ENCARDIO RITE
METASENSING FOR MEGA STRUCTURES

DYNAMIC SAFETY MONITORING OF BRIDGES USING MEMS ACCELEROMETERS

1 EXECUTIVE SUMMARY

This application note presents a proven methodology for ensuring bridge safety using wireless MEMS accelerometers for dynamic monitoring. With millions of aging bridges worldwide—including over 30,000 railway bridges in India more than 100 years old - there is an urgent need for reliable, non-destructive assessment of structural integrity under increased loading and speed conditions.

1.1 Key Solution

- Deploy paired triaxial accelerometers on both sides of each bridge span.
- Collect vibration data at 100 Hz for one minute daily (6,000 data points).
- Analyze modal frequencies using Fast Fourier Transform (FFT) & Power Spectral Density (PSD).
- Monitor structural health by comparing frequency signatures over time & between paired sensors.

1.2 Critical Benefits

- **Early damage detection**: Identifies stiffness loss, cracking, and deterioration before visual signs appear
- **Symmetry validation**: Paired sensors (left/right) detect asymmetric damage within individual spans
- **Long-term trending**: Establishes baseline "structural fingerprints" and tracks changes over months/years
- **Practical implementation**: Low data volume (few MB/day/bridge), battery-powered operation, wireless transmission
- **Cost-effective**: Enables condition-based maintenance rather than costly time-based or reactive approaches

1.3 Proven Methodology

Modal frequency analysis, conducted through FFT/PSD, has been validated as an industry-standard method for structural health monitoring. Changes in natural frequencies reliably indicate structural issues such as material degradation, cracking, structural damage or bearing dis-functioning. Real examples (in later section) from multi-span steel truss and cable-stay bridges demonstrate effectiveness of this approach.

1.4 Data Management

Encardio Rite provides the FFT and PSD data in comparative graphical form from adjacent accelerometer pairs through its customer friendly advanced Data Management Software Proqio.

1.5 System Features

Encardio Rite's wireless accelerometer system provides ± 2g range, 20-bit resolution (3.8 µg), low noise density (22.5 µg/√Hz), and LoRa RF wireless transmission, with operation from -40°C to 80°C.

This solution enables railway authorities and bridge managers to confidently assess the safety of existing infrastructure and maintain continuous monitoring for proactive maintenance planning.

2 PURPOSE

The purpose of this Application Note is to describe in simple words the use of **Accelerometers for:**

2.1 Ensuring old & present bridges are safe under enhanced loading/speed conditions.

India has more than 30,000 railway bridges that are more than 100 years old. Can it be reliably determined if these and other bridges are safe to carry heavier loads of today with higher speed requirements? Accelerometers help in determining this non-destructively.

2.2 Long term safety monitoring of bridges.

Accelerometers enable assessment of dynamic behaviour and are indispensable for long-term Structural Health Monitoring (SHM). The main objective of SHM is to detect & assess bridge condition, damage, fatigue and performance for proper and timely maintenance and safety.

Advantage is taken of the fact that any structure vibrates based on its fundamental modal frequencies. In order to identify modes of bridge characteristics, it is necessary to excite the structure in order to produce a response at each relevant mode. This however is not normally possible. Wind loads, traffic vibrations, seismic activity and nearby construction activity make structures to vibrate at well defined frequencies depending upon their construction design, geometry and materials used.

In case of structural damage, the frequency of vibration changes. This property is used to assess damage or wear/deterioration of the structure based on pattern recognition. Repeating, the vibration pattern of the structure changes in case of any damage or wear tear.

The system comprises of two wireless accelerometers mounted on both sides of each span of the bridge. Acceleration values as a function of time and frequency domains are determined. Comparison of acceleration vs. modal frequency graphs from accelerometers mounted on both sides of the individual spans, give important information on the safety of the span and predict performance of the structure.

Vibration data is used to extract features that characterize normal conditions and to use them as a template, reference or signature of the structure. During on-going structural monitoring, appropriate features are extracted from the data and compared with the reference. Any significant deviation is considered as signal novelty or possible damage. Several studies present in the literature are based on the comparison of measured vibration data such as natural frequencies and vibration modes in undamaged and damaged states of the structure. This methodology has proven to be effective and efficient.

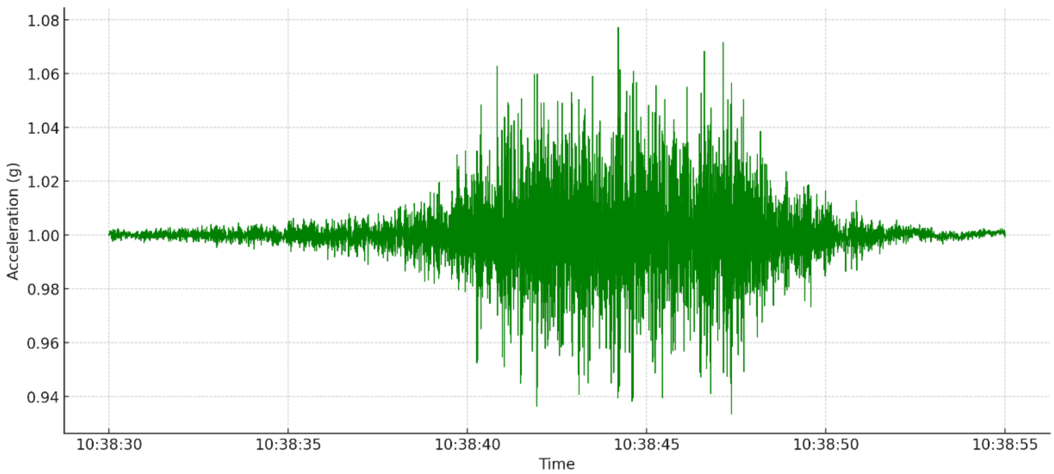


Figure 1: *Raw data of vertical acceleration with time from an accelerometer*

Above is a typical graph of acceleration in Z direction, from data extracted from an accelerometer mounted on mid-span of a bridge, when a heavy vehicle passes over it. This data, as such does not mean much. It needs processing. Vibration data when processed by FFT (Fast Fourier Transform) and PSD (Power Spectral Density) makes a lot of sense and is extensively used for long term Structural Health Monitoring (SHM). The method is extensively used for detecting structural deterioration by monitoring changes in modal parameters over time. The approach provides a robust, quantitative basis for ensuring bridge safety and optimizing maintenance. The methodology is used for:

- Safety monitoring of existing bridges
- To track changes in dynamics of the bridge over time (natural frequencies and modal analysis).
- Safety monitoring of existing bridges in whose vicinity construction activity is taking place.
- To track abnormal vibrations on bridge due to seismic activity, high wind velocities, movement of heavy traffic/railway trains or vehicle collisions etc.

Encardio Rite provides a robust wireless accelerometer system designed to precisely access acceleration in various infrastructure applications including bridges. Equipped with MEMS technology, the accelerometer captures triaxial acceleration and temperature data to help monitor the health of the bridge. It connects wirelessly via RF LoRa technology with a gateway' enabling long range data transmission, remote management and advanced data analysis.

The following sections provide a treatise on a one stop complete solution from Data Collection (sensor nodes), Transmission (RF and cellular) and Data Processing (Proqio) offered by Encardio Rite on the subject. Actual examples are provided in the latter part of this Application Note.

3 DATA RETRIEVAL

Two modes of data collection can be programmed with Encardio Rite sensor nodes:

3.1 Time triggered

Purpose is to determine the normal behaviour of an undamaged structure and then to monitor its behaviour over time to evaluate its current health.

Several options are available to set the time intervals and the sample rate for extracting the data (refer to literature – datasheet 2401-25R1). It is recommend that to start with, retrieve the data once a day at 100 Hz for a period of one minute at <u>a time when sufficient traffic is expected on the bridge</u>.

3.2 Threshold triggered

Purpose is to detects abnormal vibrations caused by seismic events, high wind speeds, or vehicular impacts.

Acceleration threshold is configurable based on site-specific requirements to detect critical vibration events. Again, several options are available to set the time intervals and the sample rate for extracting the data (refer to literature – datasheet 2401-25R1). We recommend that to start with, set retrieval of data at 100 Hz for a period of one minute pre trigger and one minute post trigger.

Monitoring in threshold trigger mode requires data to be recorded on the node continuously. This requires node to be powered by mains or solar power. Recorded data is continuously deleted in case the trigger value is not reached.

4 PROCEDURE

Vibration monitoring with focus on natural modal frequency is the best method to monitor the integral stability of a structure.

As mentioned earlier, figure 1 shows an acceleration vs. time graph from an accelerometer mounted on a bridge and as such it does not provide much information on the state of the structure. To make it simple to understand and read, the ambient frequency spectrum from the time or threshold triggered window is used to plot the FFT and PSD graphs of the structure. The FFT and PSD graphs provide the initial modal frequencies of the structure. This initial FFT/PSD *signature* is compared with future or adjacent FFT/PSD *signatures* of the structure to reliably monitor its health with time.

Accelerometers on bridges are generally mounted on both sides of every span. Under normal conditions, both the accelerometers should give similar FFT/PSD profiles. In case of damage or crack formation on any part of a span of the bridge, the FFT/PSD profile from the two accelerometers will not remain similar. This provides important information on the structural integrity of spans on the bridge.

Initial modal parameters (frequencies, mode shapes) are established when the bridge is known to be in good condition. Over time, repeated FFT/PSD analyses are performed on new data sets. Any significant, persistent shift in the identified frequencies or mode shapes may indicate:

- Loss of stiffness (e.g., due to cracking, corrosion, or joint failure)
- Mass changes (e.g., accumulation of debris, water ingress)
- Boundary condition alterations (e.g., bearing malfunction)

Note 1: It is very difficult to extract the natural frequencies of vibration (modes) of structures which are almost stationary and not moving. Activities like traffic movement, wind loads, seismic activity and nearby construction make structures to vibrate. The accelerometer is able to record vibrations of the bridge span because of these activities.

The magnitude and frequency recorded through FFT/PSD is somewhat affected by these activities and should be taken into consideration while drawing any conclusion. To explain it a little better, vibrations generated by dynamic loading of a bridge span by a car, heavy truck or a railway engine will be different depending upon their weight and speed. These effects are generally not too much and the modal frequency variation is within a few percent.

Note 2: FFT and PSD may report slightly different modal frequencies due to different resolutions and processing methods. This is normal. Always use same method consistently for trend analysis.

Note 3: It is recommended to monitor environmental parameters like wind velocity, temperature and humidity because these have an effect of the natural frequencies of the structure. For example, change in environmental temperature, changes the geometry of the structure. This will affect the modal frequencies to some extent.

Note 4: Monitoring of static strain by the use of vibrating wire strain gauges gives important information on variation of static loading on the bridge. Strain gauges are generally mounted on span or trusses.

5 Modal Analysis

For bridge structural health monitoring and to ensure its safety, it is necessary to measure its dynamic behaviour by determining its modal frequencies. Fast Fourier Transformation (FFT) and Power Spectral Density (PSD) of the waveform give important information. By monitoring vibrations over time, engineers can detect changes in the natural frequencies and modes of the bridge, which may indicate structural damage or deterioration. Modal frequencies can be assessed by using accelerometers in new bridges during construction and retrofitting of old bridges.

FFT is a mathematical algorithm that converts time-domain acceleration data into the frequency domain. By applying FFT to the acceleration signals, the dominant frequencies (natural frequencies) of the bridge can be identified. FFT is a plot of acceleration (g or m/s^2) vs. frequency (Hz).

PSD helps in better identifying the modal frequencies. It is a plot of g^2/Hz on Y axis vs. Hz on X axis.

By analyzing the vibration data, it is possible to extract modal parameters that are sensitive to changes in mass, stiffness, and boundary conditions—parameters that are directly affected by structural deterioration or damage.

By periodically recording and analyzing acceleration data, it is possible to track changes in the bridge's dynamic characteristics over time. Shifts in natural frequencies or changes in mode shapes can indicate issues such as material degradation, cracking, loosening of connections, or other forms of structural damage.

A vibration waveform can be written as the summation of simple harmonics:

Consider **A sin(ωt+ϕ)**, where

A is the amplitude,

ω is the pulsation (ω=2πf),

f is the frequency and

ϕ is the phase shift.

Then if:

$X = A\sin(\omega t+\phi)$ is the displacement

$V = A\omega\cos(\omega t+\phi)$ will be the velocity and

$A = -A\omega^2\sin(\omega t+\phi)$ will be the acceleration.

In example of a simply supported single-span beam bridge, the first four natural flexion modes are illustrated in figure 2.

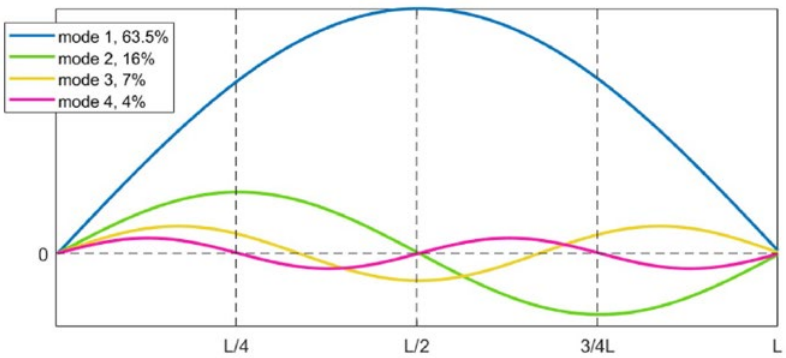


Figure 2: *First four flexional modes (vertical and horizontal) of a simply supported single span beam (length L). The percentage values in the legend indicate the modal participation factor. (Courtesy Crystal Instruments Corporation)*

Ideally, to monitor maximum amplitude, sensor should be put at L/2 for modes 1 & 3, L/4 for mode 2 and L/8 for mode 4. However to start with, we recommend that accelerometers be installed mid span for the bridge.

Note: Care should be taken to instrument every span with accelerometers **on both sides of the bridge** to ensure safety of each individual span. In case modal frequencies determined through accelerometers on both sides of a span on the bridge are almost the same, the span should be in good condition and is indicative of safety.

Modal frequencies of the span are affected by parameters like temperature variations, wind velocity and loading conditions. For example, the lane in which traffic moves, traffic volume and its type and speed affect the modal frequencies. Modal frequency data from accelerometers on both sides of the span will therefore show some variations. This is natural.

Preferred range of accelerometers in bridges and large structures is ± 2 g.

6 EXAMPLES

6.1 Multi-span Steel Truss River Road Cum Rail Bridge

Example of a FFT and PSD with two triaxial accelerometers installed on both sides of a span on the bridge is given in the graphs below (figure 3, 4,5 and 6). Data is collected on May 31 and June 2, 2025. Please particularly note that the FFT/PSD graphs from the two triaxial accelerometers superimposed on each other almost coincide with each other. This shows that the span on the bridge is in good condition structurally.

Please specifically note that the modal frequencies highlighted in the FFT and PSD graphs are very close to each other.

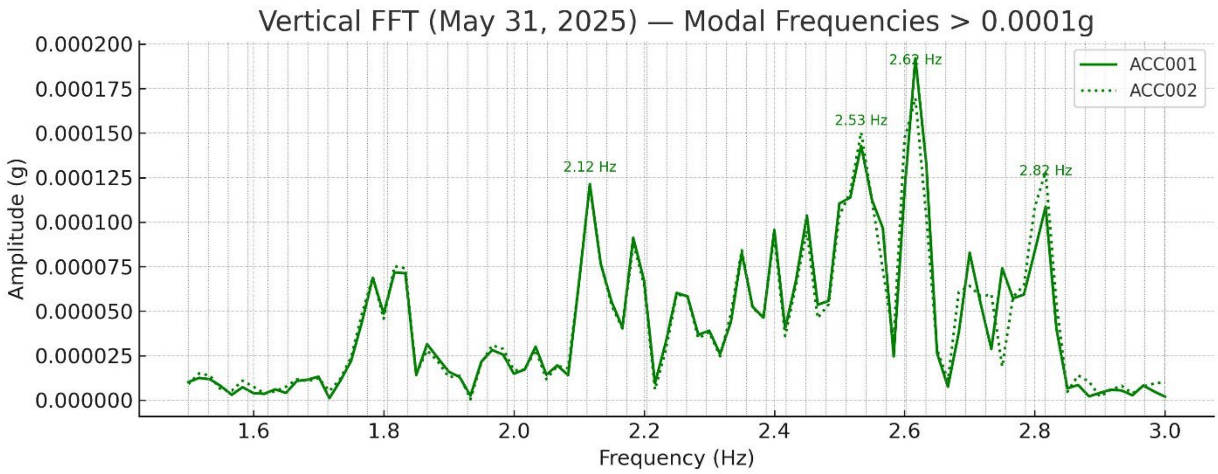


Figure 3: *Mark similarity of FFT data from the accelerometers installed on both sides of the span. The presence of high-confidence peaks on both ends of the spans validates symmetrical modal behavior and indicates structural integrity. The scale on the X axis in the FFT graph has been changed to 1.4 – 3.0 Hz as the modal frequencies fall in this range. Data taken on May 31,2025*

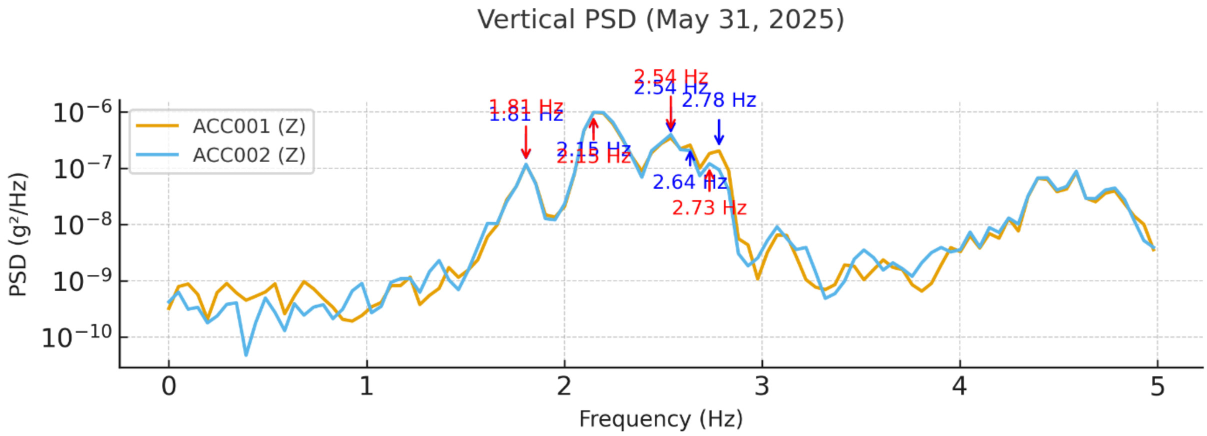


Figure 4: *Mark the PSD from the same data as in figure 3 taken on May 31, 2025 from two accelerometers mounted on both sides of a span. The similarity of the data is indicative of the span of the bridge being safe.*

ACC001 and ACC002 show closely matching dominant modes concentrated between approximately 1.8–2.8 Hz. Paired peaks differ typically by less than one frequency bin (~0.05 Hz), indicating a high degree of symmetry and consistent vertical dynamic behavior across the span during this measurement. Such consistency in natural frequencies across symmetric measurement points is widely used as evidence of unchanged global stiffness and boundary conditions, subject to confirmation over time.

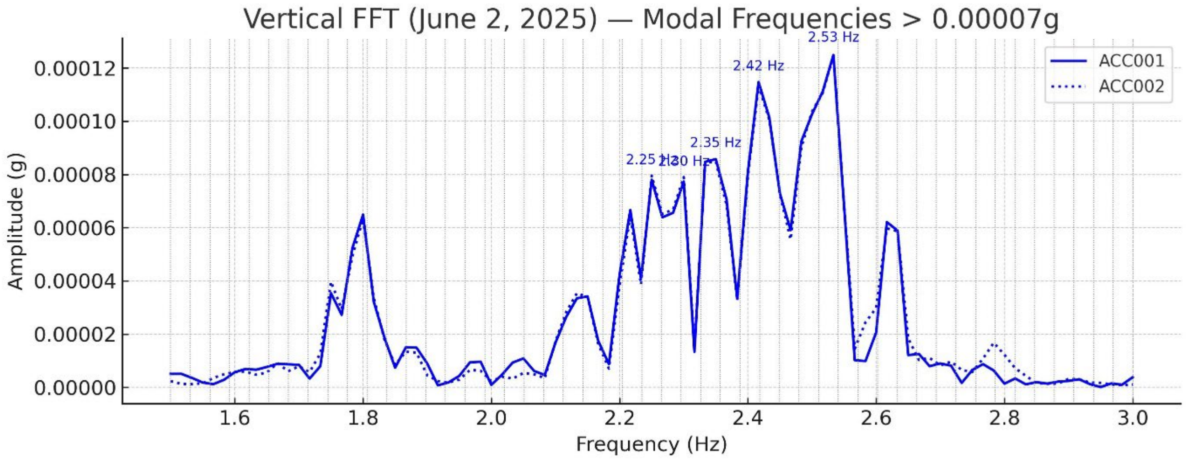


Figure 5: *FFT from data taken on June 2, 2025 from the same accelerometers as in figure 3. The variation in the amplitude from May 31, 2025 in the graph in figure 3 (0.00019 g vs. 0.00012 g) is due to different traffic loads on the two occasions. As in figure 3, the scale on the X axis has been changed to 1.4 Hz to 3.0 Hz as the modal frequencies fall in this range.*

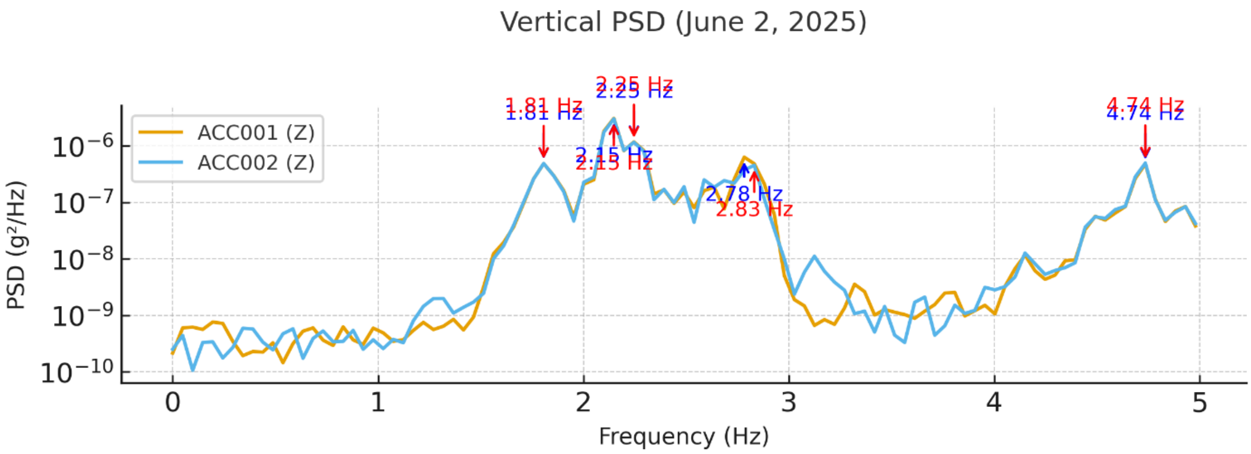
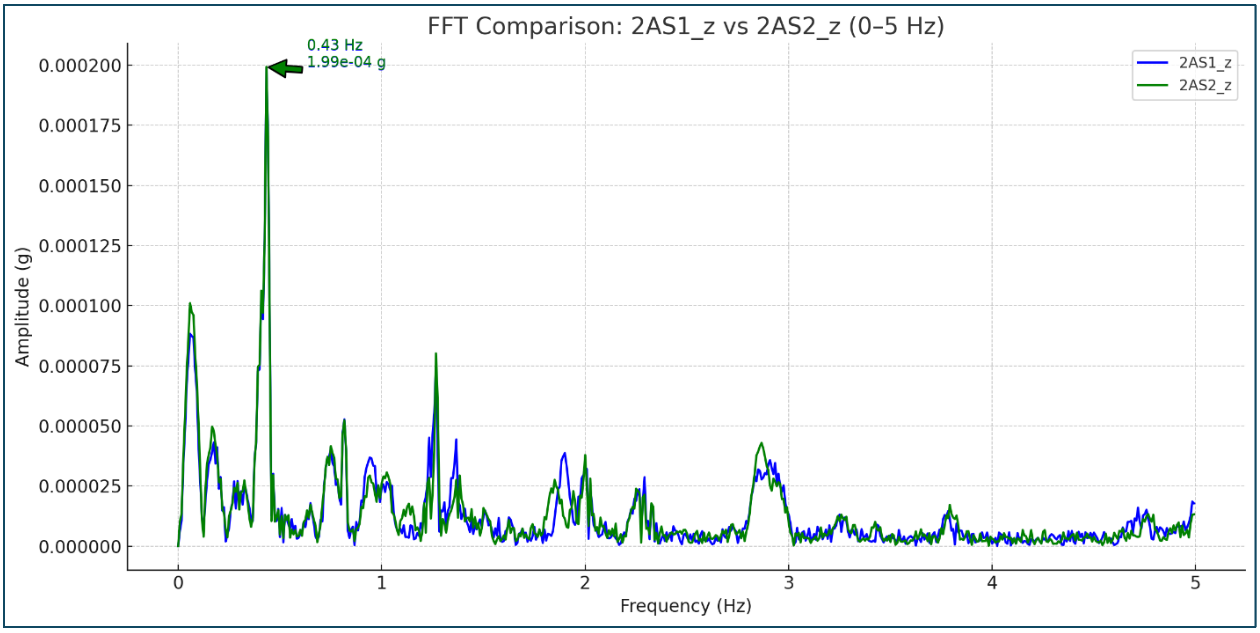


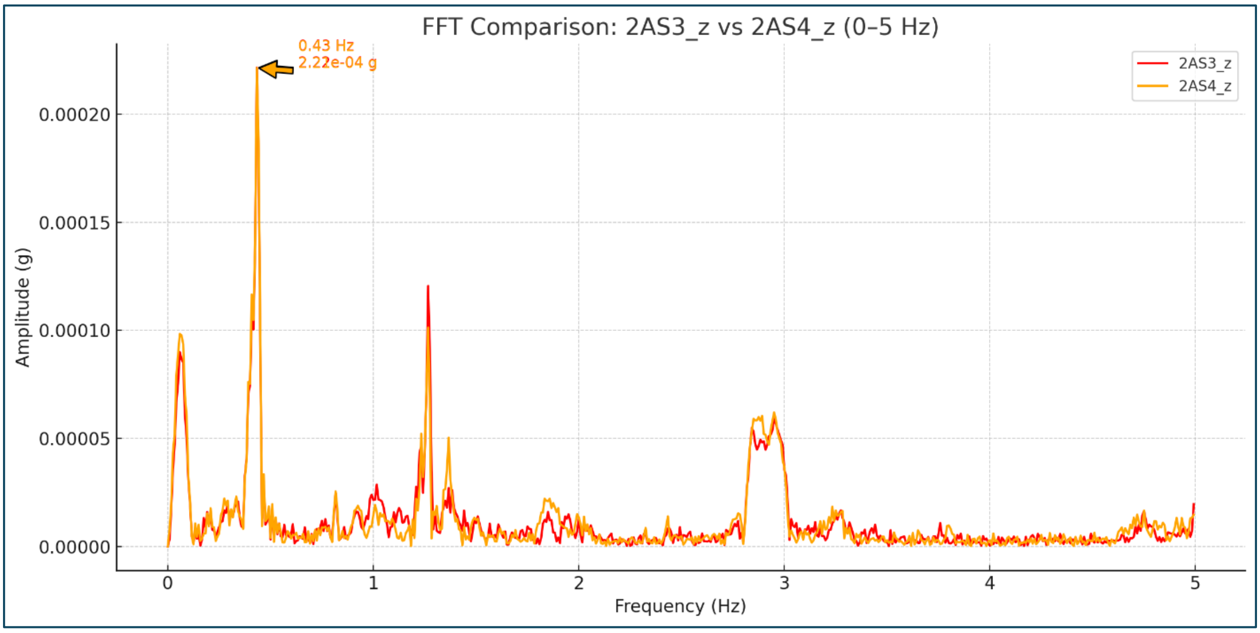
Figure 6: *PSD from data taken on June 2, 2025 from the same accelerometers as in figure 3. The variation in the amplitude from May 31, 2025 in the graph in figure 3 (0.00019 g vs. 0.00012 g) is due to different traffic loads on the two occasions. The 4.74 Hz frequency, though not as prominent in the May 31, 2025 PSD graph, is indicative here.*

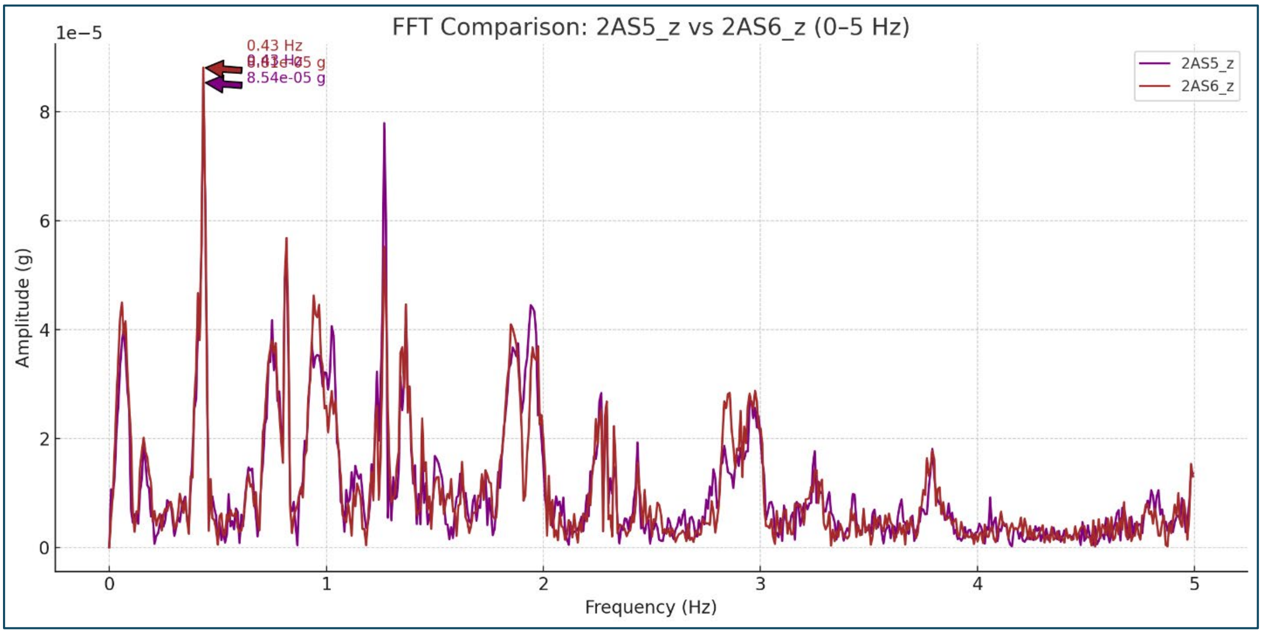
For robust safety assessment, repeat measurements should be trended after temperature variations, traffic patterns, or events and expanded with modal values. Sustained shifts > 2–3 % in key modal frequencies, should warrant closer inspection.

6.2 Cable Stay Rail Cum Road River Bridge

Data in this example is from the larger span of a rail cum road cable stay bridge on a river in India. Data from six sensors mounted longitudinally in groups of two on two sides of a cable stay bridge taken on June 7, 2025 is reproduced below. The distance of the three pair of sensors from the pillion is 75 m, 150 m and 225 m respectively. Comparative FFT and PSD graphs of each pair is reproduced below. Particularly note that the graphs from each pair coincide with each other. Also note difference in amplitude of sensors on two sides of each pair. This can be due to eccentric traffic load, slight variation in mounting of the accelerometer sensors or normal structural variation in geometry and composition of the bridge.

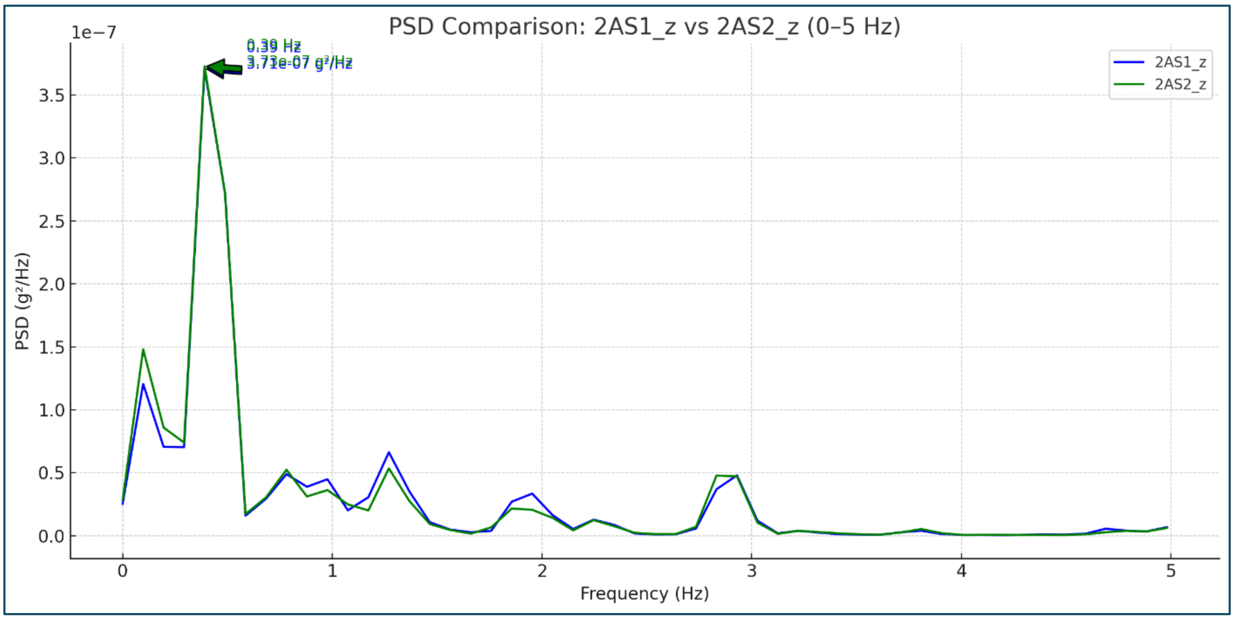

FFT Comparison: 2AS1_z vs 2AS2_z (0–5 Hz)
0.43 Hz
1.99e-04 g
2AS1_z
2AS2_z
Amplitude (g)
Frequency (Hz)

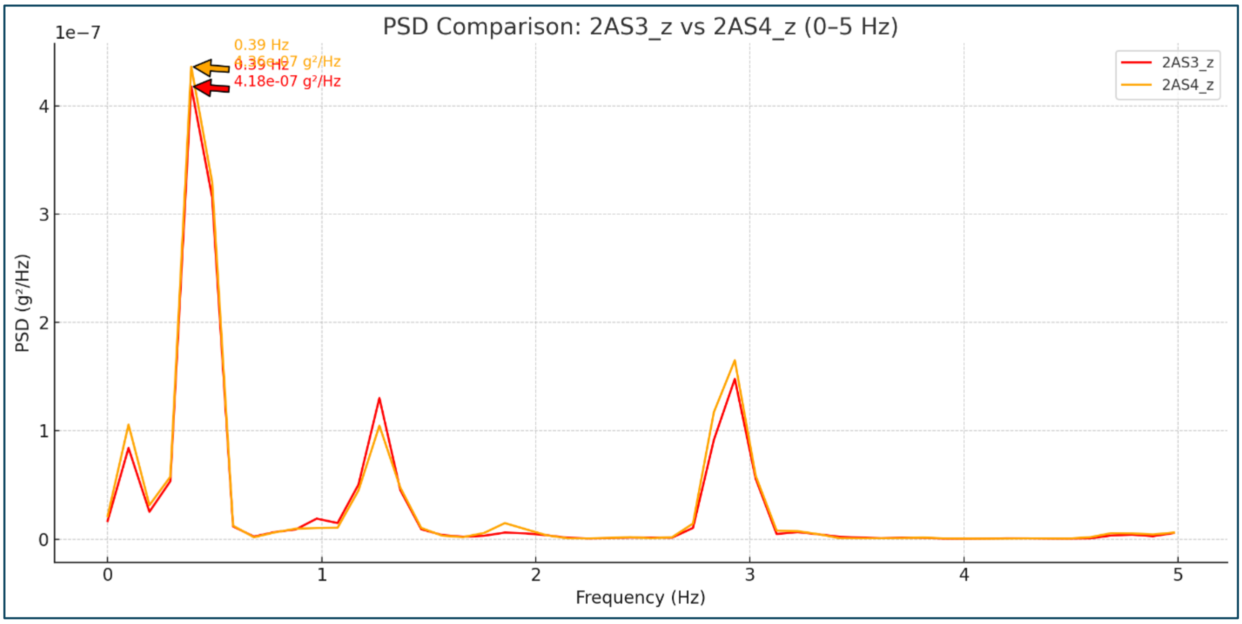

FFT Comparison: 2AS3_z vs 2AS4_z (0–5 Hz)
0.43 Hz
2.22e-04 g
2AS3_z
2AS4_z
Amplitude (g)
Frequency (Hz)

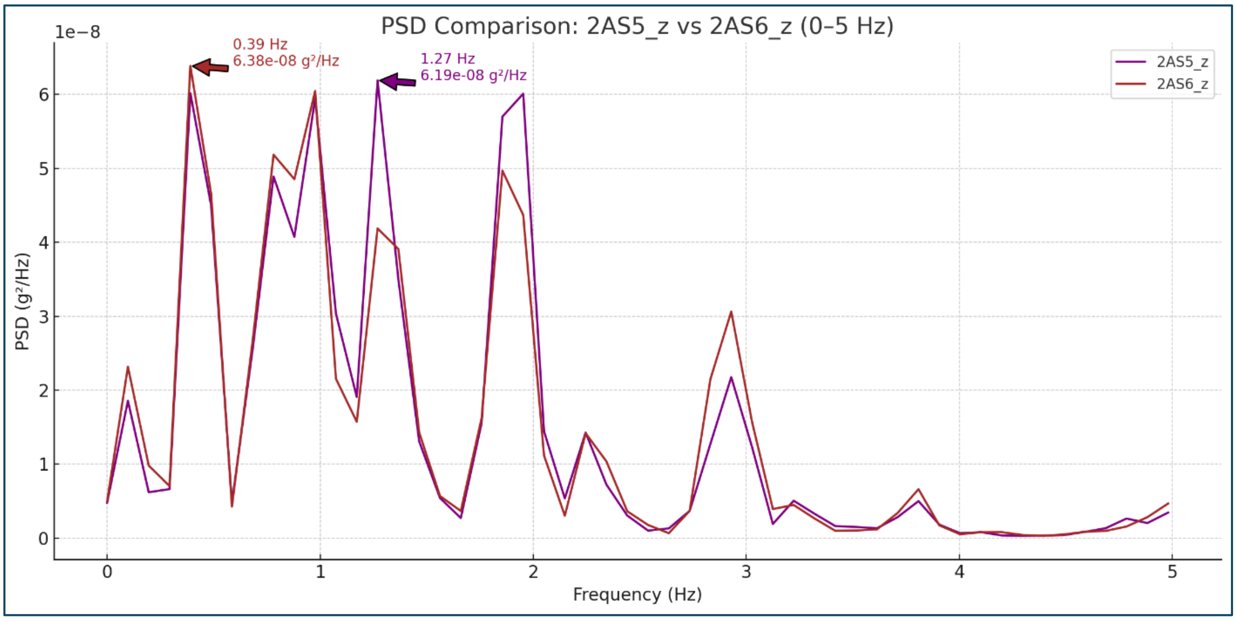

FFT Comparison: 2AS5_z vs 2AS6_z (0–5 Hz)
1e−5
0.43 Hz
8.54e-05 g
2AS5_z
2AS6_z
Amplitude (g)
Frequency (Hz)

The first modal frequencies by FFT are as follows:

Sensor	Peak frequency (HZ)	Peak FFT amplitude (g)
2AS1_z	0.433	0.000199
2AS2_z	0.433	0.000199
2AS3_z	0.433	0.000222
2AS4_z	0.433	0.000221
2AS5_z	0.433	0.000085
2AS6_z	0.433	0.000081







The first modal frequencies by PSD are as follows:

Sensor	Estimated Natural frequency (HZ)	Peak PSD amplitude (g^2/Hz)
2AS1_z	0.391	3.71E-07
2AS2_z	0.391	3.73E-07
2AS3_z	0.391	4.18E-07
2AS4_z	0.391	4.36E-07
2AS5_z	0.391	6.19E-08
2AS6_z	0.391	6.38E-08

7 CONCLUSIONS

1. Accelerometers enable assessment of dynamic behaviour and are indispensable for long-term Structural Health Monitoring (SHM) of bridges.
2. Through FFT and PSD, the vibration recorded by the accelerometer can be conveniently converted into readable modal frequencies. Generally, for safety monitoring bridges, data at 100 Hz for one minute a day (6,000 data points) is sufficient for maintaining safety of the bridge.
3. Two wireless accelerometers are mounted on both sides of each span of the bridge. In case of a cable stay bridge, accelerometer pairs are mounted on transverse sections at defined regular distances from the Pillion. Similarity of FFT and PSD data from the accelerometers installed on both sides of the bridge at same transverse sections validates symmetrical modal behaviour and indicates structural integrity. Dissimilarity indicates damage or impending failure.
4. Long term monitoring with data taken once a day at 100 Hz for one minute has following plus points:
   - A high resolution baseline of dynamic characteristics of the bridge is established. This allows detection of progressive stiffness loss, fatigue and foundation settlement etc. before visual signs appear.
   - Bridges are influenced by temperature, humidity, traffic load, and river/soil conditions. Long-term record provide data on normal seasonal/environmental variations. For example, frequency naturally drops in summer due to thermal expansion, but sudden deviations outside this band flag potential damage.

- Modal frequencies are global indicators of stiffness. In case of damage at any transverse section, frequency symmetry between left/right accelerometers will diverge. Detecting this divergence early provides a warning before catastrophic issues arise.
- Historical modal data builds a "structural health fingerprint" of the bridge. Modal shifts can be correlated with inspections, retrofits, or traffic changes. This enables condition-based maintenance instead of costly time-based or reactive maintenance. After strengthening or repair, modal frequencies can confirm whether the intervention restored expected stiffness.
- A continuous archive is invaluable in case of accidents or unusual events like earthquakes, heavy floods etc. Comparing "before vs after" frequency records pinpoint damage.

5. FFT provides higher frequency accuracy (narrower bin spacing) with a resolution of 0.0167 Hz ($\Delta f = fs/N = 100/6000 \approx 0.0167$ Hz for 100 Hz, 1 min data), allowing precise peak frequency estimation. However, raw FFT spectra are noisy, making every random fluctuation or background vibration appear as an additional spike. The FFT curve looks jagged as compared to PSD.

   PSD, computed with Welch's method is best for confidently identifying dominant modes but provides a resolution of 0.049 Hz ($\Delta f = fs/2048 = 100/2048 \approx 0.049$ Hz with n per seg = 2048). It produces smoother spectra, making modal peaks easier to identify under noisy conditions. In practice, PSD highlights modal bands while FFT refines their exact values. Together, they provide confidence and accuracy in monitoring bridge span safety.

8 THE BOTTOM LINE

The world has millions of railway bridges, a large number being older than 100 years. The bridges must be safe for carrying higher loads at much higher speeds. Monitoring of dynamic response using two accelerometers on both sides of transverse sections along the length of the bridge for one minute a day at 100 Hz is a good practical solution to undertake this vast job. Full time streaming with continuous data 24 hours a day at 100 Hz or more is unnecessary for long term safety monitoring and will only overload the data management servers/software.

- Low-frequency modal peaks (0–5 Hz for long spans) shift measurably with stiffness changes. Tracking these daily gives an early warning of deterioration (fatigue, bearing issues, scour, damage etc.)
- Paired sensors LHS/RHS per section catch damage through asymmetries even when absolute frequencies are seasonally drifting.
- Each bridge span should be independently monitored with LHS/RHS paired sensors.
- 60 s × 100 Hz (6,000 samples/sensor), i.e. a few MB/day/bridge is right size data. The order of magnitude is almost nothing 24/7 logging, yet enough to resolve modes (~0.017 Hz FFT bins; ~0.049 Hz with Welch PSD as configured).
- For environmental normalisation over long periods, co-record temperature (air/steel/concrete), humidity, wind velocity and in case of river overbridge water level. Encardio Rite accelerometer node has a built-in temperature sensor.
- Sample at 100 Hz for 1 minute per day is recommended to be taken at similar times daily or around similar traffic states.
- In case of unusual high acceleration magnitudes, the system has provision for recording trigger bursts at 100 Hz for 1 minute before and 1 minute after the peak acceleration.
- Encardio Rite's Data Management Software Proqio is configurable to provide comparative FFT and PSD data in graphical form paired sensors (LHS/RHS) along the length of the bridge.

8.1 Summary essential specifications:

Accelerometer Node	
Sensor	Mems triaxial
Accelerometer range	± 2 g
Accelerometer resolution	20 bit (~0.000004 g)
Noise density	22.5 µg/√Hz
Temperature sensor	Inbuilt
Operating temperature	-40°C to 80°C
Power supply	1 lithium battery type D 14.5 Ah 3.6 V or external 12V DC
Wireless transmission	LoRa RF 866–915 MHz
Link coverage	1 - 2 km (depends upon line of sight and site conditions)
Gateway	
Rx sensitivity (at SF 12)	- 148 dBm
Tx power	22 dBm (max)
Communication	Cellular 4G, Ethernet, Wi-Fi, Bluetooth, LoRa
Power supply	PoE or Mains adaptor 12V 2A, or 12V 60W solar (battery back-up of 15 days)