Modal Analysis using a UAV-deployable Wireless Sensor Network

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ABSTRACT

In structural health monitoring, wireless sensor networks are favorable for their minimal invasiveness, ease of deployment, and passive monitoring capabilities. Wireless vibration sensor nodes have been implemented successfully for frequency domain analysis in ambient vibration detection. To leverage advances in structural damage quantification techniques, which require modal information, nodes in a wireless sensor network must operate with a near-synchronous clock to enable the collection of the signal phase. The non-deterministic timing nature of wireless systems raises a significant challenge when trying to accurately determine the phase of a signal. In particular, the trigger time delay of the various nodes on the structure cannot be differentiated from a true phase caused by the examined system. This study investigates the reliability and error-handling capabilities of the ShockBurst 2.4 GHz wireless protocol in triggering and data transfer. Building on an open-source UAV-deployable sensor node, mode shapes from a 2-meter test specimen are experimentally determined. An optimization technique that enhances time-domain accuracy for non-deterministic wireless triggers is presented. This work quantifies latency and error management effects that contribute to enhancing the modal extraction capabilities of wireless systems in structural health monitoring applications.

Keywords: SHM, sensors, modal analysis, vibrations, dynamic

INTRODUCTION

Structural Health Monitoring (SHM), is a Nondestructive Inspection process carried out by measuring the parameters of a given system to infer the current structural state. This process relies on damage identification and quantification algorithms [1]. Furthermore, SHM is used to monitor changes (i.e. damage) in the system through its life cycle to make actionable decisions such as structural repairs. SHM is crucial in extending infrastructures' operational lifespan and maintaining safety following extreme weather conditions. Its purpose is highly dependent on the system in question. For example, the goal for SHM is drastically different between a railroad bridge and a naval ship. Continuing, SHM for infrastructure primarily assesses changes that take place on a long timescale (i.e. fatigue) while SHM for naval ships is used for various damage types that occur on short and long time scales such as Impact, fatigue, and corrosion. While SHM for both structures assesses fatigue damage, the actionable decisions conducted for each structure are different.

Vibration-oriented damage detection for structural components is used to evaluate the dynamic and structural property changes as damage indicators. A common vibration-based damage detection technique is modal analysis, where the modes of the structure's ground truth state are analytically and experimentally determined. These modes are then compared to future states in the structure's life cycle to quantify differences between each state, any differences detected signify damage in the structure.

Damage detection methods such as acoustic emission analysis is a passive Non-Destructive Testing Techniques (NDT) that has been successively used on structures such as bridges, tunnels, pipes, and buildings. This method is superior at detecting and localizing damage such as cracking, deformation, and crushing. However, its downside is that the energy emitted by the acoustic emission is very small in comparison to the structure and ambient noise conditions. This leads to interference between the Acoustic Emission and noise signals. Another approach would be numerical modeling. FEA is a good alternative when the system is expensive or difficult to test. However, it is limited by the user's experience, modeling accuracy, and computational resources. If the model is extremely accurate, then the analysis time and computational resources will be high or realistically unachievable so a middle ground should be found.

BACKGROUND

A single vibration sensor can provide information about a structure's vibration signature, however, in structural health monitoring and experimental modal analysis, a single sensor fails to provide the adequate information required to carry out such processes. Sensor networks are typically used in this case to offer more observation points. Using multiple points on the structure, gives information on how vibrations propagate through the material and where mode shapes lie [2]. Using a small number of high mobility compact sensing nodes, which can be spread throughout a given structure, offer the flexibility needed for rapid modal analysis [3]. Moving sensor packages to scan across a given structure can be done easily and with minimal invasiveness. With strides in computer vision, autonomous aerial vehicles, and swarm algorithms, such systems can offer high-mobility rapid infrastructure assessment capability [4]. In this work, an improvement on a previously designed UAV-deployable sensing node will be covered. Utilizing electropermanent magnets (EPM) and radio frequency (RF) communication, this sensing node demonstrated the ability to gather vibration signatures from remote infrastructures in inaccessible terrain, given an external excitation. Via a drone, those standalone sensors can be rapidly deployed across a structure where the accelerometer onboard collects data according to a preset schedule to later be send back for analysis. The developed open source sensing system breakdown is made available in a public repository [5]. When deploying a network of those sensors across a large structure certain challenges arise, one of the most significant is trigger synchronization [3]. Without the ability to start collecting data simultaneously, phase data, or the measure of how vibration propagates is hindered useless as differentiating between trigger delay and vibration phase cannot be done. With the addition of a real-time clock, an accurate time reference can be set between all sensors and the trigger delay can be minimized to an acceptable tolerance dictated by the sampling rate and a structure's natural frequencies.

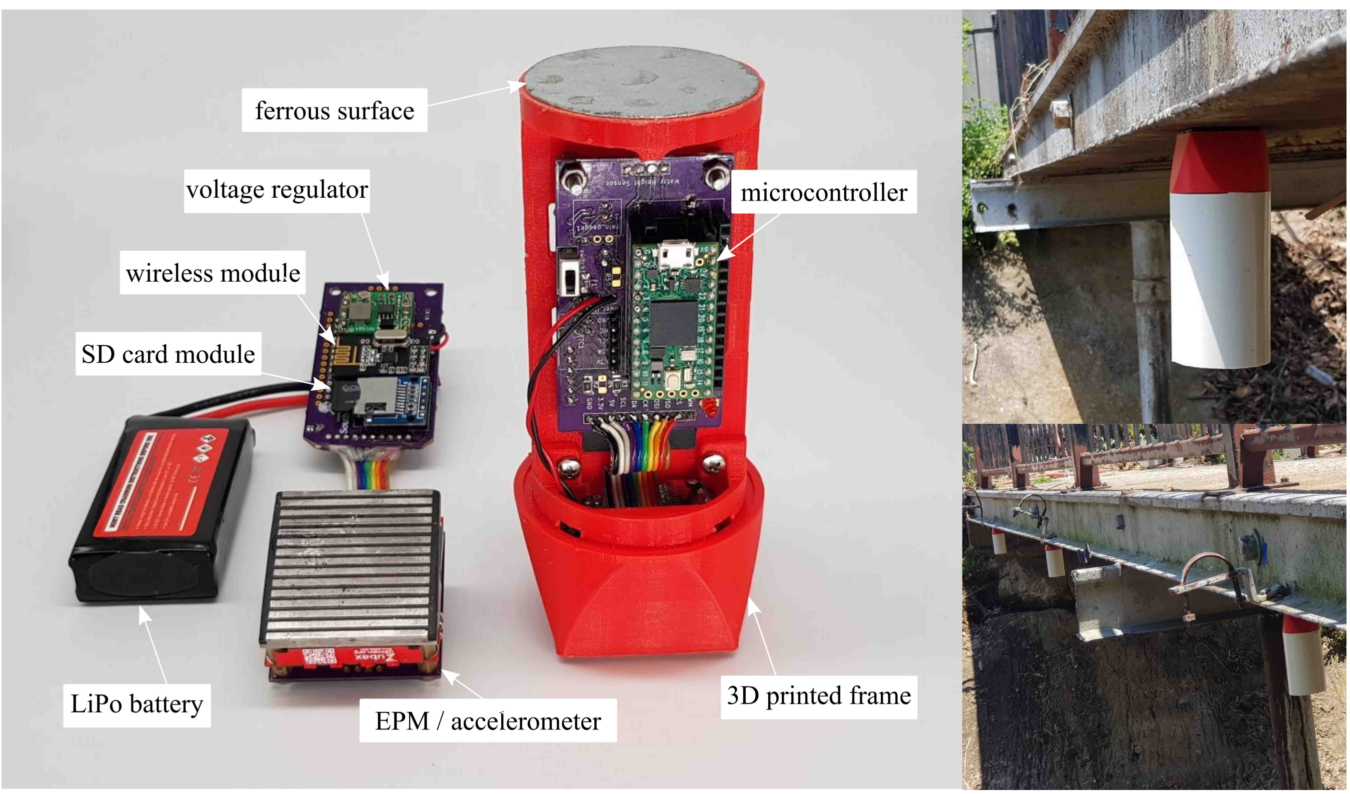

Figure 1: Vibration sensor package with key components annotated along with a field deployment on a test bridge.

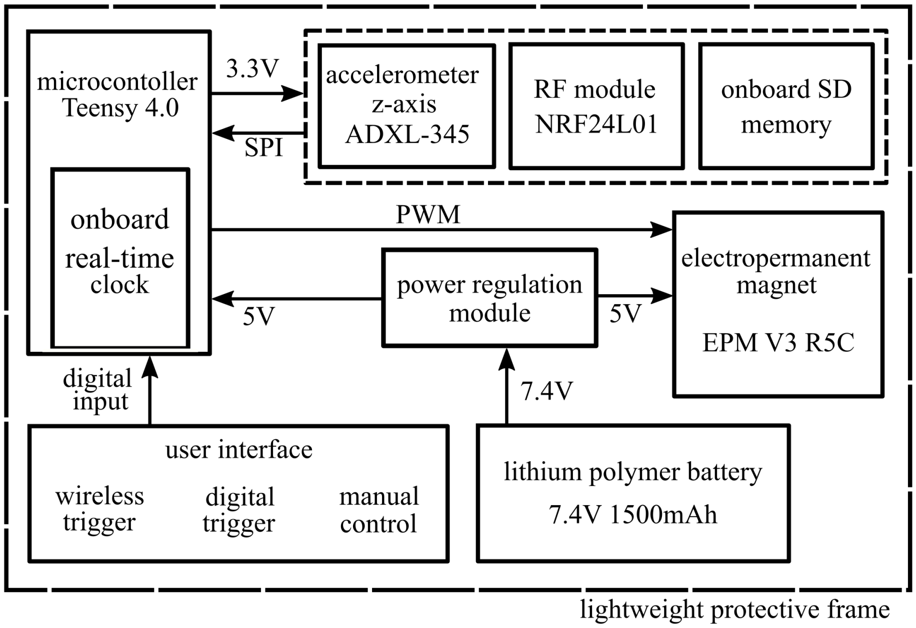

Figure 2: Block diagram of sensor package with the various modules onboard.

The sensor package utilized in this work is an embedded system-based device with the processing core being an ARM Cortex-M7 onboard a Teensy 4.0 microcontroller. With the goal being long-term deployment, the sensor package is fitted with a 1500 mAh 2-cell lithium polymer battery and a power management board to regulate the voltage to the various subsystems. The sensor onboard is a Murata SCA 3300-d01 high-performance MEMS accelerometer on the Serial Peripheral Interface (SPI) protocol to enable high sampling rates. For deployment with minimal invasiveness an EPM V3R5C NicaDrone electropermanent magnet is used. Electropermanent magnets are favorable for such applications for their low power consumption. A one-second pulse of approximately 5 W is required only when switching the magnet's state which is typically done twice per deployment. For data transfer and IO commands a Nordic Semiconductors NRF24L01 module is used. Operating at 2.4 GHz ShockBurst protocol, connection with multiple sensor nodes at once is made possible which is desirable for sensor triggering applications. Additionally, a real-time clock is included for data logging and trigger time reference as those devices are reliable and have minimal drift. Finally, nonvolatile memory (SD card module) is added to the sensor package, so data isn't lost in case of low power or shutdown. The system is fitted into a protective 3D-printed PLA shell to shield delicate electronics from harsh conditions during field deployments. The footprint and weight of the sensor package were optimized for UAV deployment [6]. Shown in Figure 2, is a high-level block diagram of the various subsystems onboard.

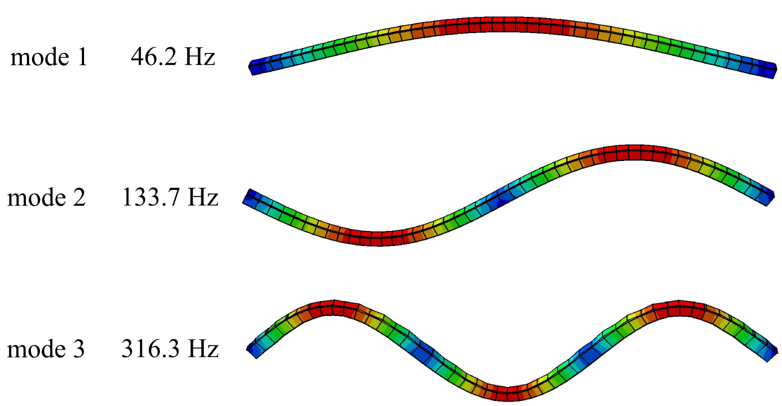

Figure 3: FEA modal simulation results indicating the first three mode shapes of the bench top experimental beam.

To validate the sensor network's ability to determine the mode shapes of a given structure, a model of a simple square beam pinned at each end is adopted. The goal of the modeling phase is to provide an estimate of the optimal location to position the sensing nodes. In experimental modal analysis, the sensors should be mounted at the antinodes of the mode desired to be measured which ensures the highest signal strength. In SHM, this can be a challenge as structures can have complex geometries where using a model can significantly aid in the process [7]. For this work, the model was constructed using finite element modal analysis where the output of the model was the mode shapes and their accompanying frequencies. Utilizing this information, the sampling rate and sensors' location are determined. The model determined the first three modal frequencies of the structure to be 46.2 Hz, 133.7 Hz, and 316.3 Hz respectively with the mode shapes shown in Figure 3.

ANALYSIS

The goal of this section is to characterize the sensor package parameters. Experiments are constructed to quantify the power consumption of the various subsystems onboard. Additionally, an investigation into the length of deployment is reported. For the wireless system, the latency of triggering between two deployed packages is presented along with an experimental modal analysis test to measure the first three mode shapes of a beam.

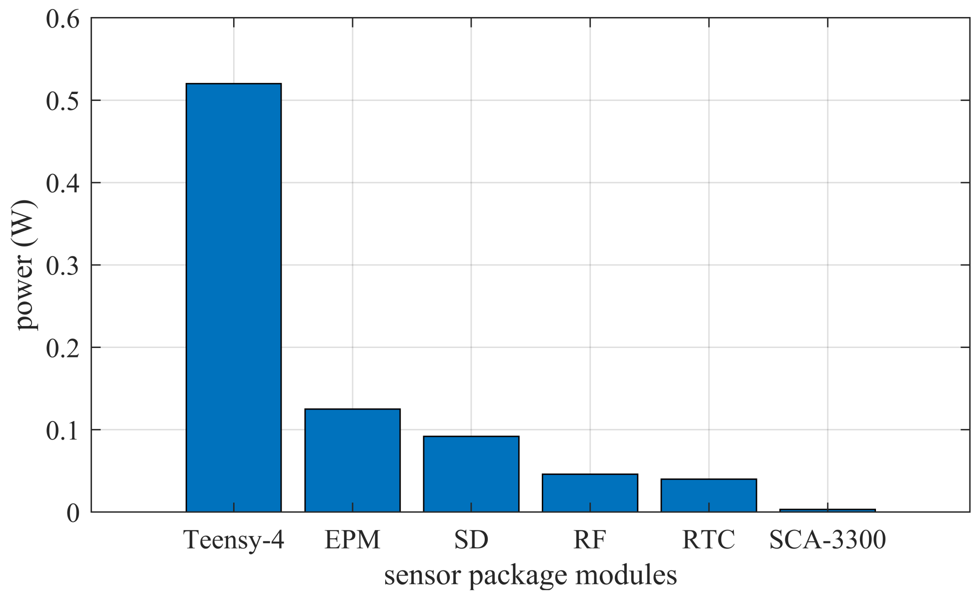

Figure 4: Power consumption of the various modules onboard the sensor package.

With longer deployment periods in mind, a standalone power subsystem is used. A lithium polymer battery was chosen as it has desirable power density per footprint, optimal for areal deployment applications where the payload is a significant concern. Solid-state voltage regulators and a power conditioning circuit are also added to step down voltage and deliver it to the various subsystems onboard. An experiment is constructed to measure each module's power consumption. As indicated in Figure 4 the Teensy 4.0 microcontroller has the highest steady-state power consumption at 0.52 W. For extended deployment ($>$10 hours) a strict power-saving mode can be deployed where the microcontroller along with non-vital modules are turned off, when not in use, further preserving power. Temperature dependencies were observed in this phase as lithium polymer's charge output can degrade in low temperatures causing voltage drops. This problem was partially rectified by adding conditioning capacitors to the package to compensate for the temperature-related voltage swings. furthermore, increasing the number of cells in the battery can ensure the voltage regulators receive adequate voltage regardless of temperature.

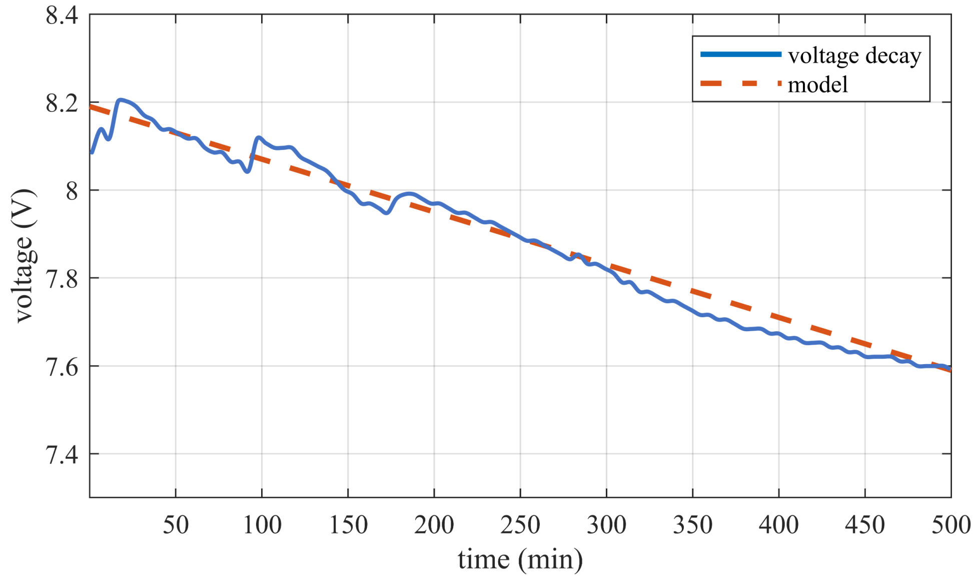

Figure 5: Voltage decay of Lithium polymer battery during sensor package deployment.

As for battery life, the capacity of the battery chosen for this work was a 1500 mAh 2-cell lithium polymer, this was chosen for medium-length deployment (<10 hours). An experiment is constructed to measure the possible deployment period before the battery voltage gets critical. A safety system with an alarm is added during this stage to prevent the battery from over draining which can decrease the lifespan and cause deformation to the battery itself. The experiment was run at constant room temperature to construct a linear model of the power system. Temperature variations can introduce high nonlinearities in the battery's state of charge making it challenging to model. In this case, only the voltage of the battery was observed as an indicator of the discharge rate. As shown in Figure 5, the experiment ran for over 8.3 hours with the voltage decay linear model shown in equation 1.

$$V = -2 * 10^{-5}(t) + 8.19 \tag{1}$$

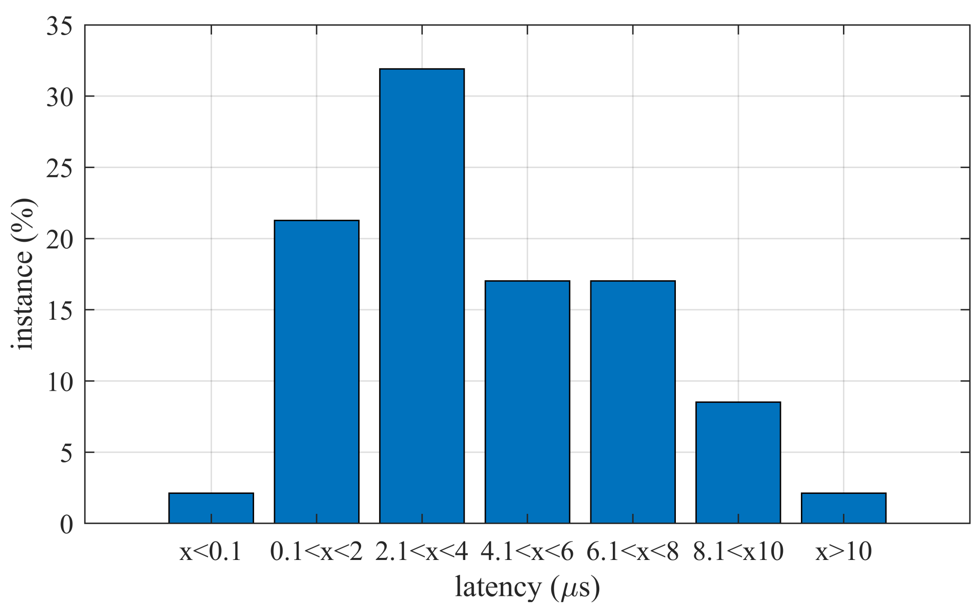

Figure 6: Timing instance of trigger latency between wireless receivers onboard two sensor packages.

To investigate trigger latency, an experimental setup was constructed to measure the time it takes for two packages to receive a wireless trigger and initiate data collection. A high-resolution oscilloscope is connected to a digital pin of both packages, a transmitter is then used to send a wireless trigger command. The time difference (trigger latency) between the two sensor packages is recorded over multiple iterations with the data normalized as a percentage. While varying the distance between the transmitter (TX) and the two receiver sensor packages (RX1, RX2), a better understanding of how antenna orientation and distance influence the sensor delay is deduced. Shown in Figure 6, the system's latency lies mainly below 10 microseconds.

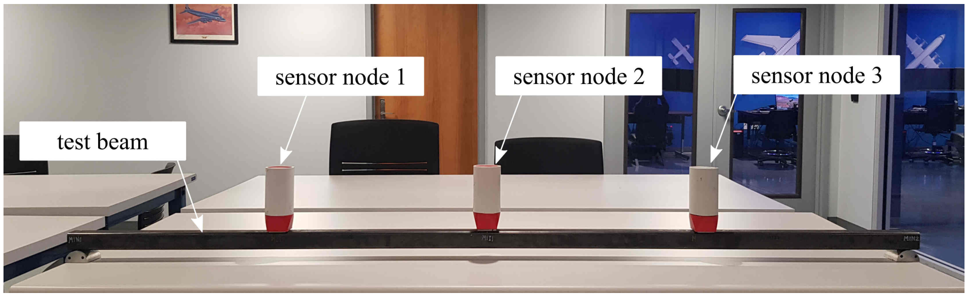

Figure 7: Benchtop experimental setup for the sensor package network deployment.

In this experiment, the simulated beam from the finite element analysis is constructed. The structure of choice was adopted for its simplicity and well-known behavior. Three sensor nodes were used as shown in Figure 7. A wireless transmitter was used to initiate all sensors within an acceptable tolerance. The beam was then excited with an impulse response using a hammer at various positions on the beam. This ensured that all mode shapes are excited. With the data of interest being the frequencies of the first three mode shapes, the time-domain data extracted from the test is converted to the frequency domain using the Fast Fourier Transform (FFT). Observed in Figure 8, the first three peaks in frequency. The peaks at 32.74 Hz, 126.62 Hz, and 281.50 Hz are of the first three modes respectively. This was compared to the FEA model presented prior. A maximum error margin of 11% was found between modal frequencies extracted from the model when compared to experimental results. This is attributed to boundary conditions and material property inconsistencies. Using mode shapes from the simulation, the sensor packages were positioned at the mode's antinodes where the vibration signal was at its highest. For mode 1 it was shown that the three sensors peak together as they all experience vibration in the same direction at 32.7 Hz. When observing mode 2 at 126.6 Hz, it is shown that sensor node 2 (middle package) does not detect any peak which correlates to a node of mode 2. Finally, peaks are observed as mode 3 at a frequency of 281.5 Hz indicating that all three sensors are on antinodes of the third mode.

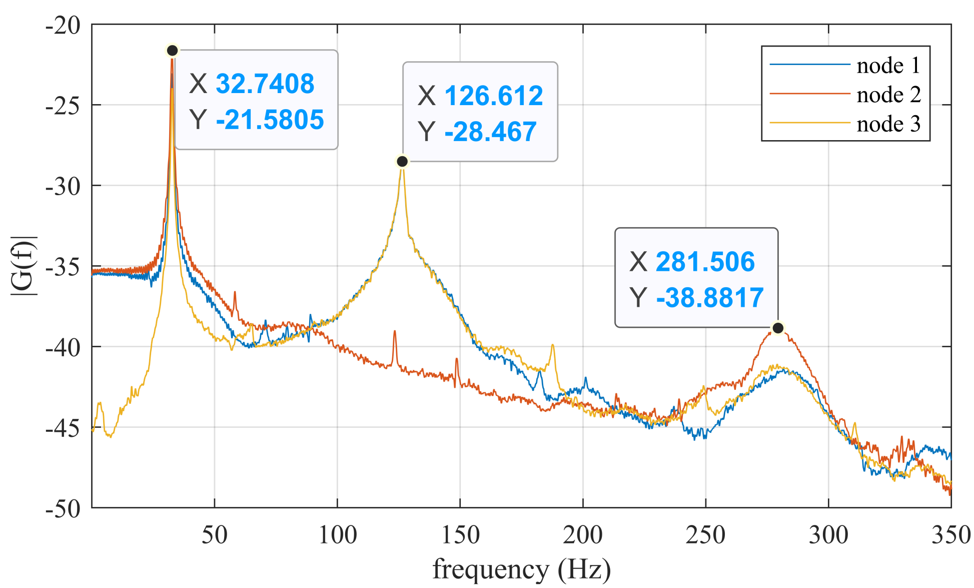

Figure 8: Frequency domain analysis of the beam impulse response test with the first three modes annotated.

CONCLUSION

In this work, an embedded system-based high-mobility sensor network is examined. During system characterization tests the network has shown the potential to be a reliable tool in structural health monitoring and experimental modal analysis applications. The ease of use and compact footprint, along with the magnetic mounting capability, makes these sensors optimal for UAV deployment where human access is challenging or dangerous. For rapid assessment of infrastructure following extreme weather conditions, such systems can be widely deployed in a very short time providing first responders with preliminary data about the infrastructure state. Experimentation has also shed the light on some system limitations. Although the wireless system ensures relatively low latency, the time non-determinism of the latency makes it challenging to accurately determine the phase. This will be further rectified by basing the trigger not only on a wireless signal but a real-time clock onboard the package, where all sensors would collect data on a preset schedule. That will enable all sensors to have an accurate time reference further minimizing latency-related error. Future work will also include error-handling capabilities with the wireless system to allow rapid data transfer and real-time monitoring capabilities.

ACKNOWLEDGEMENTS

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