PROJECT PHASE 1

Highway Bridge Health Monitoring

Time & Frequency Domain Analysis

Course: Sensing Techniques and Data Analytics
Instructor: Mohammad Talebi-Kalaleh
Institution: University of Alberta
Due Date: October 24 at 11 AM
Weight: 20% of final grade (100 points)

1 PROJECT NARRATIVE

Project Background

In summer 2023, your engineering firm installed a permanent monitoring system on the Highway 43 bridge—a critical three-span continuous structure carrying 15,000 vehicles daily. The initial measurements established a healthy baseline during warm conditions (15–30°C).

In October 2024, routine monitoring detected anomalies. Temperature had dropped (-15 to 0°C), and frequency shifts exceeded seasonal expectations. Your team was dispatched immediately for comprehensive testing:

October 20, 2024: First damage assessment revealed moderate stiffness reduction in span 3.

October 27, 2024: Follow-up testing showed damage progression to severe levels in span 2 and 3. The bridge was closed to traffic.

October 28, 2024: Final comprehensive measurements for future reference and damage pattern documentation.

As the lead SHM engineer, your task is to analyze this comprehensive dataset using time and frequency domain techniques to understand damage progression and validate the performance of the monitoring system.

2 STRUCTURAL CONFIGURATION

The structure consists of three continuous spans (20m–40m–60m) with 24 accelerometers positioned at 5m intervals for precise modal observability.

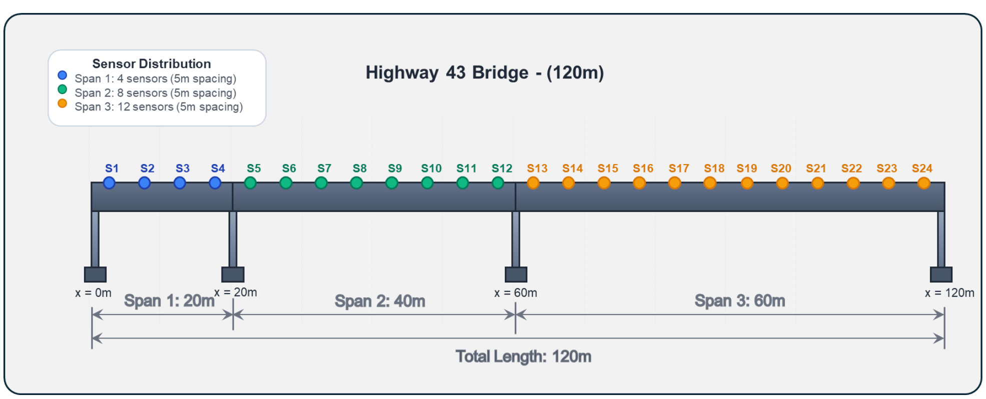

Figure 1: Highway 43 Bridge with sensor positions. Sensors are uniformly spaced at 5m intervals along the deck.

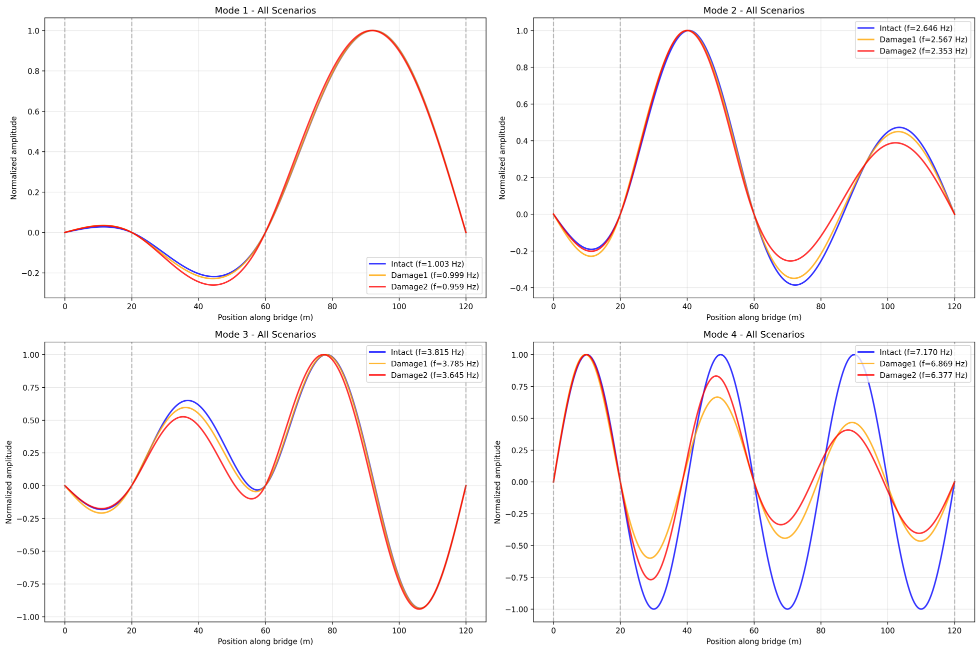

Figure 2: Simulation-based modal properties of the bridge across damage scenarios.

3 SENSOR NETWORK CONFIGURATION

Table 1: Sensor positions measured from left support (x = 0 m). Supports located at 0, 20, 60, and 120 m.

Span 1 (20m)				Span 2 (40m)				Span 3 (60m)			
ID	x(m)	ID	x(m)	ID	x(m)	ID	x(m)	ID	x(m)	ID	x(m)
S1	2.5	S3	12.5	S5	22.5	S9	42.5	S13	62.5	S19	92.5
S2	7.5	S4	17.5	S6	27.5	S10	47.5	S14	67.5	S20	97.5
				S7	32.5	S11	52.5	S15	72.5	S21	102.5
				S8	37.5	S12	57.5	S16	77.5	S22	107.5
								S17	82.5	S23	112.5
								S18	87.5	S24	117.5

4 GROUP ASSIGNMENTS

Each group analyzes a unique 9-sensor subset to ensure independent work while enabling cross-validation. Identify your group number and use ONLY your assigned sensors:

Table 2: Sensor assignments by group. Use ONLY your assigned sensors for all analyses.

Group	Span 1 (2 sensors)	Span 2 (3 sensors)	Span 3 (4 sensors)
1	S1, S2	S5, S7, S9	S13, S16, S19, S22
2	S2, S3	S6, S8, S10	S14, S17, S20, S23
3	S3, S4	S7, S9, S11	S15, S18, S21, S24
4	S1, S3	S8, S10, S12	S16, S19, S22, S24
5	S3, S4	S5, S7, S9	S13, S15, S18, S21
6	S2, S4	S6, S9, S12	S15, S18, S21, S24

5 DATA STRUCTURE AND ACCESS

JSON File Organization

The data file `bridge_vibration_data.json` contains hierarchical structure for efficient navigation:

```
{
  "scenarios": {
    "intact": {
      "impact_tests": {
        "impact_location_1": {
          "sensor_1": [6000 samples @ 200Hz = 30s],
          "sensor_2": [...],
          ...
          "sensor_24": [...]
        },
        "impact_location_2": {...},
        ... (24 impact locations total)
      },
      "ambient_tests": {
        "test_1": {
          "sensor_1": [12000 samples @ 200Hz = 60s],
          "sensor_2": [...],
          ...
          "sensor_24": [...]
        },
        "test_2": {...},
        ... (5 tests total)
      }
    },
    "damage1": {...same structure...},
    "damage2": {...same structure...}
  },
  "metadata": {
    "bridge_info": {
      "sensor_positions_m": {
        "S1": 2.5, "S2": 7.5, ..., "S24": 117.5
      },
      "support_positions_m": [0, 20, 60, 120]
    },
    "sampling_parameters": {
      "sampling_frequency_Hz": 200,
      "impact_test_duration_s": 30,
      "ambient_test_duration_s": 60
    }
  }
}
```

Data Access Examples:

```
## Access ambient measurement
data['intact']['ambient_test']['measurement_1']['sensor_5']
# Returns: array of 12000 acceleration values

# Access impact response
data['damage1']['impact_test']['impact_location_3']['sensor_7']
# Returns: array of 6000 acceleration values

# Access metadata
positions = data['metadata']['sensor_positions_m']
fs = data['metadata']['sampling_frequency_hz']
```

6 ANALYSIS TASKS

6.1 Part A: Data Processing & Visualization — 20 points

A1. Data Organization (5 pts)

- Load JSON data and extract your 9 assigned sensors
- Verify sampling rate and data integrity
- Create a clear folder structure for saving results

A2. Time-Domain Visualization (5 pts)

- Plot 5-second windows of impact responses only for one measurement of all sensors
- Plot 10-second windows of ambient vibration for one measurement of all sensors
- Select 3 sensors and use one measurement. For each sensor, compare its response across the three scenarios. Present these as 3 subplots in a single figure (one subplot per sensor). Prepare separate figures for each test type (impact and ambient).

A3. Statistical Descriptors (10 pts)

- For ambient tests only, compute the following descriptors for all 10 measurements of each sensor: RMS, crest factor, skewness, and kurtosis.
- Present the mean value of each descriptor in tables organized by sensor and damage scenario. Prepare a separate table for each descriptor (one table per descriptor).
- Select one random sensor in the second span. For this sensor, plot all descriptors across its 10 measurements in each of the 3 scenarios (30 points per descriptor). Use color coding to distinguish scenarios. Each descriptor should be plotted separately; arrange them in a 2×2 subplot layout.
- Interpret the changes in descriptor values when damage occurs. What do these changes indicate physically?

6.2 Part B: Impact Test Analysis — 35 points

B1. Impulse Response Function Extraction (20 pts)

- Explain how a set of impact tests can provide the full IRF matrix at all assigned sensor locations. Clearly state which impact location corresponds to each row of the matrix. (No plotting required.)
- Extract and plot the IRF for three locations: one in the first span, one in the second span, and one in the third span. Use the case where the hammer is at the same location as the sensor (H_{ii}). Compare the amplitudes and periods of the responses.
- Discuss whether natural frequencies or damping can be extracted directly from these time-series IRFs. Why or why not?

B2. FFT Verification of Natural Frequencies (15 pts)

- Apply FFT to impact responses for each sensor (only when the hammer hits that sensor). For 9 sensors × 3 scenarios, this yields 27 FFTs.
- Plot the FFT magnitude results in a 3×3 layout for each scenario (3 figures total). Identify peaks for the first three natural frequencies in each plot.
- Calculate the mean natural frequency of each mode across the 9 tests.
- Discuss why the identified frequencies vary across the 9 tests within the intact bridge scenario. What are the sources of error?
- Create a table listing the mean and STD of the modal natural frequencies across 9 measurements. Also, compare the mean frequency shifts between the intact case and damage cases using (compare the modes in separate rows):

$$\Delta f^2 = \frac{f^2_{damage} - f^2_{intact}}{f^2_{intact}} \times 100\%$$

- Interpret the observed frequency changes between scenarios. What patterns do you notice?

6.3 Part C: Ambient Test Analysis — 35 points

C1. Spatial Correlation Analysis (8 pts)

- Compute the correlation coefficient ρ_{xy} between all sensor pairs in your assignment
- Generate 9×9 correlation heatmaps for each scenario.
- Explain which sensors are highly correlated and why. What does this imply about mode shapes?

```python
# Compute cross-correlation between sensor pairs
corr_matrix = np.zeros((n_sensors, n_sensors))
for i in range(n_sensors):
    for j in range(n_sensors):
        corr_matrix[i,j] = np.corrcoef(responses[i], responses[j])[0,1]

# Visualize
plt.figure(figsize=(8, 6))
sns.heatmap(corr_matrix, annot=True, cmap='coolwarm',
            center=0, vmin=-1, vmax=1, square=True)
```

C2. Natural Frequency Identification (12 pts)

- Apply Welch's method to compute the Power Spectral Density (PSD) for each sensor using all 10 ambient measurements. For each measurement, average the PSDs across sensors.
- Plot the averaged PSDs of the 10 measurements (4×3 layout). Use peak detection to identify the first three natural frequencies.
- For each damage scenario, report the modal frequencies as the mean ± standard deviation across the 10 tests. Prepare one table per scenario (3 total). In each table, use rows for mode numbers and columns for measurement numbers.

$$\bar{f}_i = \frac{1}{10}\sum_{j=1}^{10} f_{i,j} \quad , \quad \sigma_{f_i} = \sqrt{\frac{1}{9}\sum_{j=1}^{10}(f_{i,j} - \bar{f}_i)^2}$$

C3. Temperature Effects (5 pts)

- For the intact scenario only, plot the frequency variations across the 10 measurements.
- Calculate coefficient of variation across the 10 measurements for each mode: $CV = \sigma/\mu \times 100\%$
- Check whether the variations are proportional across modes.
- Explain how to distinguish temperature-induced frequency shifts from structural changes. Why do all modes shift proportionally under temperature variation?

C4. Mode Shape Identification via FDD (10 pts) For each of the 3 scenarios separately:

- Identify the first three mode shapes using Frequency Domain Decomposition (FDD) on all 10 independent measurements (i.e., 10 estimates for each mode shape).
- Normalize mode shapes (maximum value = 1)
- For each mode shape, compute the average mode shape vector and the standard deviation vector from the 10 estimated values (two vectors per mode):

$$\bar{\phi}_r = \frac{1}{10}\sum_{j=1}^{10} \phi_{r,j}$$

- Plot the average mode shapes with error bars (±1 std) for each mode. Arrange in a 3×1 subplot. Provide one figure per scenario (3 figures in total).
- Compare average mode shapes of the damage scenarios with the intact baseline using the Modal Assurance Criterion (MAC). Report 3 MAC values per scenario:

$$MAC(\phi_i, \phi_j) = \frac{|\phi_i^T \phi_j|^2}{(\phi_i^T \phi_i)(\phi_j^T \phi_j)}$$

- Discuss the consistency of mode shapes and what changes indicate about possible damage locations.

Frequency Domain Decomposition Steps

(a) Build cross-PSD matrix: $\mathbf{S}_{yy}(f) = \mathbb{E}[\mathbf{Y}(f)\mathbf{Y}^*(f)]$
(b) Apply SVD: $\mathbf{S}_{yy}(f) = \mathbf{U}(f)\mathbf{S}(f)\mathbf{V}^H(f)$
(c) Identify peaks in first singular value
(d) Extract mode shapes from $\mathbf{u}_1(f_{peak})$
(e) Average across 10 measurements

Provided Analysis Tools

To assist with your FDD analysis, the following utilities are provided:

- `fdd_utility.py`: Complete FDD implementation with automatic peak detection
- `fdd_examples.py`: Working examples using the bridge dataset

6.4 Part D: Engineering Interpretation — 10 points

Provide a detailed discussion addressing:

- Why do frequencies decrease in damage scenarios?
- How do impact and ambient test results compare?
- What are the strengths and limitations of each testing method?
- Which sensors show the most significant changes, and why?

7 DELIVERABLES

Submission Requirements

Submit TWO files via the course portal:
File 1: `ProjectPhase1_GroupX.zip` - Complete project folder

```
ProjectPhase1_GroupX/
         Main.ipynb           # Complete Jupyter notebook
         figures/                  # All figures (300 DPI minimum)
         results/                # Numerical outputs
         README.txt              # File descriptions, group members
```

File 2: `ProjectPhase1_GroupX.pdf` - Exported notebook **with all outputs visible**

8 ACADEMIC INTEGRITY

While collaboration within groups is expected, each group must submit independent work. Code and interpretations must be original. Properly cite any external resources used.

9 GRADING RUBRIC

Component	Points	Key Assessment Criteria
Data Processing	20	Code correctness, visualization quality
Impact Analysis	35	IRF extraction, curve fitting accuracy
Ambient Analysis	35	FDD analysis, frequency consistency
Interpretation	10	Physical insight, engineering judgment

10 GETTING STARTED CHECKLIST

- ☐ Download `bridge_vibration_data.json` from course portal
- ☐ Download provided analysis utilities: `fdd_utility.py`, and `fdd_examples.py`
- ☐ Use provided starter code to load and explore data
- ☐ Identify your group number and note your 9 assigned sensors
- ☐ Create project folder with required structure
- ☐ Begin with Part A to familiarize yourself with the data
- ☐ Progress systematically through each part
- ☐ Focus on interpretation throughout your analysis
- ☐ Export notebook to PDF before submission deadline