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Development Of A Cost-Effective Multi-Channel Arduino-Based System For Whole-Body Vibration Analysis Across Human Body Segments

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Abstract:

Background: Prolonged exposure to whole-body vibration (WBV) is a significant risk factor for musculoskeletal disorders (MSDs), necessitating effective and accessible methods for WBV measurement and analysis.

Objective: This study aims to design and validate a cost-effective, Arduino-based multi-channel vibration analysis system for assessing WBV exposure across multiple body regions.

Methods: A prototype system was developed using ADXL-345 accelerometers and an Arduino Uno microcontroller, emphasizing affordability and user-friendliness. The system integrates seven accelerometers to capture multi-segmental WBV data, enabling the analysis of vibration transmission across different body regions. Data is stored locally on an SD card or transmitted wirelessly via Wi-Fi for further evaluation.

Results: The developed system effectively recorded and stored comprehensive WBV data, enabling detailed analysis of vibration exposure patterns. The findings revealed that the peak vibration transmissibility across body regions predominantly occurred within the 4 Hz to 8 Hz frequency range, a critical range associated with resonance effects in human body.

Conclusion: This study introduces a low-cost, user-friendly tool for WBV assessment, addressing an essential gap in occupational health research and practice. Its affordability and adaptability make it highly suitable for diverse applications, including workplace risk assessment and epidemiological studies.

Keywords: Arduino Based, Body Segmental, Cost Effective, Multi-Channel, Vibration Transmissibility, Whole-Body Vibration.

1. Introduction:

Vibration is a common phenomenon experienced in various occupational and non-occupational activities. Workers operating heavy machinery such as tractors, forklifts, mining equipment, and construction vehicles are frequently exposed to whole-body vibration (WBV) due to continuous movement over uneven terrain. WBV exposure also occurs during activities such as running, jumping, and using exercise equipment like treadmills or vibration plates, which generate oscillatory motion relative to an equilibrium state (Mansfield, 2004). In occupational settings, WBV is a significant health hazard. Its adverse effects are influenced by the duration, intensity, and frequency of exposure. While controlled WBV exposure may have therapeutic benefits, prolonged or high-intensity WBV is closely linked to musculoskeletal disorders (MSDs) such as chronic low back pain, lumbar disc herniation, and muscle fatigue (Sharma et al., 2023). Studies have identified WBV as a critical risk factor for MSDs, contributing to spinal disc degeneration, muscle discomfort, and general fatigue (Bovenzi & Gosselin, 2003). Moreover, chronic WBV exposure has been associated with complications in the circulatory, digestive, and nervous systems (Mansfield, 2004).

A systematic review by Shaikh et al. (2022) identified WBV as the leading risk factor for work-related musculoskeletal disorders (MSDs), followed by poor posture, repetitive motions, lifting tasks, and load handling. Individual factors such as age, BMI, work experience, and gender also modulate the risks. Body regions most affected in MSDs occupational settings include the neck, shoulders, upper and lower back, abdomen, pelvis, and knees (Demissie et al., 2024; Kheterpal et al., 2017). Accurate WBV measurement is essential for understanding its health impacts and designing effective mitigation strategies. Advances in accelerometer technology, particularly the introduction of piezoelectric sensors by pioneers such as Brüel & Kjær in 1945, have significantly enhanced vibration measurement capabilities. Modern accelerometers, such as ADXL-345, are lightweight, precise, and widely accessible, making them suitable for WBV studies (Liu et al., 2017). Vehicle operators are particularly vulnerable to WBV, as vibrations propagate from the vehicle body through the seat to the head, posing significant health risks (Linessio et al., 2016).

Given these challenges, there is an urgent need for cost-effective, user-friendly systems capable of capturing WBV data across multiple body regions simultaneously. Recent advances in sensor integration and data acquisition systems enable more comprehensive analyses of WBV exposure and its implications for MSDs. This study presents a novel approach for measuring WBV at multiple body locations using an integrated system comprising ADXL-345 accelerometers, an Arduino Uno microcontroller, a real-time clock (RTC) module, an SD card module, a GPRS-GSM module, and a multiplexer for sensor management.

2. Materials and Methods:

2.1 Methodology

This study developed an Arduino-based, multi-channel accelerometer system to measure WBV and acceleration along three axes (X, Y, Z). The system is designed to simultaneously capture vibration data from seven strategic body locations, enabling an analysis of vibration transmission and its effects. The system integrates seven ADXL-345 accelerometers with an Arduino Uno microcontroller. Data is processed and stored on an SD card via an SD card module or transmitted to a server in real-time using a GPRS-GSM module. This design emphasizes affordability and simplicity while ensuring reliable data acquisition for further analysis.

The primary focus is to measure vibration transmissibility—the amplification or attenuation of vibrations—across six body locations (neck, shoulders, thoracic spine, lumber spine, abdomen and pelvis) relative to the seat surface. This provides insights into WBV's health risks without directly measuring absolute WBV values.

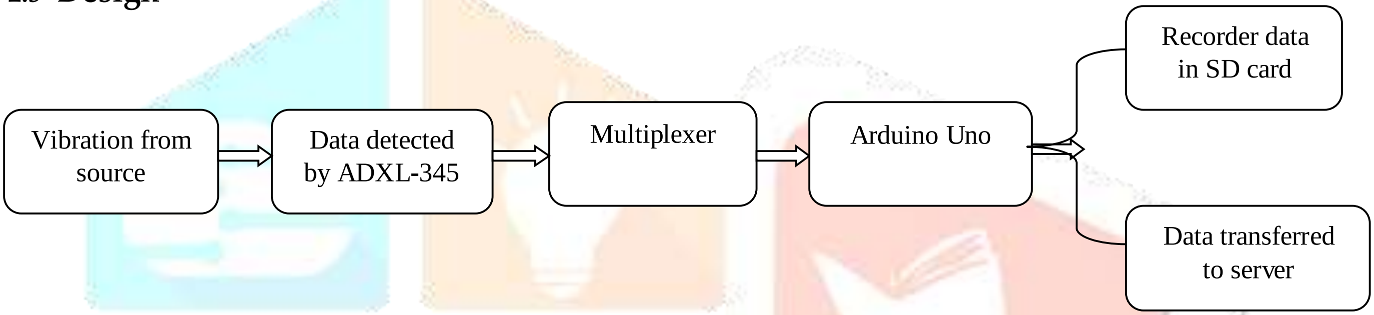
2.2 Specifications

- **Transducer:** ADXL-345 Accelerometer
- **Measurement Range:**
  - Frequency: Up to 3200 Hz
  - Acceleration: ±16g
  - Shock Resistance: 10,000g for 0.1 ms (powered and unpowered)
- **Accuracy:** ±4.6%
- **Operating Conditions:**
  - Voltage: 2–3.6 V
  - Temperature: -40°C to +85°C

- **Microcontroller:** Wi-Fi-enabled Arduino Uno
- **Additional Components:**
    - RTC Module for timekeeping
    - SD Card Module for data storage
    - GPRS-GSM Module for real-time data transfer
- **Parameters Measured:** Time and acceleration
- **Power Supply:** +5V DC
- **System Weight:** 450 grams

The accelerometers capture WBV data, which is processed by the Arduino microcontroller. Data is stored locally or transmitted wirelessly for further analysis. The system's modularity allows raw data retrieval from either the SD card or the server for advanced processing and comparison with standards.

2.3 Design



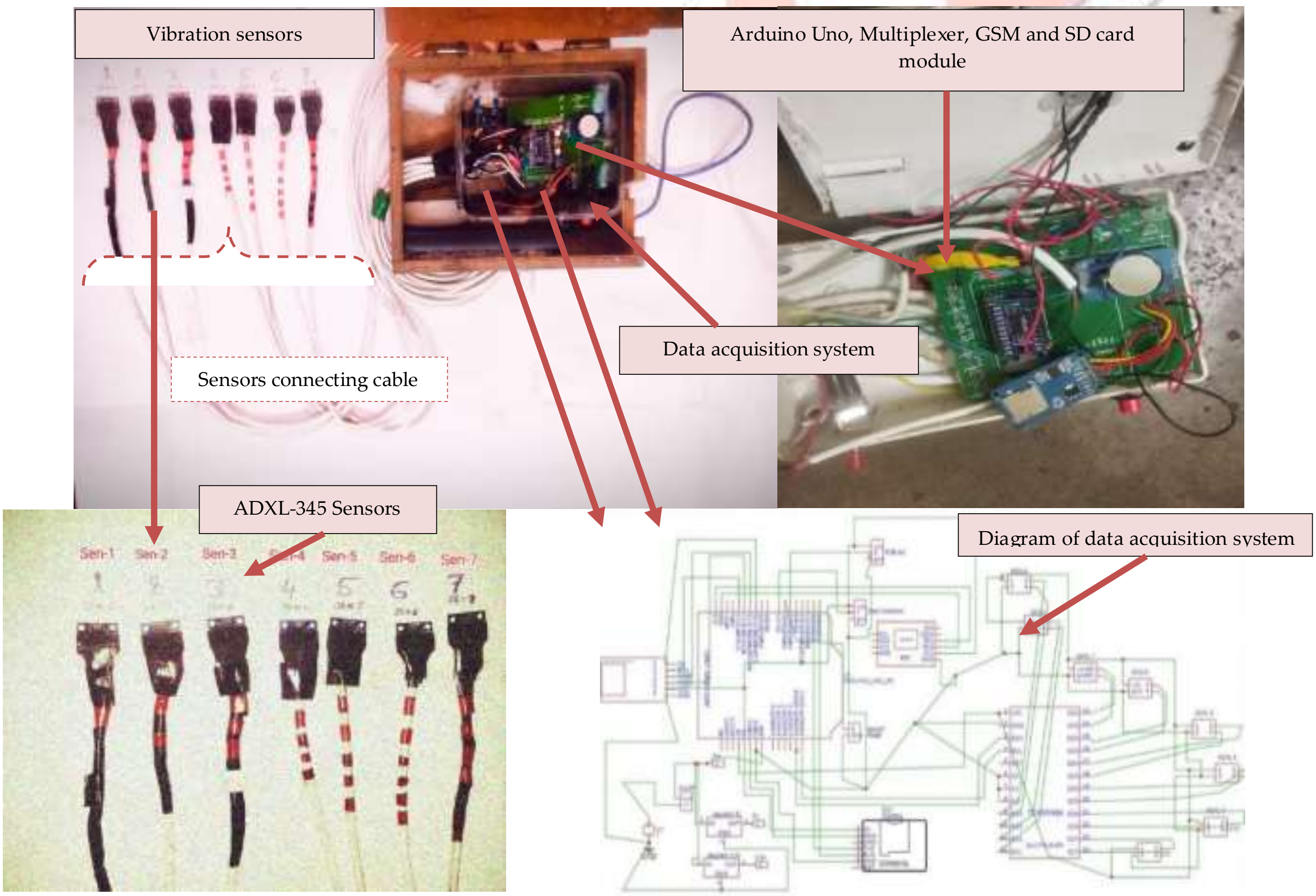


Figure 1: Experimental setup of data acquisition system with ADXL-345, Arduino Uno, Multiplexer, GSM and SD card Module

2.4 System Modelling and Integration

a. **Hardware Connections:**

- Integration of ADXL-345 accelerometer sensors with the Arduino Uno via an I2C multiplexer.
- Connection of RTC and SD card modules to the Arduino Uno.
- Integration of a GPRS-GSM module for wireless data transfer.

b. **Power Management:**

- Centralized power supply to the Arduino Uno and peripheral components.

c. **Data Flow:**

- Vibration data from accelerometers is processed by the Arduino and either stored locally or transmitted to a server for real-time monitoring.
- The collected data is analysed to evaluate WBV transmissibility across body regions with respect to seat surface.

d. **Validation:**

- The system's output is compared with data from a standard vibrometer to ensure accuracy and reliability.

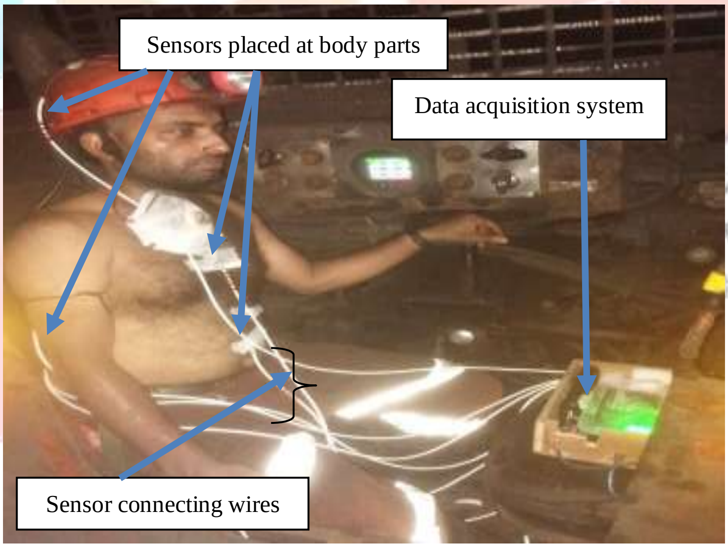


Figure 2: Body segments vibration measurement of a seated shuttle car operator

3. Results:

The integration of the ADXL-345 accelerometer with the Arduino Uno microcontroller has demonstrated an efficient and reliable system for measuring and analysing whole-body vibration (WBV) in real-world scenarios. The results provide valuable insights into vibration transmissibility and its potential health impacts on vehicle operators in underground mining environments.

3.1 Data Collection

The system was deployed to collect vibration data from six critical body regions (pelvis, abdomen, lumbar spine, thoracic spine, shoulder, and neck) of a seated shuttle car operator in an underground mine. Observations revealed that vibration levels varied significantly during shuttle car operations due to factors such as:

- **Vehicle-specific factors:** Motor mount conditions, vehicle aging, loose fittings, and disconnected hoses.
- **External factors:** Uneven Road surfaces and operational speed.
- **Operator-specific factors:** Age, weight, height, posture, and experience.

The collected data represents vibration transmissibility across body regions rather than absolute WBV values, offering insights into how vibrations propagate from the vehicle seat through the body regions.

3.2 Data Storage to SD Card

During the data acquisition process, each of the seven ADXL-345 accelerometer sensors was interfaced with the Arduino Uno, powered by a 5V external supply. The acceleration data was recorded in all three axes (X, Y, Z) and stored on an SD card via the SD card module. Data formatting was standardized as time (seconds) versus acceleration (m/s²), ensuring organized and reliable data capture.

3.3 Data Transmission to Server

In addition to local storage, the system supports wireless data transmission through an integrated GSM module or a Wi-Fi-enabled Arduino board. This feature facilitates real-time monitoring by transmitting data directly to a remote server, enabling timely analysis and interventions when needed.

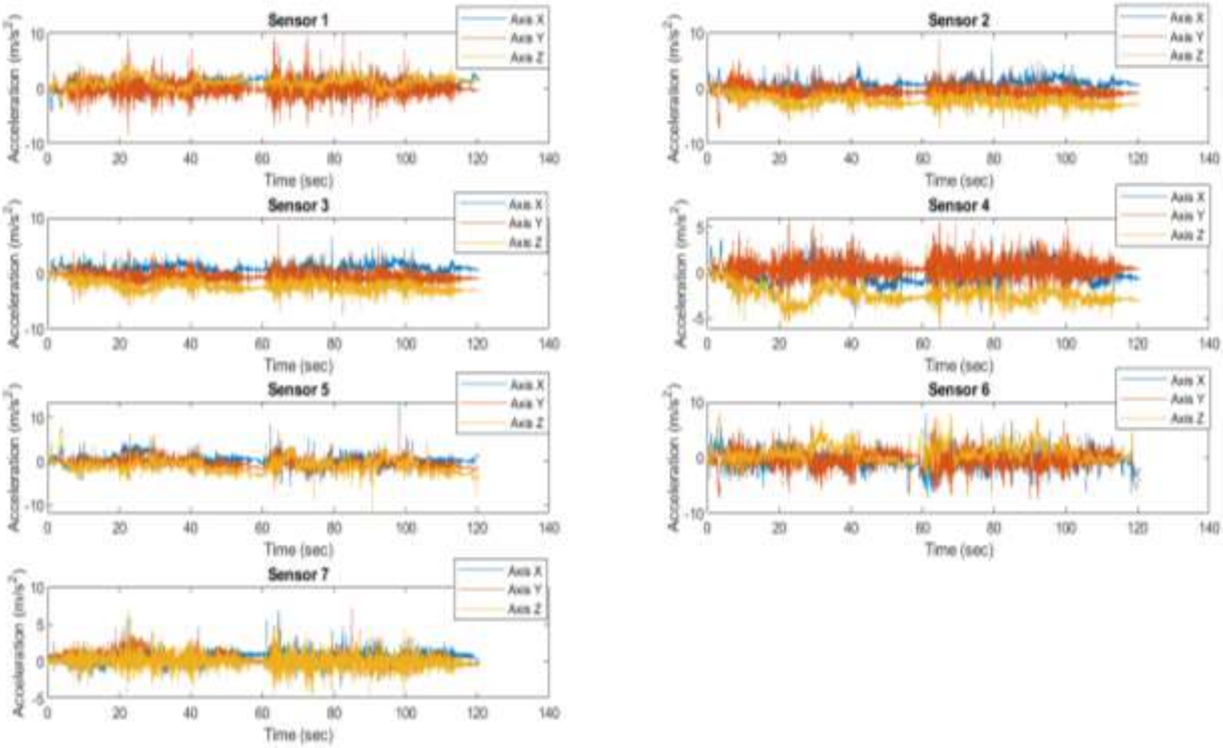


Figure 3: Acceleration values of seven sensors in of X, Y, Z axis

3.4 Analysis of Acceleration Data

The vibration data underwent rigorous analysis in both time and frequency domains, yielding critical metrics such as peak acceleration, root mean square (RMS) acceleration, and frequency distribution. figure 3 and figure 4 present graphical representations of these analyses, with the following key observations:

- Acceleration peaks varied across body regions and axes (X, Y, Z), highlighting distinct vibration characteristics.
- For the X-axis, peak values ranged from 5.2 m/s^2 to 11.8 m/s^2, with maximum acceleration recorded at 90.85 seconds.
- For the Y-axis, the highest acceleration values ranged from 4.06 m/s^2 to 13.5 m/s^2, with peaks observed at 98.25 seconds.
- For the Z-axis, peak accelerations ranged from 5.23 m/s^2 to 9.5 m/s^2, recorded within a narrow time interval around 64.52 seconds.

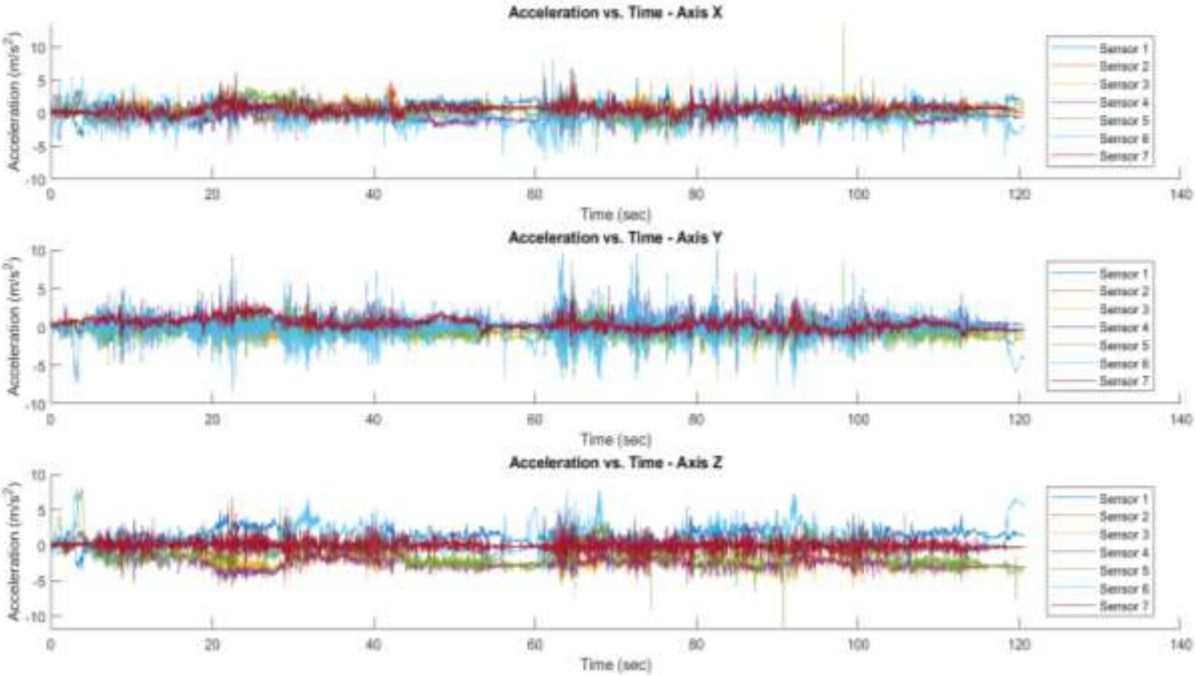


Figure 4: Acceleration data of X, Y, Z axis of seven sensors

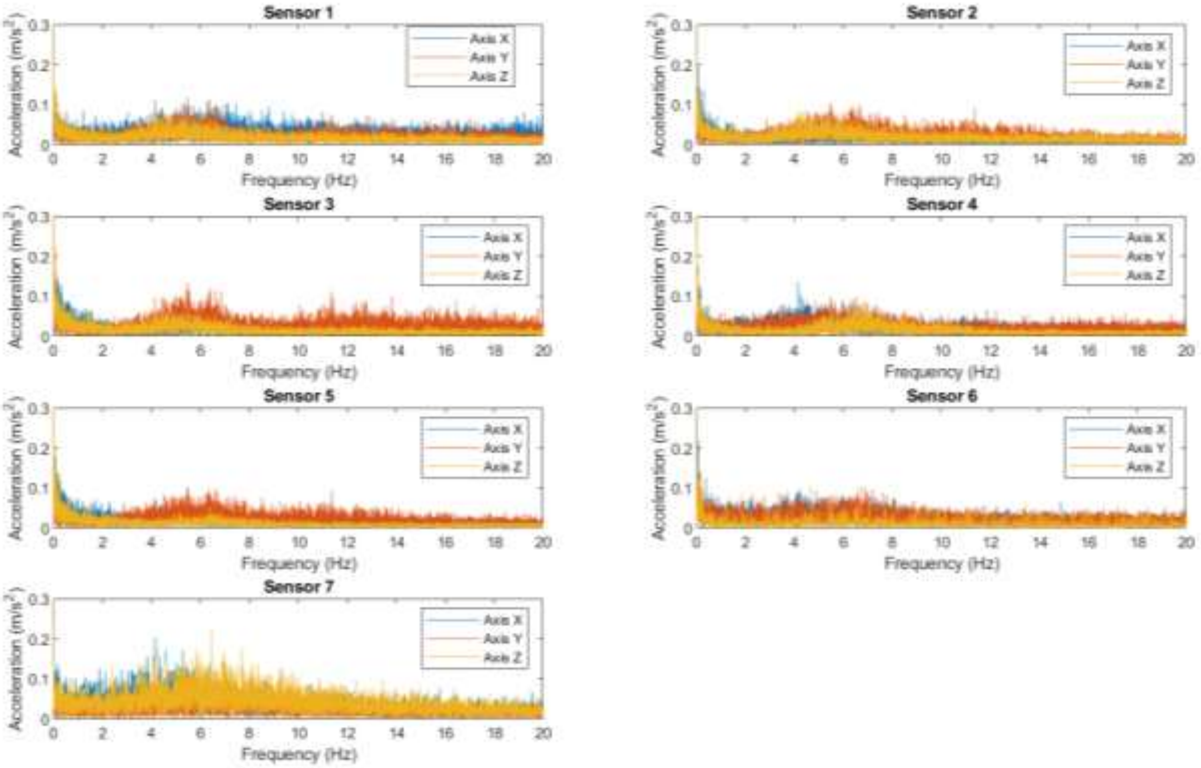


Figure 5: Frequency vs acceleration in three directions (X, Y, Z) of seven sensors

3.5 Frequency Analysis

The frequency analysis revealed resonant frequencies in the range of 4 Hz to 6 Hz across all sensors, aligning with established WBV standards. Graphical representations in figure 5 and figure 6 effectively highlight the relationship between frequency and acceleration, allowing comparisons with standard WBV thresholds.

- The graphical outputs confirm that vibration amplitudes and frequencies vary significantly based on body segment, providing a comprehensive view of WBV propagation.
- High resonance frequencies (4–6 Hz) correspond to critical vibration effects on the human body, warranting targeted interventions for safety and health improvement.
- The system's capability to measure, store, and transmit data in real-time enhances its utility for continuous monitoring and analysis.

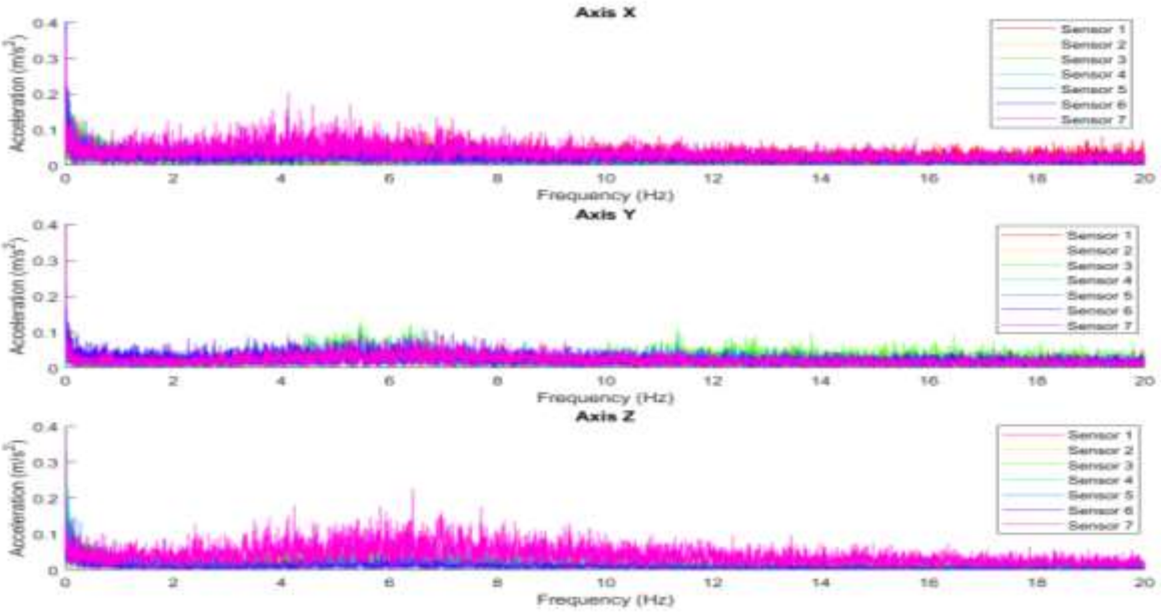


Figure 6: Frequency vs acceleration in X, Y, Z directions of seven sensors

The results validate the system's effectiveness in capturing WBV data and analysing vibration transmissibility across body segments. These findings serve as a foundation for implementing evidence-based safety measures and optimizing operator health in high-vibration environments such as underground mining. The integration of time-domain and frequency-domain analyses further strengthens the understanding of vibration impacts, enabling targeted strategies to mitigate occupational health risks.

4. Discussion:

When subjected to vibration, the human body exhibits distinct resonant frequencies for each body segment. These resonant frequencies are influenced by various factors, including age, weight, height, posture, experience, and the input excitation frequency at the seat. To mitigate the adverse effects of mechanical resonance, which can amplify vibration and lead to potential harm, it is critical to ensure that input excitation frequencies remain outside the resonant frequency range. Figures 3 and 4 present the acceleration data across the X, Y, and Z axes from seven strategically placed sensors over time. Additionally, Figures 5 and 6 depict the corresponding frequency-domain data, offering a detailed representation of vibration characteristics across different body segments. Results indicate that peak vibration transmissibility values occur between the 4–8 Hz frequency range, consistent with findings from previous studies (Alphin et al., 2012; Guruguntla et al., 2023; Dong et al., 2024).

The prototype design for segmental vibration measurement demonstrates significant potential for improving safety protocols through precise vibration monitoring. By analysing the effects of vibrations on various body regions, the device enables early identification of potential health risks, facilitating the development of preventative strategies to reduce musculoskeletal disorders. Furthermore, the system's capability to monitor vibrations in machinery components can help prevent equipment malfunctions and accidents. Real-time monitoring of vibration acceleration and frequency patterns allows for the rapid identification of anomalies, ensuring timely implementation of corrective measures and reinforcing safety standards.

Comparison with Existing Systems

The proposed model offers notable improvements over existing vibration measurement systems in terms of affordability, accessibility, and functionality. Many commercial vibration measuring devices are prohibitively expensive, whereas the proposed model provides a cost-effective solution without compromising performance. Key features, such as the GSM module for efficient data transmission to servers via the internet and a Wi-Fi module for local data transfer, enhance the system's usability. However, the Wi-Fi module is limited by the coverage range, which may restrict its utility in remote locations. Table 1 summarizes a detailed comparison between the proposed and existing accelerometer systems, highlighting the proposed system's advantages in cost, accuracy, and data transfer capabilities.

Table 1: Comparison between Proposed and Existing Accelerometer Systems

Feature	Proposed accelerometer	Existing Accelerometer
Sensor type	Tri-axial ADXL 345 accelerometers were used	Most cases used novel optic accelerometer (i.e. Nor1286/1287 Vibrometer)
Sensor placement	Open and can be placed as required to measure specific values	Built-in sensor inside a pad that senses vibration
Measurement process	Real time vibration measurement	Real time vibration measurement
Data Storage and Transmission	Stores data on an SD card; can transmit data via Wi-Fi/GSM module	Stores data on an SD card; no data transmission module
Frequency Sensing Range	3200Hz	10Hz to 1KHz.
Accuracy	±4.5%	±5%
Data Transfer Rate	Data transferring rate is faster.	No data transfer option available

Limitations and Future Enhancements

While the proposed model successfully delivers comprehensive vibration measurement and analysis at multiple points using the ADXL-345 triple-axis accelerometer, certain limitations must be addressed for future advancements. Transitioning to a Raspberry Pi platform could improve data processing speeds and streamline server communications, allowing for more sophisticated data analysis. Additionally, the inclusion of advanced signal processing algorithms could enhance the system's ability to detect subtle vibration patterns, expanding its utility across diverse industrial environments. Future enhancements should also explore extending the device's application to more challenging and dynamic operational settings.

5. Conclusion:

The proposed vibration measurement model represents a significant breakthrough in occupational health and safety, particularly in the monitoring and analysis of whole-body vibration. Leveraging advanced accelerometer technology, the device offers high precision with a minimal error margin, outperforming traditional instruments in accuracy, functionality, and cost-effectiveness. Its capability for wireless data transfers further integrates real-time monitoring with economic advantages, making it a practical tool for industrial applications. Nevertheless, ongoing research and innovation are vital to address current limitations and enhance the system's versatility, ensuring its effectiveness across diverse operational contexts.

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7. Funding/Conflicts of Interest:

This study was conducted without any external funding. The authors declare no conflicts of interest in relation to this research.

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