Non-contact structural damage detection by natural frequency measurement with microphone

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ABSTRACT

Structural Damage Detection are crucial for infrastructure maintenance. This paper introduces an innovative non-contact approach to Structural Damage Detection, using acoustic method through microphone recording, which offers both convenience and cost-effectiveness when compared to traditional contact and optical techniques. The general principle of the method involves the identification of changes in natural frequencies due to stiffness reductions. The paper aims to assess the feasibility of this method in terms of damage severity detection, damage location identification, and overall accuracy through experimental testing.

Seven types of I-beam specimen, with four damage severities (intact, 10%, 25%, and 50% depth saw cut) at two locations (middle and quarter span) are tested in a free beam scenario. The first three bending natural frequencies in the strong axis direction are analysed. Results from the proposed microphone method are compared to the accelerometer method and Finite Element simulations. Impact factors such as knocking locations, sensor placement, and microphone distance to the beam are also considered.

Results demonstrate a clear reduction in frequencies as damage severity increases, affirming the feasibility of the proposed method for detecting structural damage. The microphone-based results closely match those obtained from accelerometers, underscoring its accuracy. This outcome serves as a foundational step and bolsters confidence in the continued development of innovative non-contact Structural Damage Detection technology. Such advancements can be applied to a broader spectrum of structural conditions, addressing diverse market needs.

1 INTRODUCTION

Structural Damage Detection (SDD) contributes to Structural Health Monitoring, and it is essential for investigating and maintaining structural health. Current SDD techniques are categorized into local and global methods. Local methods, such as Visual Inspection, Radiography, and Ultrasonic testing, are only suitable for smaller-scaled areas within infrastructures or detachable specimens and can require destructive testing (Lu and Wong, 2017). Global methods, so-called vibration-based methods, can assess the overall structural health and indicate structural damage by monitoring vibration responses such as natural frequency change and are normally non-destructive testing methods (Avci et al., 2021).

For Traditional global SDD methods, accelerometers, strain gauges, and load cells are commonly used in the market. They are contact-based methods and require installation (Adewuyi et al., 2006). In contrast, contactless methods are more convenient and innovative. Optical method, for example, utilizes laser reflection to capture vibration frequencies, but the optical instruments are costly (Baqersad et al., 2017). Another contactless approach will be the acoustic approach. It uses microphones to record and transfer natural frequencies through sound waves, which presents a more economical alternative. Despite its cost-effectiveness, the acoustic approach remains underexplored, with limited research focusing on its application. Only one past paper (Luo and Yang, 2019) has recorded retrieving natural frequencies acoustically with microphone recording, which highlights a notable gap in applying acoustic methods in SDD.

This paper aims to propose an acoustic SDD method by demonstrating the feasibility of detecting structural damage in a contactless approach using microphone recording, and also define its accuracy, feasibility of detecting damage severity, and limitations on impact factors.

1.1 Background Theory

Sound is generated by acoustic wave vibrations, which cause microphone diaphragms to create electrical currents by moving magnets and coils. This forms the basis of microphone audio recording. When structures vibrate, they produce different modal shapes, each with its frequency, known as modal or natural frequency. Since sound waves have the same frequency as these vibrations (Fahy and Gardonio, 2007), they can be captured by microphones, allowing us to extract the natural frequencies of structural elements using microphone audio recording.

Fast Fourier Transform (FFT) is a widely used Fourier Analysis-based algorithm that transforms signal functions on space or time domains into frequency domains, highlighting signal frequency by decomposing the signal functions into multiple trigonometric functions. It is used as the background algorithm to obtain the frequencies of the sound wave data in this paper.

2 METHODOLOGY

The proposed microphone SDD method is experimented with on a free beam scenario based on Luo and Yang (2019)'s paper. The free beam scenario tries to simulate beams without any boundary conditions. Model simulation and two different experimental tests are carried out including both the proposed microphone method and accelerometer method to obtain three sets of data for better comparison results.

2.1 Specimens

EasySteel 100UC 14.8 I-shape beam, 1.5 meters in length, is selected and used for the experiment to create seven testing scenarios. These scenarios encompass an intact beam, damaged beams with two locations (quarter and middle span) and three severity levels (10%, 25%, and 50% saw cut of the beam depth). Table 1 summarises the specimen conditions.

Table 1 Specimen codes.

Specimen No.	Damage location	Severity	Specimen code
Spec1	Quarter span	10%	Spec1_10%
		25%	Spec1_25%
		50%	Spec1_50%
Spec2	Middle span	10%	Spec2_10%
		25%	Spec2_25%
		50%	Spec2_50%
Spec	N.A (Intact)	N.A (intact)	Spec_intact

2.2 Finite Element Simulation

ANSYS Workbench is used as the simulation software to obtain the natural frequencies of the specimens, serves as a comparative method. All seven sets of specimens are modelled using the SpeceClaim based on EasySteel product handbook (EastSteel, 2020) .

Saw cut is applied to the specimens to simulate cracks and damage. The crack width is assumed to be 5 mm as an average measurement from the saw cut. Mesh size is set as 4 mm as the finest size within ANSYS's capability for this geometry. Other material properties are taken from EasySteel product handbook. No additional boundary conditions are applied as the experiments intend to create free beam scenario.

The frequency results of the first three modes in the vertical strong axis direction from simulation are recorded as the theoretical results.

2.3 Experimental Testing

2.3.1 Equipment and Setup

The following table summarises the involved equipment, their functions, and important specifications for the tests.

Table 2 Equipment list.

Equipment list	Function	Specification
Steel shaft hammer	Beam's excitation	Fuller steel shaft hammer 16oz
Condenser Microphone	Record the excitation sound for the proposed acoustic method	Sampling rate: 48 kHz Bandwidth: 20-20,000 Hz
IEPE triaxial Accelerometer	Record vibration acceleration in the vertical direction (Z-direction) for the acceleration test	Sensitivity: Z: 1.013 mv/(m/s^2) X: 0.98 mv/(m/s^2) Y: 0.98 mv/(m/s^2)
CoCo-80 DAQ unit	Data acquisition unit to record vibration response in time domain	Input mode: IEPE Input sensitivity: 1.013 mv/(m/s^2)

The test location is chosen in a quiet and medium-sized laboratory without noises from other testing activities or echoes. The initial testing setups for both microphone test and accelerometer test are shown in Figure 1.

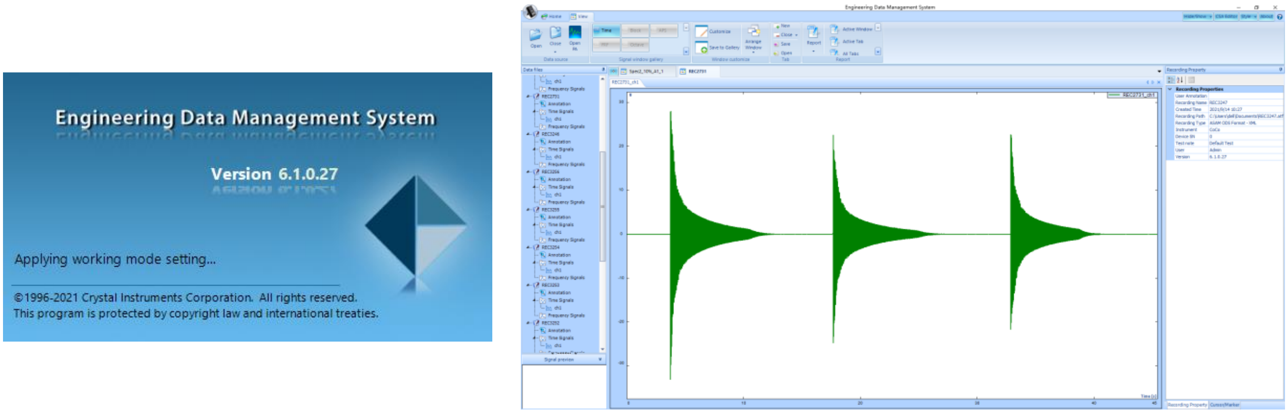
Figure 1 Microphone test setup (left); Accelerometer test setup (right).

Both the microphone and accelerometer are placed at the specimen's middle span. Steel hammer impact is chosen as the beam's excitation method. It is controlled to be at one-third of the beam span for a better natural frequency excitation.

2.3.2 Data collection and processing

A total of 14 tests including both microphone test and accelerometer test across seven beam specimens are performed. The test data were recorded using CoCo-80. Each test record contains three hammer knocks on the specimens for a thorough excitation, and the specimen is ensured to fully stop between each impact. Additionally, environment sound has been captured for noise analysis.

Engineering Data Manager (EDM) and Waveform Editor, the recommended software by CoCo-80's manufacturer Crystal Instrument, are used as post experiment data processing tools. EDM converts raw recorded data into ATFX readable data of acceleration (m/s^2) in time domain (s) for waveform Editor (Figure 2**)** then Waveform Editor can process the data to auto-power spectrum with frequency domain, which includes the desired result, with velocity diagram, displacement diagram, and histogram for acceleration percentage (shown in Figure 3).



Engineering Data Management System

Version 6.1.0.27

Applying working mode setting...

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Figure 2 Engineering Data Management system software (left) and user interface example showing the audio record of three knocks (right).

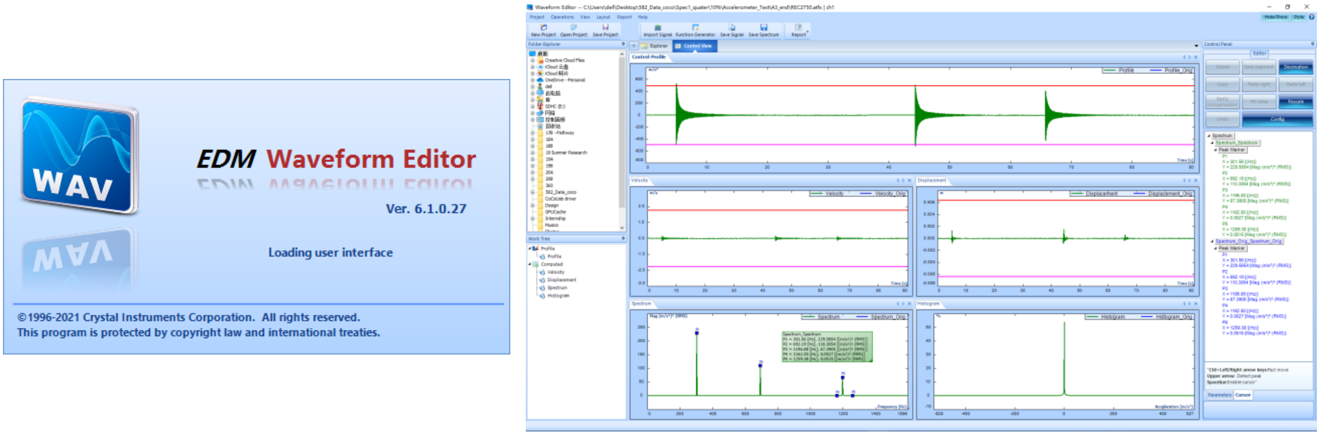
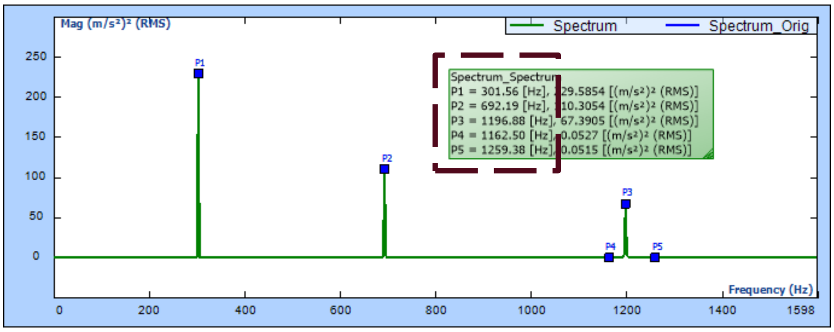


Figure 3 EDM Waveform editor (left) and user interface example showing the data record, velocity, displacement, spectrum and histogram (right).

The auto-power spectrum with frequency domain from Waveform editor uses Fast Fourier Transform (FFT) to convert the original waveform data of acceleration with time domain to frequency domain. The spectrum type used is root mean square (RMS) of the acceleration square to get the best presentation of data as it emphasizes the data with higher amplitude and minimizes the data point with lower amplitude.

Peak Marker is a feature in Waveform Editor to obtain information on the first five magnitude peaks in the window. It is used in the spectrum with frequency domain to obtain the relative frequency values of the five largest magnitude points as shown in Figure 4.



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Spectrum_Spectrum
P1 = 301.56 [Hz], 29.5854 [(m/s²)² (RMS)]
P2 = 692.19 [Hz], 10.3054 [(m/s²)² (RMS)]
P3 = 1196.88 [Hz], 67.3905 [(m/s²)² (RMS)]
P4 = 1162.50 [Hz], 0.0527 [(m/s²)² (RMS)]
P5 = 1259.38 [Hz], 0.0515 [(m/s²)² (RMS)]
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Figure 4 Example of the Peak Marker in spectrum window picking up the derived natural frequencies.

The first three modal frequency results for each test are recorded for analysis and discussion.

3 RESULTS AND DISCUSSION

3.1 Microphone test

The microphone test results of natural frequency of the first three modes are summarised in Table 3 below.

Table 3 Microphone test results

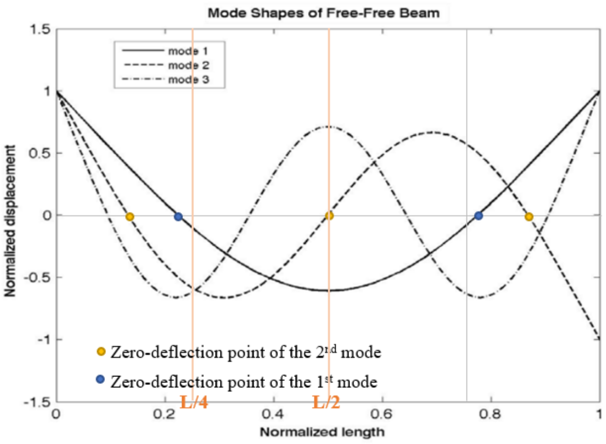
Spec 1 - Quarter cut				**Spec 2 - Middle cut**			
Damage severity	**Natural frequency (Hz)**			**Damage severity**	**Natural frequency (Hz)**		
	1st mode	**2nd mode**	**3rd mode**		**1st mode**	**2nd mode**	**3rd mode**
Intact	320.3	771.5	1275	Intact	320.3	771.5	1275
10% cut	301.6	692.2	1198	10% cut	275	770.3	1202
25% cut	284.4	635.9	1155	25% cut	239.1	768.7	1147
50% cut	234.4	540.6	1102	50% cut	175.8	761.7	1057

The result table above shows the retrieved natural frequencies for both specimen 1 and 2 with different damage severities. It shows that microphone audio recording can be used to measure and distinguish different modes of natural frequency successfully.

Table 4 Natural frequency reduction rate of microphone test results.

Spec 1 - Quarter cut				**Spec 2 - Middle cut**			
Damage severity	**Reduction rate (%)**			**Damage severity**	**Reduction rate (%)**		
	1st mode	**2nd mode**	**3rd mode**		**1st mode**	**2nd mode**	**3rd mode**
Intact	0%	0%	0%	Intact	0%	0%	0%
10% cut	6%	10%	6%	10% cut	14%	0%	6%
25% cut	11%	18%	9%	25% cut	25%	0%	10%
50% cut	27%	30%	14%	50% cut	45%	1%	17%

The frequency reduction rate has been computed in Notably, the first mode of specimen 2 exhibits the highest reduction rate at a 50% cut, whereas the second mode shows no significant decrease in frequency. This discrepancy can be caused by the damage location of the mode shapes. In a free beam scenario, the first mode shape peaks in the middle, while the second mode shape has its zero deflection point in the middle (see Figure 6). Consequently, damage at the middle span primarily affects the first mode frequency and has a lesser impact on the second mode. This finding suggests that multiple mode frequencies should be considered and analysed for this method's further implementation, and further research can be carried out on the correlation between the frequency reduction rate of each mode and the mode shapes to extrapolate the damage location.



, which demonstrates the decrease in the frequency with the increase of damage severity for both specimens 1 and 2, confirming the feasibility of an acoustic contactless global structural damage detection method.

Notably, the first mode of specimen 2 exhibits the highest reduction rate at a 50% cut, whereas the second mode shows no significant decrease in frequency. This discrepancy can be caused by the damage location of the mode shapes. In a free beam scenario, the first mode shape peaks in the middle, while the second mode shape has its zero deflection point in the middle (see Figure 6). Consequently, damage at the middle span primarily affects the first mode frequency and has a lesser impact on the second mode. This finding suggests that multiple mode frequencies should be considered and analysed for this method's further implementation, and further research can be carried out on the correlation between the frequency reduction rate of each mode and the mode shapes to extrapolate the damage location.

Figure 5 Mode shapes - free beam (Bhagat and Ganguli, 2014).

3.2 Comparison study

The results from accelerometer tests and ANSYS simulation are recorded and documented as comparison tests with percentage differences compared to microphone test in Table 5 and 6 for specimen 1 and 2 respectively.

Both specimens demonstrate a close alignment between the microphone and accelerometer test results, with negligible differences – largest at 0.4%, several at 0.1%, and the remainder at 0%. This highlights the accuracy of the proposed microphone method compared to the commonly used accelerometer method, irrespective of the structural damage location.

The ANSYS simulation results consistently deviate by approximately 7% from both the microphone and accelerometer test results. This discrepancy may arise from subtle inaccuracies in the model or boundary conditions. Despite this, the ANSYS results exhibit the same decreasing frequency trend with worsening structural damage, affirming the viability of the proposed microphone SDD method.

Table 5 Natural frequency (Hz) of Specimen 1 (quarter cut) from microphone test, accelerometer test and ANSYS simulation, with percentage difference compared to microphone test.

Mode	**Specimen code**	**Microphone test results (Hz)**	**Accelerometer test results (Hz)**	**%Difference (Acc vs. Mic)**	**ANSYS simulation result (Hz)**	**%Difference (ANSYS vs. Mic)**
1st mode	Spec_intact	320.3	320.3	0%	300.3	6%
	Spec1_10%	301.6	301.6	0%	284.6	6%
	Spec1_25%	284.4	284.4	0%	267.1	6%
	Spec1_50%	234.4	234.4	0%	214.7	8%
2nd mode	Spec_intact	771.5	771.5	0%	719.8	7%
	Spec1_10%	692.2	692.2	0%	651	6%
	Spec1_25%	635.9	635.9	0%	595.8	6%
	Spec1_50%	540.6	540.6	0%	510.2	6%
3rd	Spec_intact	1275	1275	0%	1179	8%

mode	Spec1_10%	1198	1197	0.1%	1114	7%
	Spec1_25%	1155	1155	0%	1074	7%
	Spec1_50%	1102	1100	0.1%	1024	7%

Table 6 Natural frequency (Hz) of Specimen 2 (middle cut) from microphone test, accelerometer test and ANSYS simulation, with percentage difference compared to microphone test.

Mode	**Specimen code**	**Microphone test results (Hz)**	**Accelerometer test results (Hz)**	**%Difference (Acc vs. Mic)**	**ANSYS simulation result (Hz)**	**%Difference (ANSYS vs. Mic)**
1st mode	Spec_intact	320.3	320.3	0%	300.3	6%
	Spec2_10%	275	275	0%	256.9	7%
	Spec2_25%	239.1	239.1	0%	223.9	6%
	Spec2_50%	175.8	176.6	0.4%	159.1	9%
2nd mode	Spec_intact	771.5	771.5	0%	719.8	7%
	Spec2_10%	770.3	770.3	0%	720.0	7%
	Spec2_25%	768.8	768.8	0%	718.8	7%
	Spec2_50%	761.7	760.9	0.1%	713.2	6%
3rd mode	Spec_intact	1275	1275	0%	1179	8%
	Spec2_10%	1202	1200	0.1%	1116	7%
	Spec2_25%	1147	1145	0.1%	1065	7%
	Spec2_50%	1057	1056	0%	984.2	7%

3.3 Ambient noise

The raw ambient sound is shown below in Figure 6. It is a total of 11 seconds, and the y-axis (i.e., acceleration) ranges from -300 to 300 m/s^2.

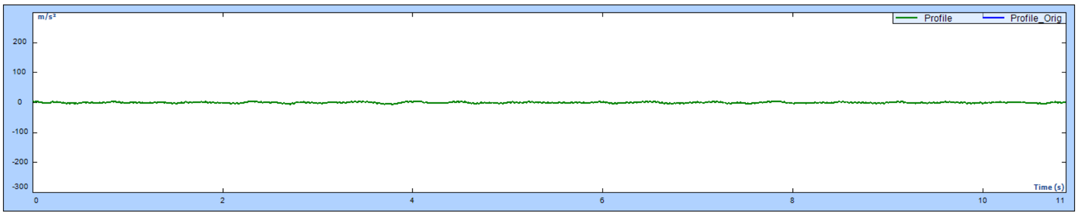


Figure 6 Ambient sound.

The relative spectrum result of ambient sound frequency is computed in Waveform Editor and shown below with potential frequencies captured by Peak Marker. It can be observed that the most significant frequency is 1.56 Hz with a 2.2126 (m/s^2)^2 RMS and other minor data with magnitudes close to zero. The bandwidth of the Microphone is from 20 Hz to 20 kHz, the peak frequencies in this spectrum are outside this available range. This suggests that the peak data for ambient sound might be due to signal transmission errors, which are negligible for the analysis.

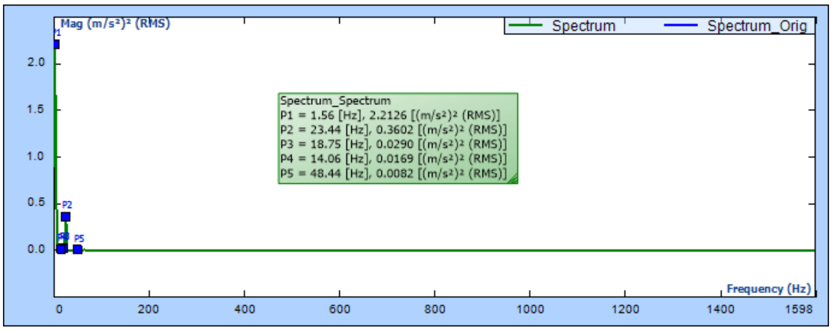


Figure 7 Ambient sound spectrum.

4 LIMITATIONS AND RECOMMENDATIONS

Despite the successful testing results of the proposed microphone method to detect structural damage, there are limitations subjected to this test programme. Recommendations for further research and implementation are:

- The current results are from an idealised free beam scenario in laboratory testing. More real-life structures and their boundary conditions can be examined, such as columns, truss structures, portal frames and walls, etc.
- The saw cut damage on I-beam specimens in this test program is also idealised. More structural damage types and materials can be investigated such as cracking, corrosion, deformation for timber, reinforced concrete, and other metals like aluminium.
- More excitation methods can be integrated, such as different hammers with different impact patterns, certain frequency transmitters to activate resonance.
- The correlation between the frequency reduction rate of each mode and the mode shapes can be further investigated to extrapolate the damage location.
- Outdoor environments and data collecting impact factors can be investigated to confirm the practicality of this method in terms of different locations of the microphone sensor, distance from the microphone sensor to the specimens in an open environment.

5 CONCLUSION

Structural Damage Detection techniques are essential for structure maintenance, and a contactless global SDD method using microphone is more efficient, easier to use in comparison with traditional methods, and more economical than optical method. This paper proposes a contactless SDD method with a microphone recording acoustic frequencies. The proposed microphone method is examined on seven I-beam damage scenarios, and the results are compared to both accelerometer tests and ANSYS simulations. The test results successfully demonstrate the feasibility of determining structure's natural frequency from microphone recordings, and the accuracy was confirmed by its minimum deviation to accelerometer test results and ANSYS simulations. This outcome provides confidence for an innovative SDD method development and can be served for further application on real-life structures.

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