Experimental investigation on frequency shifting of imperfect adhesively bonded pipe joints

F N Haiyam¹, I Hilmy¹, ESulaeman², T Firdaus¹, E Y T Adesta¹

¹Department of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, 53100 Kuala Lumpur, Malaysia
²Department of Mechanical Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, 53100 Kuala Lumpur, Malaysia

Email:ihilmy@iium.edu.my

Abstract. Inspection tests for any manufactured structure are compulsory in order to detect the existence of damage. It is to ensure the product integrity, reliability and to avoid further catastrophic failure. In this research, modal analysis was utilized to detect structural damage as one of the Non-Destructive Testing (NDT) methods. Comparing the vibration signal of a healthy structure with a non-healthy signal was performed. A modal analysis of an adhesively bonded pipe joint was investigated with a healthy joint as a reference. The damage joint was engineered by inserting a nylon fiber, which act as an impurity at adhesive region. The impact test using hammer was utilized in this research. Identification of shifting frequency of a free supported and clamped pipe joint was performed. It was found that shifting frequency occurred to the lower side by 5%.

1. Introduction

There are many non-destructive methods/testing that are currently used in the engineering structure such as electromagnetic, radiographic, magnetic particle, ultrasonic, vibration and visual testing. Vibration Analysis (VA) refers to the process of monitoring the vibration signatures of the structure. With VA, a decision whether urgent action is necessary for example to replace the critical component or whether it is still able to withstand for duration of time. Vibration analysis benefits the maintenance technician in which it enables the identification of machine faults, provides information on root causes, localizes the affected components and allows early planning of maintenance measures. Many evidences show that the recovery cost that needed to replace a failure system due to no predictive maintenance is much higher than the cost of regular predictive maintenance using any kind of NDT. Mobley [1] stated that VA is a useful tool for predictive maintenance techniques and diagnostics that is used to monitor, analyze and evaluate critical
structures, machines and systems in a typical plant. VA can be displayed in time domain. Nevertheless, to have an easier interpretation, presenting VA in frequency domain is preferred as shown in figure 1 (a) and (b). In frequency domain, contribution of vibration signal from particular component can be identified. Each component in a multi body structure has a unique vibration signal. This is the basis of the analysis in this research.

Previous findings show that damage of an engineering structure reduced the stiffness of the damaged region [2], [3], [4]. It was a practical application to detect damage-induced loss of stiffness by measuring frequency shifting. It will be useful as long as the damage part contribute significantly in its dynamic behavior as stated by Huston [5]. Some also introduced the impurity or the auxiliary mass instead of the existence of void as proposed by Wang et. al[6]. Shifting frequency was preferable than mode shape analysis because the measurement of frequency gives better accuracy as identified by Zhang[7]. Shifting frequency was utilized to identify the damage evolution of an engineering structure. Piping failures due to vibration was one of the major problems occur in industrial plant over the past years as stated by Wachelet. al[8].

![Figure 1](attachment:image.png)

**Figure 1.** (a) Time vs Frequency domain, (b) Vibration measurement in Frequency domain.

Structures like pipe joint are widely used in all sorts of areas such as plumbing, constructions, and mechanicals. However, undesirable damage like void or micro cracks cannot be seen in the structures and it will develop gradually through time. It will lead to a catastrophic failure. Because the damage of the pipe joint was not known, the lifetime of the structure could not be predicted too. This will be hard for the maintenance technician to get prepare for any potential problems in the field. Due to the unnoticeable damage in the pipe joint, any maintenance could not be performed before it been officially manufactured. Thus, every time the pipe joint is damage the company need to replace a new one because the damage cannot be repair anymore. One damage pipe joint also can affect the failure of the whole plumbing system and this will cost the owner more for the maintenance and replacement.

The objectives of this research were: (1) Design and fabricating the pipe joint with the “perfect condition” and “damage condition”, (2) design the set up experiment of the impact test, (3) Detect the shifting phenomenon of natural frequency. The outcome of this research will give positively impact on the community especially the design engineers and industries. This research will be able to identify the natural frequencies of a structure and analyze the responses when forces excite the structure. From this, it will helps the engineers to design a better structure and also be able to resolve the potential maximum of the structures before it will destruction.
2. Methodology
Since many types of pipe joints are available, this research focused on the adhesively bonded butt joint of pipe. The consideration was the practicality to introduce or fabricate damage in the adhesive region. Damage defined as the presence of the void, micro crack or impurity. The damage was defined by introducing the impurity. To achieve the damage condition, a set of nylon strings were inserted in the adhesive region. The vibration characteristics in terms of modal analysis between the damage pipe joint and undamaged pipe joint were investigated. Flowchart of the research is shown in figure 2(a).

![Flowchart of the research](image)

**Figure 2.** (a) Methodology, (b) Setup configuration.

Configuration of the experimental setup is shown in figure 2(b). Hammer DYNAPULSE with model 5800B2 was used as the exciter. This stainless steel hammer has a range of 222.4 N with maximum force of 4448 N. The attached load cell measures the force generated during excitation. To read the response signal, the DYTRAN 3035B1G was utilized to record the acceleration level. LMS Scadas data acquisition system with the installed LMS Test Lab software was utilized to analyze the response.

Four hollow identical cylinders were cut equally from the same aluminum pipe. The dimension of each pipe was measured thoroughly using digital vernier caliper as well as the weight. Before the dimensions were taken, post processing were conducted due to the surface of the pipes were rough and unsymmetrical. Thus, facing operations were performed on both surfaces of each pipe. The constant gap length between the pipes need to be maintained.

Epoxy resin was used as the adhesive bonding substrate due to the popularity in many industrial applications. The adhesive consists of an epoxy resin and a hardener. Both were mixed together in equal portion. The resin and hardener reacted to produce a tough, rigid, high strength bond towards variety of materials for gap bonding, surface repairs and others. Fail to maintain the equal portion will cause the adhesive either too flexible or too brittle. Figure 3(a) shows the attachment of epoxy resin mix. Figure 3(b) shows the insertion of the nylon thread. To fabricate “damage condition” of pipe joining, nylon threads were inserted before applying epoxy. This treatment was to represent the impurity condition of the join. Gap gauge was inserted to determine the distance or gap between pipe was attached as shown in figure 3(c).
The upper part of pipe was hanged to maintain the position during the curing.

![Nylon threads](image1.png)

**Figure 3.** (a) Applying epoxy, (b) Inserting nylon thread and (c) curing while maintaining gap

For the fabricated damage pipe joint, the similar procedure was performed refer to figure 3 (b). An additional step is inserting nylon threads at every 30° angle locations as shown in figure 3 (b).

Figure 4 (a) shows the test on the free-free condition. To simulate this condition, the specimen was supported with a soft platform as shown in figure 4 (b). Figure 4 (c) shows the point of hammering.

![FRF Testing](image2.png)

**Figure 4.** (a) Setup of FRF Testing (b) Free-free configuration, (c) points of the hammering

Figure 5 (a) shows the test on the fixed-free condition. To simulate this condition, the specimen was clamped at one end that acts as a cantilever. Figure 5 (b) shows the points of hammering.
3. Results and Discussion

Modal analysis tests were conducted with one accelerometer sensor attached at one end and excitation at several point of interests as shown in figure 4 (b) for free-free condition and figure 5 (a) for fixed end condition respectively. Details of the results were listed in Table 1.

Table 1. Frequency Result of impact hammer test of Free-Free condition (in Hz)

| Point | $F_1$ | $F_2$ | $F_3$ | $F_1$ | $F_2$ | $F_3$ |
|-------|-------|-------|-------|-------|-------|-------|
| A     | 4.61  | 32.07 | 978.32| 3.98  | 29.05 | 966.57|
| B     | 3.98  | 31.19 | 976.83| 3.98  | 29.05 | 964.68|
| C     | 2.97  | 32.95 | 968.75| 2.85  | 30.05 | 965.72|
| D     | 4.11  | 28.92 | 977.87| 3.85  | 29.93 | 966.57|
| E     | 3.98  | 28.04 | 968.75| 3.98  | 29.05 | 966.57|
| F     | 3.98  | 28.16 | 968.75| 3.98  | 28.04 | 965.39|
| G     | 3.85  | 28.04 | 975.43| 4.11  | 29.17 | 970.12|
| H     | 3.98  | 30.18 | 976.38| 4.11  | 30.18 | 968.35|
From Table 1, the first two columns for both Undamage and Damage (F1 and F2) are ignored since the result came from the noise. The third frequency for both Undamage and Damage are considered. The first column with the title Point refers to figure 4 (c). From this Table, the chart comparing F3 for both cases are generated and displayed in figure 6. The drop of frequency or shifting to the lower value occurred consistently in all point of hammering.

![Figure 6. Frequency comparison of free-free configuration (in Hz)](image)

Table 2 shows the FRF result for fixed-free condition. The first columns of F1 for both cases were ignored as well due to the low value. The analysis will be done to the second and third column (F2 and F3 for both cases). In this analysis, second mode of frequency which is the F3 from both conditions was evaluated. The first column with the title Point refers to figure 4 (c). From this Table, the chart comparing F3 for both cases were generated and displayed in figure 7. The drop of frequency or shifting to the lower value occurred consistently in all point of hammering except in point 4. This was due to measurement error. If the second column was evaluated (column F2), consistency of the drop of frequency were also occurred.

| Point | Undamaged | Damage |
|-------|-----------|--------|
|       | F1        | F2     | F3      | F1        | F2     | F3      |
| 1     | 23.88     | 911.34 | 1245.74 | 22.12     | 901.23 | 1232.61 |
| 2     | 24.01     | 922.22 | 1242.54 | 21.89     | 905.89 | 1237.18 |
| 3     | 24.01     | 912.56 | 1242.54 | 22.87     | 894.78 | 1232.61 |
| 4     | 24.01     | 911.34 | 1226.87 | 21.87     | 902.55 | 1232.61 |
| 5     | 24.13     | 921.11 | 1236.76 | 23.13     | 905.89 | 1228.96 |
| 6     | 24.01     | 910.17 | 1242.54 | 23.00     | 905.89 | 1233.73 |
4. Conclusion

Different location of excitation or hammering will make the level of amplitude different. In the other hand, the resonance or natural frequency will be remaining the same because it is a characteristic or identity of the structure. Both cases that were obtained clearly show the drop of the natural frequencies between the undamaged pipe and damaged pipe. Damaged of the pipe joint contain impurities and air bubbles that will slightly disturb the adhesive bonding between the pipes. The stiffness of the pipe joint were affected and the frequencies decrease. Therefore, the changes of the natural frequencies can become an indicator that there is a degradation of the integrity of a structure.

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