Chapter 3

Extending Sensing Area

3.1 Global Modes and Local Modes

A modal-dependent model-based technique usually deals with global modes of the structure in question and the frequency range is generally low (< 10 kHz). Contrarily, a piezoelectric impedance-based technique deals with local modes of the structure at high frequencies (typically > 50 kHz). In this section, the influence of incipient-type damage on the global modes and the local modes is investigated experimentally.

A 1/4 scale model of a steel bridge joint is used for the experiment. The bridge joint model consists of steel angles, channels, plates, and over 200 bolts. It is 1.8 m tall and weighs over 250 kg.

Firstly, an impact test was carried out to examine the global modes at low frequencies (0 - 200 Hz). Figure 3.1 is a schematic of the test. The excitation (hammering) point was located on the left-upper corner (Point 1) of the bridge joint model and a total of 21 acceleration measurements was taken in two cases; without and with damage. The numbers in the figure indicate the measurement points. All the bolts were tightened by 40.73 N-m (30 foot-pounds) torque except a bolt near Point 13 was loosened in the “with damage” case. Since the loosened bolt is only one of over 200 bolts, this still can be considered as incipient-type damage. A Kistler impact hammer (model 9724A2000), a Kistler accelerometer (model 8630B50), a PCB signal conditioner (model 482A16) and a Tektronix FFT analyzer (model 2630) were used for the test. The test was performed only for one impact direction (x-direction).
Figure 3.2 shows FRFs (the output voltage from the accelerometer / the output voltage from the impact hammer) of the bridge joint model at Point 1 and 13 in two cases; with and without damage. All the resonant peaks can be considered as global modes because they are identical at each measuring point. Very little difference between the healthy condition and the damaged condition exists even at Point 13 which is very close to the loosened bolt. This indicates that detecting incipient-type damage such as a loosen bolt by tracking global modes is difficult. Figure 3.3 displays some of the mode shapes. Since they all look reasonable, it can be said that the test was performed well.
Figure 3.2: FRF of the bridge joint model

Figure 3.3: Mode shape of the bridge joint model
Secondly, the local modes at high frequencies (200 - 210 kHz) were investigated by using the impedance-based structural health monitoring technique. Figure 3.4 shows a schematic of the experiment. Four PZTs (Piezo Systems PSI-5A, 12.7 mm x 12.7 mm x 0.254 mm) were bonded on the bridge joint model and their electrical impedance was measured by a Hewlett-Packard electrical impedance analyzer (model HP4194A) in the healthy and the damaged condition. Damage was simulated by loosening a bolt of the joint as was done in the impact test.

![Schematic of the impedance-based test](image)

**Figure 3.4:** Schematic of the impedance-based test

The real part of electrical impedance of PZT 1 and PZT 3 are shown in Figure 3.5. PZT 1 is located very close (30 mm) to the loosened bolt, while PZT 3 is located far away (600 mm) from it. Since the peaks of these plots do not match up together, modes at this frequency range can be considered as local ones. Although the electrical impedance of PZT 1 shows a significant difference between the healthy and damaged cases, that of PZT 3 does not. This indicates that the impedance-based technique is very sensitive to damage close to a PZT sensor-actuator but completely insensitive to damage far from the PZT. In other words, it can be said that the sensing region is very limited.
Through the experimental study on the influence of incipient-type damage on the global modes (low frequency range) and the local modes (high frequency range), such a small damage as the global structural integrity is not affected cannot be detected by monitoring the global modes of the structure, while the impedance-based technique at high frequencies can successfully detect it. It is true that the impedance-based structural health monitoring technique is extremely sensitive, but a PZT sensor-actuator can cover only a limited area. Because of the small sensing region, large structures may need more than one PZT sensor-actuator at any critical location. To limit the number of PZT sensor-actuators, extending the sensing area of this technique is required.

### 3.2 Evaluating Wave Propagation by Coherence Measurements

In the conventional impedance-based structural health monitoring technique, the
electrical impedance (or admittance) of PZT sensor-actuators at different locations are measured individually and only the ‘self’ or ‘point’ impedance is used to assess damage. This may be the reason why its sensing area is limited. If we could utilize multiple PZT sensor-actuators effectively, perhaps more global information can be obtained and the sensing area can be extended.

Does the wave generated by a PZT propagate a long distance? In this section, this question is examined experimentally by coherence measurements. Figure 3.6 shows the experimental setup. A Hewlett-Packard function generator (model HP3314A) applied an excitation voltage (chirp) of 1 Vp-p to PZT 3 and the propagated wave or vibration was measured by a Kistler accelerometer (model 8630B50) with a PCB signal conditioner (model 482A16). A ZONIC analyzer (WCA model) was used for data acquisition. The FRF and coherence between the applied voltage to the PZT and the response acceleration were computed. A, B, C and D indicate the accelerometer locations.

![Figure 3.6: Schematic of the wave propagation test](image)

Figure 3.6: Schematic of the wave propagation test
Figure 3.7: Wave propagation test at Point A

Figure 3.8: Wave propagation test at Point B
Figure 3.9: Wave propagation test at Point C

Figure 3.10: Wave propagation test at Point D
Figure 3.11: Coherence at each point (using PZTs as sensors)

Table 3.1: Average coherence above 20 kHz

<table>
<thead>
<tr>
<th></th>
<th>Accelerometer</th>
<th>PZT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point A</td>
<td>0.9905</td>
<td>0.9765</td>
</tr>
<tr>
<td>Point B</td>
<td>0.9424</td>
<td>0.9356</td>
</tr>
<tr>
<td>Point C</td>
<td>0.9163</td>
<td>0.9228</td>
</tr>
<tr>
<td>Point D</td>
<td>0.9192</td>
<td>0.9095</td>
</tr>
</tbody>
</table>

Figure 3.7 to 3.10 show the experimental results at Point A, B, C and D, respectively. Each figure consists of four graphs; the input voltage to the PZT in time domain, the response acceleration in time domain, the FRF and the coherence between them. Surprisingly, even the accelerometer at Point D could detect some vibration. Although the amplitude of acceleration is smaller than other points, the coherence above 20 kHz is higher than 0.9 (Table 3.1). This indicates that the acceleration measured at Point D is very much related to the input signal to the
PZT, i.e., the wave or vibration generated by the PZT propagated through the structure and then was detected at Point D. Figure 3.11 shows the coherence at each point obtained by using PZTs instead of accelerometers as sensors. The average coherence in this case is also higher than 0.9 (Table 3.1). Thus, we can use PZTs as actuators and sensors.

In fact, we should conduct the experiment at the higher frequencies normally used by the impedance-based technique, but the frequency range of the experiments was limited by the analyzer. The maximum measurable frequency is 40 kHz. However, we can guess from the results that the wave or vibration of higher frequency also may propagate through the structure. If some structural changes occur along the wave propagation path, there should be some changes in the FRF and other data. Therefore, it may be possible to extend the sensing area by utilizing multiple PZT sensor-actuators and evaluating the mutual information.

### 3.3 Electrical Transfer Admittance

In order to utilize multiple PZT sensor-actuators and to obtain the mutual information between them, the electrical transfer admittance is introduced in this section. The idea is that the FRF of the structure can be deduced from the electrical admittance of PZT as a result of the electromechanical interaction. The electrical transfer admittance between two PZTs is related to the mechanical transfer mobility between two locations, while the electrical self admittance of a single PZT represents the mechanical point impedance of the structure [33].

Figure 3.12 shows the schematic of the electrical transfer admittance measurement. When two PZT sensor-actuators are electrically connected in parallel, the total electrical admittance can be expressed as:

\[
Y_{12} = \frac{I}{V} = \frac{I_{11}}{V} + \frac{I_{22}}{V} + \frac{I_{12}}{V} + \frac{I_{21}}{V} = Y_{11} + Y_{22} + Y_{12} + Y_{21}
\] (3.1)
where $Y_{t12}$ is the total electrical admittance of PZT 1 and 2 connected in parallel, $V$ is the applied voltage to the PZTs, $I$ is the total current, $I_{11}$ is the current from PZT 1 induced by the excitation of PZT 1, $I_{22}$ is the current from PZT 2 induced by the excitation of PZT 2, $I_{12}$ is the current from PZT 1 induced by the excitation of PZT 2, $I_{21}$ is the current from PZT 2 induced by the excitation of PZT 1, $Y_{11}$ is the electrical self admittance of PZT 1 measured individually, $Y_{22}$ is the electrical self admittance of PZT 2 measured individually, $Y_{12}$ is the electrical transfer admittance of PZT 1 induced by the excitation of PZT 2, and $Y_{21}$ is the electrical transfer admittance of PZT 2 induced by the excitation of PZT 1.

\[
Y_{t12} = Y_{21} = \frac{Y_{t12} - (Y_{11} + Y_{22})}{2}
\]

\( (3.2) \)

The electrical transfer admittance cannot be measured directly, however, Equation (3.2) indicates that it can be calculated from three measurements; the self admittance of each PZT and the total admittance of two PZTs connected in parallel. One of the benefits from focusing on the

**Figure 3.12:** Measurement of electrical transfer admittance between two PZT sensor-actuators

As the mechanical FRF of a structure between two locations is reversible, the electrical transfer admittance $Y_{12}$ and $Y_{21}$ can also be considered as identical. Therefore, they can be simply expressed as:

\[
Y_{12} = Y_{21} = \frac{Y_{t12} - (Y_{11} + Y_{22})}{2}
\]

\( (3.2) \)
electrical admittance is that high frequency measurements even above 100 kHz are very easy, while the mechanical FRFs at such high are not readily measured.

3.4 Experimental Results

3.4.1 Bridge Joint Model

First, experiments on the bridge joint model were carried out to verify the validity of the concept presented in the previous section. Figure 3.5 shows the experimental setup. Four PZT sensor-actuators (Piezo System PSI-5A, 12.7 mm x 12.7 mm x 0.254 mm) were bonded on the model. The electrical admittance of each PZT (self admittance) and of pairs of PZTs connected in parallel (total admittance) were measured by an HP4194A impedance analyzer. The measurements were taken at five frequency ranges; 20 - 30 kHz, 50 - 60 kHz, 100 - 110 kHz, 150 - 160 kHz and 200 - 210 kHz, and in two cases; without damage (healthy) and with damage (damaged). Damage was simulated by loosening a bolt near PZT 1. In order to check the repeatability and the variation of the measurements, the admittance of the healthy case was measured twice. The electrical transfer admittance was derived from the measured self admittance and the total admittance by Equation (3.2).

In order to compare all the admittance data together, the correlation-based damage metric is introduced here. Since the damage metric given by Equation (2.10), which is not normalized, strongly depends on the absolute value of impedance or admittance, we cannot compare the results at different frequency ranges or of PZTs at different locations with each other. The mathematical formulation of the correlation-based damage metric is one minus the correlation coefficient between the baseline measurement and the subsequent measurement. Hence, if the baseline and the subsequent measurement are exactly the same, the correlation coefficient equals one, and then the damage metric becomes zero. Contrarily, if they are completely unrelated, the correlation coefficient equals zero, and then the damage metric
becomes one. The correlation-based damage metric is expressed as:

\[
M_c = 1 - \rho_{\text{Re}(Y_{i,1}) \text{Re}(Y_{i,2})} = 1 - \frac{\text{Cov}(\text{Re}(Y_{i,1}), \text{Re}(Y_{i,2}))}{\sigma_{\text{Re}(Y_{i,1})} \sigma_{\text{Re}(Y_{i,2})}}
\]  

(3.3a)

\[
\text{Cov}(\text{Re}(Y_{i,1}), \text{Re}(Y_{i,2})) = \frac{1}{n} \sum_{i=1}^{n} (\text{Re}(Y_{i,1}) - \mu_{\text{Re}(Y_{i,1})})(\text{Re}(Y_{i,2}) - \mu_{\text{Re}(Y_{i,2})})
\]  

(3.3b)

\[
\sigma_{\text{Re}(Y_{i,1})} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\text{Re}(Y_{i,1}) - \mu_{\text{Re}(Y_{i,1})})^2}
\]  

(3.3c)

\[
\sigma_{\text{Re}(Y_{i,2})} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\text{Re}(Y_{i,2}) - \mu_{\text{Re}(Y_{i,2})})^2}
\]  

(3.3d)

where \( M_c \) is the correlation-based damage metric, \( \rho \) is the correlation coefficient, \( \text{Cov} \) is the covariance, \( \sigma \) is the standard deviation, \( \mu \) is the mean value, \( Y_{i,1} \) is the original admittance at frequency interval \( i \) (baseline measurement), \( Y_{i,2} \) is the interrogated admittance at frequency interval \( i \) (subsequent measurement), and \( n \) is the number of data points. In Equation (3.3), \( Y_{i,2} \) is assumed to be compensated, \( i.e., \) not affected by temperature changes.

Figure 3.13 shows the repeatability of the admittance measurements. The real parts of electrical self admittance of PZT 1, 2, 3 and 4 are presented at 150 - 160 kHz frequency range. The solid lines (No Damage 1) represent the baseline measurements and the dashed lines (No Damage 2) represent the measurements two hours after the baseline measurements. Both measurements were taken from a healthy structure, \( i.e., \) no loose bolts. Since the solid line and the dashed line in each plot are almost identical, it can be said that the measurements are repeatable and the variation is small enough.
Figure 3.13: Electrical self admittance of PZTs bonded on the bridge joint model to check the repeatability
Figure 3.14: Electrical self admittance of PZTs bonded on the bridge joint model
Figure 3.15: Electrical total and transfer admittance of PZTs bonded on the bridge joint model

Figure 3.14 shows the change in the self admittance plots by the damage which is simulated by loosening a bolt. We can easily recognize significant changes in the plots of PZT 1 and 2. However, it is very hard to find even a small change in PZT 3 or 4. This indicates that only the PZTs located near the loosened bolt can detect the damage.

The total admittance and the transfer admittance of PZT 3 and 4 are shown in Figure 3.15. Although almost no change can be found in the total admittance plot, the transfer admittance indicates some change by the damage.

The damage metric chart gives us much clearer information. Figure 3.16 demonstrates the correlation-based damage metric computed from the admittance measurements at 150 - 160 kHz frequency range. ‘W/O Damage’ shows the damage metric of the second measurements in the healthy case. It represents a variation in the admittance measurements. ‘W/ Damage’ shows the damage metric of the measurements in the damaged case, i.e., a bolt loosened.
As can be seen, the damage metric of $Y_{34}$, the electrical transfer admittance between PZT 3 and 4, of ‘W/ Damage’ is almost as large as that of $Y_{11}$, the electrical self admittance of PZT 1. This means that we can detect the damage, which can be considered as incipient-type, using PZT 3 and 4 instead of PZT 1. In other words, using the electrical transfer admittance could extend the sensing area of the impedance-based structural health monitoring technique. It can also be found that the variation in $Y_{34}$, *i.e.*, the damage metric of ‘W/O Damage’, is larger than others. However, it is small enough to be distinguished from damage.

Incidentally, the damage metric of the electrical self admittance related to the distance between the damage and the PZT sensor-actuator. The relation is expressed as follows:

**Damage Metric:** PZT 1 > PZT 2 > PZT 4 > PZT 3

**Distance from the Damage:** PZT 1 < PZT 2 < PZT 4 < PZT 3

The closer to the damage the PZT is located, the larger the damage metric becomes.
Figure 3.17: Correlation-based damage metric of bridge joint model (20-30kHz)

Figure 3.18: Correlation-based damage metric of bridge joint model (50-60kHz)
**Figure 3.19:** Correlation-based damage metric of bridge joint model (100-110kHz)

**Figure 3.20:** Correlation-based damage metric of bridge joint model (200-210kHz)
Figure 3.21: Correlation-based damage metric of bridge joint model (average)

Figure 3.17, 3.18, 3.19 and 3.20 are the damage metric charts at 20 - 30 kHz, 50 - 60 kHz, 100 - 110 kHz and 200 - 210 kHz, respectively. Figure 3.21 shows the damage metric which is the average of five frequency ranges. The same conclusions as mentioned in Figure 3.16 can be derived from these figures.

3.4.2 Bolted Pipe

Second, experiments on the bolted pipe were carried out. Figure 3.22 shows the experimental setup. Four PZT sensor-actuators (Piezo System PSI-5A, 12.7 mm x 12.7 mm x 0.254 mm) were bonded on the flange. The procedure of the experiments was similar to that of the bridge joint model. The electrical admittance of each PZT (self admittance) and of pairs of PZTs connected in parallel (total admittance) were measured by an HP4194A impedance analyzer. The measurements were taken at five frequency ranges; 20 - 30 kHz, 50 - 60 kHz, 100 - 110 kHz, 150 - 160 kHz and 200 - 210 kHz, and in two cases; without damage (healthy) and
with damage (damaged). Damage was simulated by loosening a bolt (1/6 turn) near PZT 1. In order to check the repeatability and the variation of the measurements, the admittance of the healthy case were measured twice. The electrical transfer admittance was derived from the measured self admittance and the total admittance by Equation (3.2).

![Schematic of the electrical transfer admittance experiment on the bolted pipe](image)

**Figure 3.22:** Schematic of the electrical transfer admittance experiment on the bolted pipe

![Correlation-based damage metric of bolted pipe (average)](image)

**Figure 3.23:** Correlation-based damage metric of bolted pipe (average)
Figure 3.23 shows the correlation-based damage metric, which is the average of four frequency ranges. The damage metric of $Y_{34}$, the electrical transfer admittance between PZT 3 and 4, of `W/ Damage’ is almost as large as that of $Y_{11}$ and $Y_{22}$, the electrical self admittance of PZT 1 and 2. Thus, it is again shown that using the electrical transfer admittance is very effective to extend the sensing area of the impedance-based structural health monitoring technique. In this experiment, the damage can be detected even by $Y_{33}$ and $Y_{44}$, the electrical self admittance of PZT 3 and 4, which are located far from the loosened bolt, since the structure is relatively small.

### 3.5 Conclusions

The influence of incipient-type damage such as small cracks or loose joints on the global modes and the local modes of structure was investigated experimentally. Through the experiments on the massive bridge joint model, it was found that the global modes at low frequencies were not affected by incipient-type damage. Hence, this kind of small damage cannot be detected by tracking the global modes. On the contrary, the local modes at high frequencies were significantly affected and the impedance-based structural health monitoring technique could detect incipient-type damage successfully. However, it was also found that the sensing area of the impedance-based technique was small relative to the dimension of the structures.

The wave propagation through the bridge joint model was examined by coherence measurements. It was demonstrated that the wave or vibration generated by a small PZT could propagate at least all over the 1.8 m high massive bridge joint model. This implies that useful information about structural integrity can be obtained if the multiple PZT sensor-actuators bonded on the structure are utilized effectively.
A new impedance-based structural health monitoring technique using the electrical transfer admittance was presented. This technique utilizes multiple PZT sensor-actuators and evaluates mutual information among them, while the conventional impedance-based technique uses only the self impedance or admittance of PZT sensor-actuators. It was successfully demonstrated by experiments on the bridge joint model and the bolted pipe that the new technique could extend the sensing area of the impedance-based method. Moreover, it can reduce the number of PZT sensor-actuators compared with the conventional technique.

Figure 3.24 and 3.25 demonstrate the concept of the new technique using the electrical transfer admittance.

![Concept of the electrical transfer admittance method (1)](image)

**Figure 3.24:** Concept of the electrical transfer admittance method (1)

\[
\text{Transfer Admittance} = \text{Total Admittance} - \text{Self Admittance} \\
(Y_{12} + Y_{21}) = Y_{112} - (Y_{11} + Y_{22})
\]

![Concept of the electrical transfer admittance method (2)](image)

**Figure 3.25:** Concept of the electrical transfer admittance method (2)
Assume that two PZT sensor-actuators, PZT 1 and 2, are bonded on a structure. As shown before, the electrical self admittance or impedance is very sensitive to damage near the PZT, however, the sensing area is limited. In Figure 3.24, two circles indicate the sensing areas of $Y_{11}$ and $Y_{22}$, the electrical self admittance of PZT 1 and 2, respectively. Damage exists out of these sensing areas in this case, i.e., the damage cannot be detected by the self admittance. Basically, the transfer admittance is determined by the current from a PZT induced by the excitation of the other PZT. If the wave or vibration received by the PZT changes, it will lead to changes in the induced current and then the transfer admittance will change as well. Therefore, damage located on the wave propagation path can be detected by monitoring the electrical transfer admittance, $Y_{12}$ or $Y_{21}$, since the damage may cause some change in the propagated wave. This is the basic concept of the new technique.

The total admittance, $Y_{12}$, will also change because it includes the transfer admittance components. However, this portion is much smaller than the self admittance components. The transfer admittance is usually less than 1% of the self admittance (Figure 3.14 and 3.15). Hence, it is difficult to find any change in the total admittance. As shown in Figure 3.25, calculating the transfer admittance is just like extracting useful information from a noisy, contaminated signal. This is the reason why the new technique can detect distant damage and extend the sensing area effectively.

It is true that the variation of the transfer admittance is larger than others (Figure 3.21). This may be because the absolute value of the transfer admittance is much smaller than others and is closer to the noise level. However, the dynamic range of the HP impedance analyzer, which is 16 bits (96 dB), and the maximum resolution, which is $10^{-8}$ A/V, are good enough to deal with the transfer admittance in this research. Moreover, the damage metric of the damage which can be considered incipient-type is much larger than that of the variation. Therefore, we can say that the electrical transfer admittance is a useful and reliable index for damage detection.