IoT-Enabled Vibration Analysis for Smart Stingless Beekeeping

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Abstract – *Smart stingless beekeeping, which emphasises protection through non-invasive and data-driven monitoring has been implemented at the International Islamic University Malaysia (IIUM), Gombak campus in Kuala Lumpur. This study introduces an intelligent monitoring framework for characterising the health of a stingless beehive by analysing hive vibration patterns, along with internal temperature and humidity data. Collected over a four-week period, the vibration data were processed using Fast Fourier Transform techniques to convert time-domain signals into frequency-domain representations. This enabled the precise identification of consistent vibrational signatures associated with the normal hive condition. The X-axis exhibited a mean frequency of 167.54 Hz (SD = 116.01Hz), with mean amplitudes of 0.00925 g (SD = 0.01452 g). The Y-axis showed mean frequencies of 196.48 Hz (SD = 153.83 Hz) with amplitude values of 0.00628 g (SD = 0.0085 g), while the Z-axis recorded the highest mean frequency at 294.6515 Hz (SD 139.36 Hz). The system is capable of detecting anomalies by alerting to the presence of high-frequency components, which are indicative of vertical vibration transmission induced by wind disturbance. It was noted that the amplitude was the lowest and most stable, with a mean of 0.003 g and SD of 0.000 g, suggesting very low vibration intensity in the vertical direction. These patterns were recorded under stable temperature (27.6–33.8°C) and humidity (80.73–82.50%) conditions, supporting their validity as baseline indicators of a healthy stingless beehive. The integration of Internet of Things (IoT)-enabled smart technologies into stingless bee management contributes directly to the United Nations Sustainable Development Goals related to sustainable agriculture (SDG 2).*

Keywords: *frequency domain, FFT analysis, non-invasive monitoring, intelligent monitoring, smart stingless beekeeping, time domain.*

I. Introduction

Traditional beekeeping practices typically involve time-consuming manual inspections, which often fail to detect problems in a timely manner, leading to increased hive mortality and decreased honey production (Edmund & Ab Rahman, 2021). Extreme weather conditions driven by climate change pose risks to both bee colonies and the structural stability of beehives. For example, strong winds can cause mechanical disturbances in the form of surface vibrations, which may serve as early indicators of structural stress or environmental agitation. Neumann and Straub (2023) highlight that extreme weather events increase colony loss and disrupt apiary operations, leading to the need for resilient and well-monitored hive systems.

Rifat et al. (2022) proposed smart beekeeping to ensure the well-being, health, and productivity of bee colonies. The IoT has created new opportunities for monitoring and managing systems remotely in beekeeping, compared to traditional systems. The smart systems allow beekeepers to monitor hive conditions in real time, receive alerts for potential issues, and make data-driven decisions to improve hive health and productivity. However, Ilić et al. (2024) argued that current monitoring methods do not provide detailed insights into bee activity and environmental conditions, which are critical for identifying potential issues for intervention.

This gap will be addressed in this study, focusing on how vibration, temperature, and humidity measurements can serve as indicators inside beehive and vibration sensor to detect potential disturbances outside or variations in beehive conditions. The system will continuously monitor critical hive parameters such as motion, temperature, and humidity. It applies a dual setup to collect real-time environmental data and monitor hive vibrations, allowing for the assessment of bee activity levels. The advantage of stingless bees (Meliponini) has been selected for this study because they do not pose a sting hazard and are native to Malaysia.

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II. Materials and Methods

A. System Integration

Figure 1 illustrated the integration layout involved connecting the hardware components to ensure seamless operation. The primary components required for this project were the ESP32 microcontroller, which facilitated data processing and internet connectivity; the ADXL345 accelerometer, which measured vibrations across three axes; and the DHT11 sensor, which measured the temperature and humidity of the beehive's internal conditions.

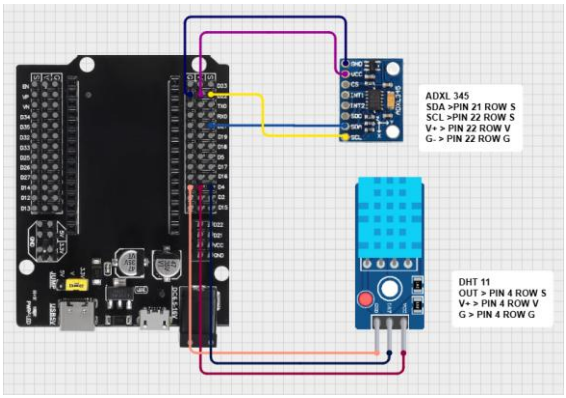


Fig. 1. Layout for IoT-Enabled Vibration Analysis for Smart Stingless Beekeeping

A user-friendly dashboard, as shown in Figure 2, was developed in this study using ThingSpeak to visualize the collected data and provide mitigation for the protection and security of the hive's well-being. This system provides an interface that presents environmental parameters and hive vibration data, facilitating straightforward interpretation. It includes real-time alerts for unusual hive conditions and displays historical data trends, empowering beekeepers to monitor changes over time.

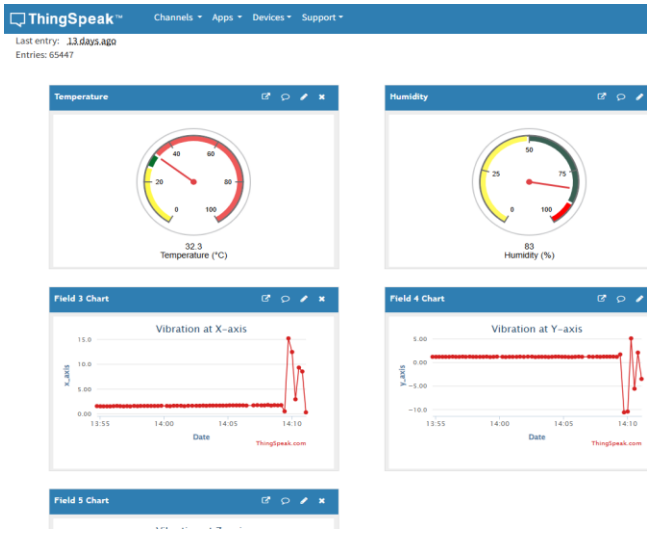


Fig. 2. IoT-Enabled Vibration Analysis for Smart Stingless Beekeeping Dashboard in ThingSpeak for data visualization

B. Device Installation

The developed system was installed inside and outside a stingless beehive located at the Kelulut Research Lab, Building E4, Kulliyyah of Engineering at International Islamic University (IIUM) Gombak, Kuala Lumpur, as shown in Figures 3, 4 and 5. All sensors and the microcontroller were securely mounted externally to minimize disturbance to the bee colony, optimizing data collection for continuous monitoring of internal and external hive conditions throughout the experimental period in April and May 2025. The experiment was conducted at an average highest speed of 8.5 km/hour.



Fig. 3. Installation of the ESP32 microcontroller on the stingless beehive.

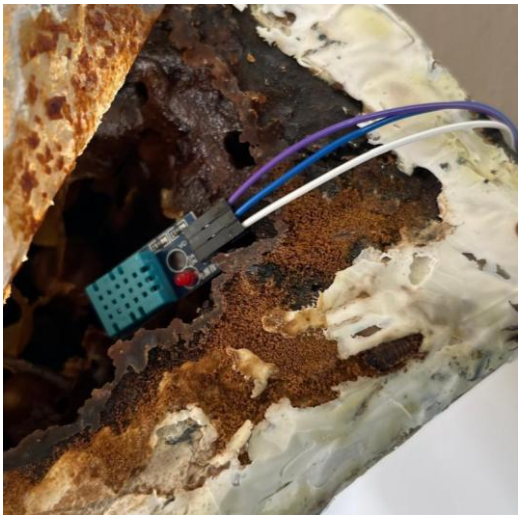


Fig. 4. Placement of the DHT11 sensor in the stingless beehive.

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Fig. 5. Placement of the ADXL345 accelerometer on the stingless beehive.

C. Data Collection and Storage

The raw vibration data was systematically collected and published to the IoT Cloud platform, ThingSpeak, where datasets representing the beehive's condition were recorded hourly each day. These data were stored then used to identify patterns correlated with hive health and structural responses (Rigakis et al., 2023).

D. Signal Processing

Vibration data collected from the ADXL345 accelerometer were analyzed using MATLAB. The Fast Fourier Transform (FFT) spectrum analysis was applied to convert time-series data into a frequency-domain representation for X-axis, Y-axis, and Z axis. This approach facilitated visualization of surface vibrations and identification of specific frequency patterns that corresponded with normal hive conditions or potential structural issues.

III. Results and Discussions

Table 1 and Table 2 summarize the temperature and humidity data recorded under normal environmental hive conditions. During the monitoring period, the internal hive temperature ranged from 27.6°C to 33.8°C, averaging 30.08°C, which is within the biologically acceptable range for stingless bee colonies, as suggested by Edmund & Ab. Rahman (2021). The humidity data showed variability. The average humidity ranged between 80.73% and 82.50%, with peaks below 86%. Anthony and Yek (2024) recommended a humidity range of 50–70%. Even if the internal temperature and humidity were within acceptable limits, structural agitation is a possible cause of changes in vibration behavior (Hrncir et al. 2008).

Table 1: Comparison Of Minimum, Maximum And Average Temperature In Stingless Beehives At Normal Condition

Temperature (°C)		
Min	Max	Average
28	33.8	30.07
28	31.8	30.09
27.6	32.8	29.77
28	33.3	30.42

Table 2. Comparison Of Minimum, Maximum And Average Humidity In Stingless Beehives At Normal Condition.

Humidity (%)		
Min	Max	Average
77	85	82.24
79	84	81.83
79	86	82.50
78	84	80.73

Next, the time-domain analysis of hive surface vibration signals measured across three spatial axes (X, Y, and Z) with the ADXL345 accelerometer. The X-axis indicates horizontal surface vibrations (left-right), the Y-axis records vertical surface vibrations (top-bottom), and the Z-axis demonstrates vibrations perpendicular to the stingless beehive surface. These measurements show the hive's structural response to internal activity and environmental factors like wind and humidity.

Figure 6 presented the X-axis vibration signal recorded on one of the experimental days. During the normal monitoring days, the X-axis signal demonstrated consistent low displacement amplitude oscillations with a smooth waveform pattern and fluctuations. These characteristics indicate a relatively stable environment with minimal horizontal mechanical disturbances to the hive's structure.

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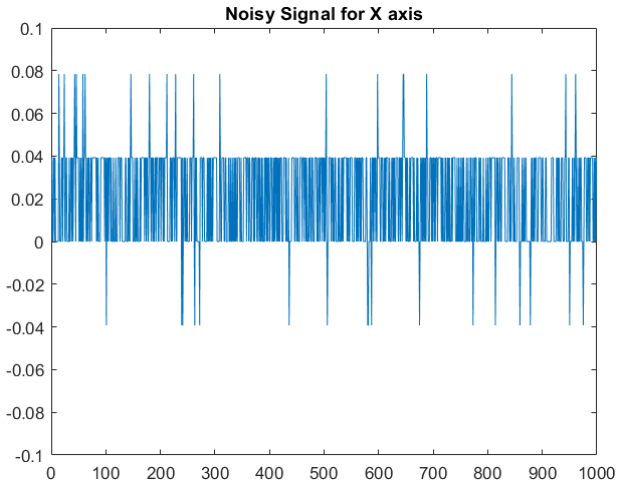


Fig. 6. Noisy Signal in Time-Domain for X-axis for Normal Condition.

Figure 7 illustrated the Y-axis vibration signal captured during one of the monitoring days. The Y-axis, which measures vertical surface vibrations of the hive, demonstrated consistently low displacement amplitude oscillations under normal conditions. The amplitude remained confined within a narrow range, and the waveform appeared clean and periodic, indicating minimal structural agitation or vertical disturbances throughout the observation period.

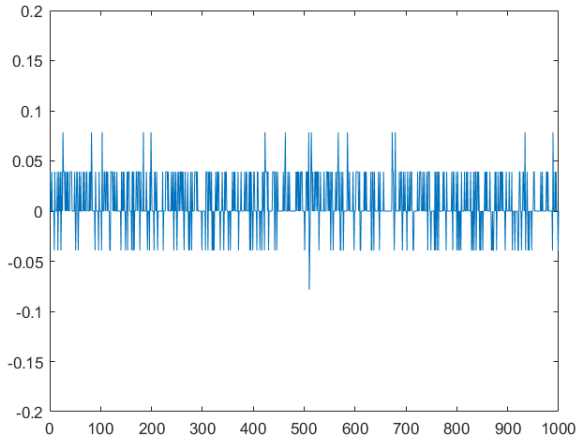


Fig. 7. Noisy Signal in Time-Domain for Y-axis for Normal Condition.

Figure 8 portrayed the Z-axis vibration signal obtained during one of the monitoring days. The Z-axis recorded minimal activity, characterized by low displacement amplitudes and few irregularities. These stable readings suggest that the hive experienced negligible movement along the inward–outward direction, reinforcing the assumption of a stable environmental condition.

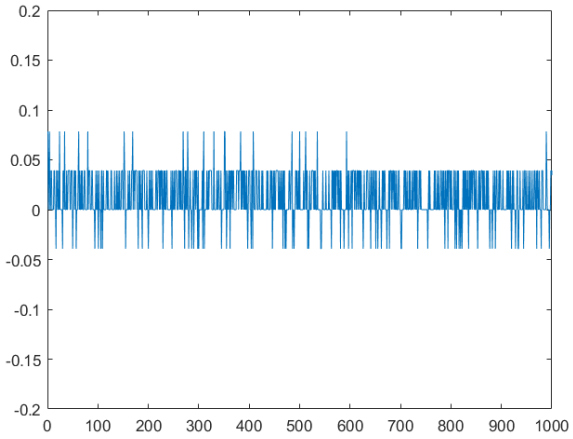


Fig. 8. Noisy Signal in Time-Domain for Z-axis for Normal Condition.

Table 3 presented the surface vibration's mean and standard deviation value of the beehive structure was measured along three axes using single-sided amplitude of FFT spectrum. Both frequency and amplitude components were analyzed to characterize the structure's vibrational behavior under normal conditions.

Table 3: Mean And Standard Deviation Values Of Fft Spectrum For X, Y And Z Axis

Measurement	Single-Sided Amplitude of FFT spectrum					
	X axis		Y axis		Z axis	
	f (Hz)	amplitude (g)	f (Hz)	amplitude (g)	f (Hz)	amplitude (g)
Mean Value	167.5355	0.00925	196.484	0.006275	294.6515	0.003
Standard Deviation Value, σ	116.01	0.01452	153.83	0.00855	139.36	0

The vibration analysis reveals axis-specific behavior of the beehive structure. For the X-axis, moderate vibration activity was observed, with a mean frequency of 167.535 Hz (SD = 116.01 Hz) and amplitude of 0.00925 g (SD = 0.01452 g). The Y-axis showed a slightly higher mean frequency of 196.484 Hz (SD = 153.83 Hz) and a more stable amplitude of 0.006275 g (SD = 0.00855 g), indicating response to external influences. The Z-axis recorded the highest mean frequency at 294.6515 Hz (SD = 139.36 Hz), but with minimal and constant amplitude (0.003 g, SD = 0.000 g), suggesting rapid yet weak vertical vibrations. These patterns support consistent amplitude ranges under normal conditions (Gan, 2020; Zgank, 2020) and provide a reliable baseline for monitoring future deviations (Pal et al., 2022), enabling non-intrusive structural assessment (Rigakis et al., 2023).

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Based on the analysis performed, the influence of real-time monitoring of stingless beehive data can be reviewed. The implementation of real-time monitoring via IoT technology enabled immediate observation of key parameters—vibration, temperature, and humidity—within the stingless beehive. This real-time access provided a clearer understanding of hive dynamics and potential stress indicators. For example, the vibration amplitude reached 0.031 g at 55.84 Hz on the X-axis, suggesting strong lateral activity, likely from active foraging or hive regulation behavior. The temperature and humidity were within optimal biological ranges (30.07°C and 82.24%, respectively), supporting normal behavior as reported by Anthony and Yek (2024) and Gan and Battaglia (2024). The visualized frequency data helped identify this pattern as part of the colony's typical activity. These findings affirm that real-time monitoring provides a valuable context for interpreting hive conditions (Edmund & Ab. Rahman, 2021). It not only facilitates early detection of abnormal behavior but also reduces reliance on manual inspections that might disturb the colony. This objective was fulfilled through the system's continuous data acquisition and integration into a visual dashboard (Farooq et al., 2020).

Although this study does not directly assess internal hive health parameters such as colony strength, brood development, or the presence of pests, the recorded vibration and environmental data offer foundational insights that may inform the development of future non-invasive hive condition monitoring systems. The measured vibrations along the X, Y, and Z axes represent the hive's structural response to internal activities and external environmental factors. Under normal conditions, vibration frequencies on all three axes remained within moderate ranges with low amplitude values, indicating a state of mechanical equilibrium. In particular, Z-axis amplitudes remained consistently low (0.002 g–0.003 g), which suggests stable vertical structural behavior with minimal disruption from either internal or environmental influences (Gan, 2020; Zgank, 2020). These stable patterns could serve as baseline references for identifying future anomalies.

Furthermore, the vibration thresholds have practical implications for beekeepers. For instance, sustained amplitudes above 0.031 g at 55.84 Hz on the X-axis may indicate abnormal hive structural stress, while deviations from the stable 0.003 g amplitude on the Z-axis may indicate environmental disturbances such as wind or predator interference. Beekeepers can set up real-time alert systems for abnormal hive activity by incorporating these thresholds into IoT-enabled dashboards. Moreover, predictive monitoring also reduces the need for manual inspections, which promote non-invasive hive management. This approach is consistent with the results of Hrncir et al. (2008) and Pal et al. (2022), who emphasized the utility of vibration patterns as indicators of colony health.

Based on this study, it can be concluded that the combination of surface vibration analysis and environmental monitoring holds potential as a non-invasive diagnostic tool for beekeepers (Hrncir et al., 2008; Pal et al., 2022). Despite these contributions, several limitations should be acknowledged. First, the monitoring period was restricted to four weeks, which limits the ability to capture long-term seasonal or climatic influences on vibration patterns. Second, the study was conducted at a single site in Gombak, Kuala Lumpur, Malaysia, and the results may therefore reflect location-specific environmental conditions such as wind speed and humidity. Third, the analysis was performed exclusively on *Heterotrigona itama*, a species native to Malaysia, which restricts the generalizability of findings to other stingless bee species that may exhibit distinct vibrational signatures. Future studies should therefore consider longer monitoring durations, multi-site deployments, and cross-species validation to enhance the robustness of the findings.

Although more data collection is required, these findings help to lay the groundwork for future research aimed at correlating physical hive responses with bee activities inside hive to indicate colony's health and well-being.

IV. Conclusion

This study contributed to mitigating climate change challenges which decreased the number of bee population by demonstrating that combining surface vibration analysis with environmental monitoring provides a valuable, non-intrusive approach to assessing stingless beehive conditions. Under normal environmental conditions, specifically temperature ranging from 27°C to 33.8°C (average 30.07°C) and humidity from 77% to 86% (average 82.24%), vibration signals across all three axes exhibited consistent amplitude patterns. Additionally, the low and stable amplitude observed on the Z-axis serves as a reference for structural equilibrium within the hive. Real-time monitoring further enabled continuous tracking of hive behavior without disturbing colony activity. The ability to visualize vibration, temperature, and humidity data via an integrated dashboard offered a smart monitoring system and reduced dependence on manual inspections. In practice, the system provides beekeepers with real-time alerts and supports predictive, non-invasive hive management. Future research should extend the monitoring duration, test across multiple sites and stingless bee species, and enhance scalability for multi-hive deployments with improved energy efficiency. These steps are necessary to advance IoT-enabled vibration analysis toward reliable and sustainable applications in

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apiculture. These findings establish a solid foundation for future development of non-invasive, sensor-based diagnostic tools to correlate hive structural conditions with colony health.

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