steady at γ , and the estimated natural frequency remained at the nominal 8. All monitored parameters remained within safe operating limits, the alarm LED remained unlit, and the status display confirmed NORMAL operation⁸.

• Stepped Frequency Sweeps and Resonance Amplification

During stepped frequency sweep tests across a range of 0.50 Hz to 4.00 Hz, the system exhibited pronounced frequency-dependent amplification⁸. At low excitation frequencies (γ), the roof tracked the base motion almost unity-for-unity (γ)¹⁰. As the excitation frequency approached the 1.81 Hz natural frequency, response amplitudes grew substantially, peaking near 1.80 Hz⁸. When the input frequency was increased above resonance to (γ), the transmissibility dropped to approximately 8. This response matches theoretical base-isolation behavior, where excitation frequencies exceeding yield vibration attenuation (γ)¹⁰. In Resonance mode, the base excitation frequency was set to γ , matching the natural frequency of the structure (γ)⁸. Over several cycles, energy accumulated within the lightly damped oscillator, amplifying the roof acceleration to approximately ten times the input motion (γ) and driving peak roof accelerations toward 8. The transmissibility threshold (γ) and roof acceleration threshold (γ) were both crossed, triggering the alarm LED and activating the RESONANCE ALERT display⁸.

Returning the system to Normal mode produced an exponential ring-down decay, confirming proper integration of the viscous damping term⁸.

- **Simulated Stiffness Degradation And Natural Frequency Shift**

The Damage mode evaluated structural degradation by reducing lateral stiffness from down to 8. In response, the calculated natural frequency dropped from to 8. The resulting frequency shift of exceeded the configured damage threshold, triggering the alarm LED and updating the status display to DAMAGE ALERT⁸. This result demonstrates the theoretical sensitivity of natural frequency tracking for detecting global structural stiffness loss⁸.

4. Static Tilt And Transient Seismic Bursts

In Tilt mode, an angular offset was introduced to simulate foundation settlement, increasing the inclination angle to 8. Crossing the threshold activated the alarm, confirming independent operation of the tilt monitoring logic⁸. In Earthquake mode, the system was driven with a multi-frequency pseudo-random acceleration burst simulating seismic ground motion⁸. Transient roof accelerations exceeded the threshold, triggering the alarm and verifying the instrument's multi-parameter detection capability⁸.

VI. PROPOSED HARDWARE INTEGRATION AND DATA INGESTION

1. Sensor Placement, Mounting, And Mechanical Rigidity

The planned physical measurement framework incorporates two digital MEMS sensors selected for experimental instrumentation on a laboratory scale frame⁸: an Analog Devices ADXL345 mounted to the shake-table base, and an InvenSense MPU6050 mounted on the top roof slab⁵. The ADXL345 is configured for a measurement range with 10-bit resolution (yielding a sensitivity of approximately 256 LSB/g) to record actual applied ground motions⁸. The roof-mounted MPU6050 utilizes a 16-bit analog-to-digital converter, providing a sensitivity of 16,384 LSB/g at to record subtle roof oscillations and static tilt⁸. To ensure measurement fidelity, sensors must be rigidly attached using mechanical fasteners or stiff cyanoacrylate adhesives rather than compliant

mounting tapes, which can introduce parasitic resonances and attenuate high-frequency dynamics⁸. Furthermore, both sensors must be co-aligned so that their primary measurement axes remain parallel to the direction of shake-table motion⁸. Misalignment introduces cross-axis sensitivity errors that corrupt transmissibility calculations⁸.

Functional Block Proposed Hardware Component Interface Specification Operational Role in Experimental System Foundation Monitoring ADXL345 MEMS Accelerometer Bus (Address: 0x53) Measures true ground/shake-table base acceleration⁸ Roof Slab Monitoring MPU6050 6-DOF Inertial IMU Bus (Address: 0x68) Measures dynamic roof response and static tilt angle⁸ Embedded Acquisition ESP32 Dual-Core Microcontroller 3.3V Logic, Synchronous sensor sampling at 100 Hz; serial streaming⁸ Dynamic Actuator MG995 Metal-Gear Servo Motor PWM Control (, GPIO 25) Drives shake-table kinematic linkage (travel)⁸ Dedicated Actuator Power Regulated 6.0V / 3A DC Supply Common Ground with MCU Isolates servo electrical transients from sensor lines⁸ Host Data Communications USB-to-UART Serial Bridge 115,200 Baud, 8-N-1 Transmits ASCII data packets to PC running LabVIEW⁸ Supervisory Virtual Instrument NI LabVIEW Execution Host VISA Serial Driver API Parses serial records, computes indicators, displays UI⁸

2. Firmware Architecture And Serial Protocol

The embedded acquisition routine was developed in MicroPython for the ESP32 microcontroller⁸. The firmware initializes the bus at a Fast-Mode clock speed, configures the ADXL345 into full-resolution measurement mode, and clears the sleep register bit on the MPU6050⁸. Operating on a deterministic 10 ms timer interrupt loop, the microcontroller samples both sensors at 100 samples per second (⁸). The raw 16-bit signed registers are scaled into engineering units (⁸), and a static tilt estimation is derived⁸. The microcontroller formats these measurements into a newline-delimited ASCII string using a comma-separated syntax: A representative telemetry string transmitted over the 115,200 baud serial connection is:

3. Visa Ingestion And Data Parsing In Labview

On the host computer, the LabVIEW Block Diagram utilizes the Virtual Instrument Software Architecture

(VISA) API to ingest and decode the serial stream⁸. The VISA Configure Serial Port block initializes the COM port to 115,200 baud, 8 data bits, no parity, 1 stop bit, and configures the line-feed character (\n, hex 0x0A) as the packet delimiter⁸. Within the main execution loop, VISA Read captures incoming ASCII packets⁸. The ingestion logic checks that each string begins with the prefix character D and contains exactly ten comma-separated elements, discarding corrupted or incomplete packets caused by buffer contention⁸. Valid packets are parsed into numeric floating-point values using Scan From String, routing acceleration and tilt values directly to the display charts and alarm evaluation subroutines⁸. This physical hardware integration pipeline represents a planned experimental architecture rather than an end-to-end verified deployment⁸.

4. Practical Limitations And Analytical Constraints

A rigorous technical assessment of the presented system highlights several theoretical and practical limitations that govern its application⁸: The single-degree-of-freedom idealization represents a primary theoretical simplification⁸. Full-scale multi-story structures possess distributed mass and elasticity, exhibiting higher-order modal frequencies, inter-story drift distributions, and torsional coupling between asymmetric floor diaphragms¹. Furthermore, material degradation under strong earthquakes exhibits hysteretic, non-linear stiffness degradation rather than idealized, instantaneous linear reductions¹⁰. Calculating structural tilt from accelerometer readings relies on isolating the static 1 g gravity vector⁸. During strong ground motions, horizontal dynamic accelerations corrupt the gravity projection, causing dynamic errors in orientation estimation unless isolated using low-pass filtering or multi-sensor data fusion⁸. Evaluating transmissibility as a ratio of peak responses () is sensitive to baseline sensor noise, high-frequency spikes, and near-zero base acceleration denominators⁵. Production systems require frequency-domain Transfer Function () estimation using cross-spectral density averaging to improve stability¹³. Scale disparities also influence dynamic behavior⁸. Small laboratory scale frames exhibit fundamental natural frequencies between 1 Hz and 20 Hz, whereas large high-rise buildings possess long natural periods with fundamental frequencies well below 1 Hz ()¹⁰. Low-cost

MEMS accelerometers exhibit increased pink noise at frequencies below 0.5 Hz, which can reduce measurement signal-to-noise ratios in tall structures. In inexpensive shake tables driven by hobbyist servomotors, mechanical deadbands, gearbox backlash, and velocity limits distort commanded waveforms⁸. Ground excitation must therefore always be directly measured using a base accelerometer rather than inferred from actuator control signals⁸. Furthermore, natural frequencies in full-scale structures are sensitive to environmental factors, including temperature-induced changes in foundation soil stiffness and material elasticity⁵. Attributing a frequency shift solely to structural damage without environmental compensation can result in false positive alarms¹⁴.

5. Future Research Directions

Future development of this virtual instrumentation platform should focus on transitioning from numerical simulation to validated multi-channel physical testing⁸. Key research avenues include: Parameter estimation can be advanced from time-domain peaks to automated frequency-domain peak picking using real-time Fast Fourier Transforms (FFT) and Welch-method power spectral density (PSD) averaging to track modal frequencies under broad-band ambient excitations⁵. Sensor fusion algorithms, such as discrete-time Complementary Filters or linear Kalman Filters, should be implemented on the embedded microcontroller to fuse gyroscope angular rate integration with low-pass filtered accelerometer gravity vectors, providing dynamic tilt measurements during strong shaking⁸. Expanding the single-mass mechanical frame into a multi-story scale structure equipped with distributed MEMS sensor nodes on each floor will enable empirical extraction of multi-degree-of-freedom operational mode shapes and inter-story drift profiles⁸. Automated baseline tracking should also be incorporated to normalize modal data against ambient temperature, using Shewhart control charts to detect anomalous frequency shifts while minimizing false alarm rates². Transitioning the cabled serial architecture to a wireless sensor network utilizing ESP-NOW, ZigBee, or Wi-Fi MQTT protocols will enable scalable structural monitoring without extensive physical cabling⁹. Finally, interfacing the shake-table controller with international earthquake ground motion databases (such as PEER NGA-West2) will allow playback of recorded seismic

acceleration histories, enabling comparative validation of simulated and physical structural responses⁸.

environment necessary to complete this work⁸.
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VIII. CONCLUSION

This paper presents the design, mathematical formulation, and implementation of a virtual instrumentation framework developed in LabVIEW for seismic building vibration analysis and structural damage detection⁸. By integrating a base-excited single-degree-of-freedom mass-spring-damper numerical model with an interactive user interface, the system simulates and visualizes structural dynamics under normal shaking, resonant amplification, stiffness degradation, structural tilt, and pseudo-random earthquake ground motion⁸. The virtual instrument extracts key operational indicators—including fundamental natural frequency, roof-to-base transmissibility ratio, instantaneous roof acceleration, and inclination angle—evaluating them through multi-criteria threshold alarm logic⁸. Simulation results confirm theoretical dynamic relationships: driving the structure near its 1.81 Hz natural frequency induces a resonant amplification factor of approximately 1.5, while a 48.5% loss in lateral stiffness (from 1300 N/m to 670 N/m) produces a measurable 0.51 Hz downward shift in natural frequency (from 1.81 Hz to 1.30 Hz), confirming frequency tracking as a viable indicator of structural distress⁸. A physical hardware integration architecture utilizing an ADXL345 base accelerometer, an MPU6050 roof IMU, an embedded microcontroller, and LabVIEW VISA serial decoding is established to guide future benchtop experimental validation⁸. The platform serves as a modular, cost-effective instrumentation prototype and educational testbed, providing a foundation for future research into multi-degree-of-freedom civil structural health monitoring⁸.

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