Dynamic Responses of Crack Welded Pipe Based on Frequency Response Function (FRF) for Fault Detection

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ABSTRACT

Welding technique is one of the most important and often used methods for joining metals in industry. Welded joints are used in almost every industry depending on various applications and where the permanent joints with high strength are deemed necessary. Some of the applications are used in structural supports, automotive joints, piping industries, pressure vessels etc. Welded joints, particularly in the welded pipe structure have a complex non-linear behavior which may be due to the material's geometry or the contacts itself at the joints. However, cracksin a structure can happen either at the interfacial contacts or in the material of the components. The cracks may change the dynamic properties of the structure such as natural frequency, mode shapes and structural performance that may lead to premature failure to the structure. Therefore, this paper presents a crack detection method using a vibration-based damage detection techniqueusing the frequency response function (FRF) data. A combination of the numerical model and physical welded pipe structure with and without cracks in pipe structure will be investigated using the experimental modal analysis (EMA). A finite element analysis (FEA) utilizing HyperMesh Version 13.0 software has been utilized to model the scheme. A validation procedure is also employed to detect the presence of cracks in the welded pipe structure based on the FRF data from the parameter values used in both the benchmarked and cracks models. The comparison of the with/without cracks welded pipe structure has revealed that the effect of the FRF between with/without cracks welded pipe structure is clearly influenced by the stiffness reduction in the crack structure.

Keywords: *Weldedjoints, crack welded pipe, experimental modal analysis (EMA), frequency response function, finite element analysis (FEA)*

1.0 INTRODUCTION

From Ewins definition, modal analysis is defined as the study of the dynamic characteristics of a mechanical structure under vibration excitation [1]. A field of measuring and analyzing the dynamic response of structures or fluid when excited by an input is classified as modal analysis. The mechanics of the excitation can be achieved by connecting a vibration generator or by using some forms of transient input, such as a hammer blow or sudden release from a deformed position.

Zhang*et al*. (2009) mentioned on the application of the theory experimentally measured data has changed significantly while modal analysis theory has not changed over the last century[2]. The advances of recent years, with respect to measurement and analysis capabilities have caused a re-evaluation of what aspects of the theory relate to the practical world of testing. Vibration trouble shooting, structural dynamic modification, analytical model updating, optimal dynamic design, and vibration control are the modal analysis procedures that have been widely used and implemented.

LePage in his book,highlighted that since the digital forms of the integral transforms are in constant use, the aspect of transforming the related relationships has taken on renewed importance [3]. More detailed understanding of how the structural parameters, i.e.., the mass, damping, and stiffness can be studied based on the impulse response function (time domain), the frequency response function (frequency domain), and the transfer function (*Laplace* domain) for single and multiple degree of freedom (DOF) systems are the subject of investigation from the vibrations theoretical point of view

The Frequency Response Function (FRF) is a fundamental measurement that isolates the inherent dynamic properties of a mechanical structure. Experimental modal parameters (frequency, damping, and mode shape) were also obtained from a set of FRF measurements. Figure 1 shows the relationship between the excitation input and output signals of a measuring point on a mechanical system withfrequency response function (FRF). The concept of FRF is the basis of modern experimental modal analysis (EMA) and the experimental FRF data are generally acquired from physical vibrational testing.

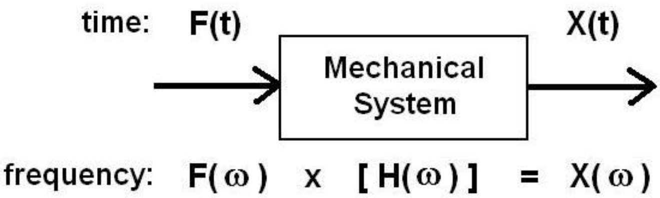


Figure 1: Block diagram of a FRF [4]

In FRF, the following equation is typically expressed:

$$\{\mathbf{X}(\omega)\}=[\mathbf{H}(\omega)]\{\mathbf{F}(\omega)\} \quad (1)$$

Where,

$\{\mathbf{X}(\omega)\}$	:	Output force vector
$[\mathbf{H}(\omega)]$	:	Response model vector (ratio of output to input)
$\{\mathbf{F}(\omega)\}$	:	Input force vector

Therefore, the relationships between the response model $\mathbf{H}(\omega)$ to modal model and spatial can be arranged and expressed by:

$$\mathbf{H}(\omega) = (-\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K})^{-1} \quad (2)$$

Where,

M	:	Mass matrix
C	:	Damping matrix
K	:	Stiffness matrix

Since the input force to the structure and dynamic response of the structure are acquired from physical measurement, it is hypothetically conceivable to get a mathematical description of the structure through experiment. The FRF data is one of the options for vibration-based damage detection method. Essentially, an FRF entity is a numerical representation of the relationship between the input and output system. They may also be identified regarding magnitude and phase. Besides, it also covers the data for both natural frequencies and mode shapes [5-7]. The main purpose of this research is to observe the welded crack on the carbon steel pipe (CSP) structure and its influence to the dynamic properties using EMA and finite element modelling (FEM). One of the main challenges to predict accurately the dynamic behaviour of a welded pipe structure using FEA is due to absence of the joint properties which is complex to model. The predicted result from the numerical analysis showed huge discrepancies from the measured mode parameter because of the invalid assumptions of the FEM of the welded joints.

Therefore, a contribution of the study is to model the welded pipe crack in finite element mode to predict the natural frequencies accurately. The prediction accuracy of the dynamic behaviour of the welded pipe structure is determined by the accurate assumptions of the model properties of the analytical joints model. This is because the physical phenomena in the joints are complex and difficult to model in details due to the fact that the welded joints have a particularly complex non-linear behaviour that comes from the material, geometry or the contacts at the joints. However, crack in a welded pipe structure can happen due to either the defect in the weld itself or the material of the components. The effect of the crack structure on the CSPcan change the dynamic properties of the structure such as natural frequencies and structural performance thus can cause premature failure to structure.

On the other hand, Rizos*et al*. (1990) highlighted that the cracks may grow and the modal frequencies of the cracked structure may change if the structure is subjected to dynamic or static loads [8]. Given that cracks cannot be easily seen with the naked eyes, the non-destructive testing (NDT) methods can be used to detect them. The vibration-based structural health modal parameters related to the frequencies, shape and damping should be examined to detect the cracks. A study in [9] suggested that by implementing the modal analysis method, the crack locations and depths can be determined in which it is based on the frequency information from the database.

EMA is also called the output-only modal analysis as it is essentially a method that makes the job conveniently at ease even though it is still new and the fact not everyone acknowledges it. Zhang*et al*. (2005) reiterated that this method is easier from the other modal testing techniques because any input would be deemed suitable for the testing[10]. Moreover, the concern or focus is more on attaining or getting the appropriate output. Au *et al*. (2012) explored the modal information resulted from the separation of noise and input [11]. Since EMA is typically a Multiple-Input-Multiple-Output (MIMO) system, it is reasonableand sensible that this technique is capable of estimating closely the space models and even repeated modes with a high degree of accuracy.

This paper presents a crack detection method using a vibration-based damage detection strategy using the FRF data. A combination of the numerical model and physical welded pipe with crack structure will be investigated.

2.0 EXPERIMENTAL SET-UP

Carbon steel pipe(CSP) of the *American Petroleum Institute (API) 5L Grade B* (6” Pipe Schedule 40) was chosen to be the specimen material for this project. Most of the oil and gas industry such as Petronas, Shell, and Exxon-Mobil use CSP to prevent paraffin wax that comes with the production of crude oil. It is because in colder climate, the wax may typically build up in an oil and gas pipeline. Other than pipeline transport, carbon steel also can be selected to be the material for offshore construction. Carbon steel contains carbon content between 0.12% and 2.0% as a main alloying component. Note that cobalt, nickel, titanium, vanadium, tungsten, zirconium, chromium, molybdenum or niobium is normally not required for a carbon steel. Figure 2 shows a set of CSPs after cutting them to size.

Figure 2: CSPs after cutting

There are several features of the pipeline that are typically used in oil and gas pipeline fabrication related to the material, length, and diameter depending on the project itself. Prior to performing the testing and analysis, there are a number of things that need to be followed. The first thing is to select suitable material for the CSP (Figure 3) in advance to be used for the testing and analysis procedure. The dimension of the CSP as listed in Table 1 for this procedure should be in the following form: 16.8 cm outer diameter, 16 cm inside diameter (0.8 cm thickness) and 10 cm in length. The small size of the pipe is preferred in accordance with the EMA testing itself to be held in the laboratory. Further details of theCSP areshown in Table 2.

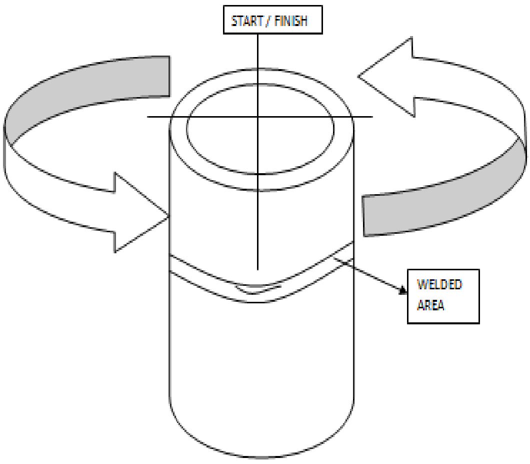


Figure 3: CSPstructure

Table 1: Dimension of the CSP

Parameter	Value
Length	20 cm
Thickness	0.8 cm

Outside diameter	16.8 cm
Inside diameter	16 cm

Table 2: Properties of typical steel

Property	**Value**
Density	7.87 g/cm^3
Young modulus, *E*	200 GPa
*Poisson*ratio	0.2

The CSP need to be joined together or welded using the shielded metal arc welding (SMAW) process on a 6G position using Code & Standard of *AWS D1.1* with a 45^{o}jig and fixture to make sure that the pipe is fixed at certain position. It is necessary to weld the pipe because cracks will be created on a welding region of the pipe using copper-nickel(Cu-Ni) as the electrode. The SMAW facility is available at the Welding Technology Workshop at *Kolej Vokasional Setapak*, Kuala Lumpurusing *SHIYO* SMAW welding machine model. Figure 4 shows the the SMAW facility with jig and fixture for the 6G pipe position.

Figure 4: Jig and fixture for 6G pipe position

Figure 5 shows the method to create the crack region. The top right figure shows the electrode applied along the welding process of CSP for this taskin the SMAW. Most of the time, the electrode needs to be dragged at about 5 degrees inclination while pointing the rod to the center of the pipe, i.e., need to point the SMAW electrode to the center of the pipe and keep the keyhole centered to minimise lack of weld fusion. In the event that the keyhole is closing up, the rod needs to be led and maintained at about 5 to 10 degrees inclination. The hard part of the root is the bottom half of the pipe

Figure 5: Creating the crack region process

After the welding was made, cracks with range of crack lengths will be initiated on the welded pipe in the crack area region. Then, EMA process will be applied to the testing pipe. Normally in EMA, there are two ways to measure in order to get the response needed. One way is that the mounted sensors have to move from one point to another and several measurements were then made. For this research, sensors were mounted at specified positions (suitable welding crack locations) on the pipe outer surface for the measurements.

Figure 6 shows a set of photographs related to the experimental set-up for the measurement of the dynamic behaviour of the welded pipe crack structure utilising the *Bruel & Kjaer* Pulse Multi Channel Spectrum Analyser

Using an impact testing method as shown in Figure 7, the pipe structure was first tested on a free-free boundary condition. The sponge was used to simulate the free-free boundary condition to the test structure. The calculated numerical results were used to determine the FRF of the test structure. The frequency of interest of the structure was within 0 to 3000Hz.

Figure 6: The *Bruel & Kjaer* Pulse Multi Channel Spectrum Analyser

Figure 7: Excitation using an impact hammer (metal tip) on the CSP test specimen

An impact hammer was used to excite the CSP structure and accelerometers were used to acquire the dynamic data. The accelerometers were mounted using bee wax because the frequency of interest was not more than 10 kHz which is acceptable for this kind of adhesive mounting. The reference accelerometer was mounted at the centre of the welded pipe crack area in which the measured FRF will be used for pairing purposes. The load and response signals were interpreted by *LMS SCADAS* to analyze the followings:

Input 1 - Force: 9.9 mV/bf (actual sensitivity based on accelerometer used)
Input 2 - Acceleration: 102.2 mV/g
Input 3 - Acceleration: 102.3 mV/g
Input 4 - Acceleration: 103.8 mV/g

3.0 SIMULATION USING HYPERMESH V 13.0

Besides EMA, natural frequencies of the experiment can be obtained from FEM using *HyperMesh Version 13.0* software. The finite element model was constructed by using a *2D CQUAD4* shell element. The geometry of the structure was discretized into 16627 elements by using a 2mm element size. The nominal values of the carbon steel material and 8mm thickness were assigned to all the elements. For the welded zone, a 14mm thickness has been set. Figure 8 shows the FEM for no crack condition for the CSP (2D and 3D elements) while Figure 9 depicts the FEA of the cracks according to various.

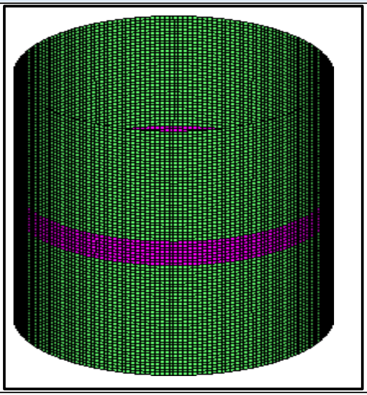
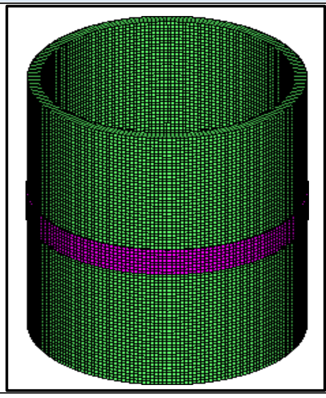
2D shell element	3D illustration with 8mm thickness
	

Figure 8: FEM for no crack

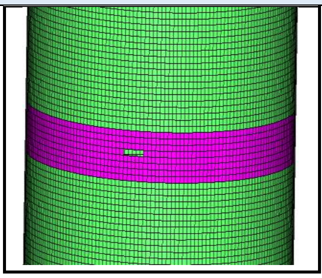
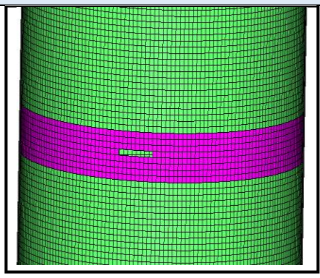
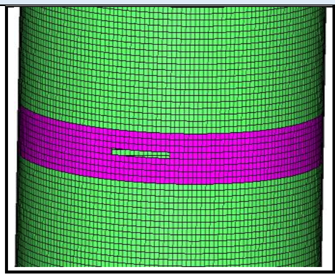
10mm crack	20mm crack	30mm crack
		

Figure 9: FEA of cracks

The mesh convergence study for 20mm, 10mm, 5mm and 2mm element sizes was performed via normal mode analysis. The 2mm element was selected for the meshing size as they are no significant improvements between 5mm and 2mm. A convergence test is always needed to be conducted to determine the size of the elements in FEM. A finer mesh typically results in a more accurate solution.

4.0 RESULTS AND DISCUSSION

4.1 Natural Frequencies on the CSPStructure Using FEA

Based on this tabulation graph in FE, there are no significance differences in FRF for all the FE models. Therefore, the calculated and theoretical FRF are unable to detect the crack of the pipe because all the FRF shown are almost similar. However, the crack shows some differences for the EMA for fixed-free boundary conditions. Figures 10 and 11 show the graphs of comparison of the natural frequencies using FEA for the logarithmic and normal modes, respectively.

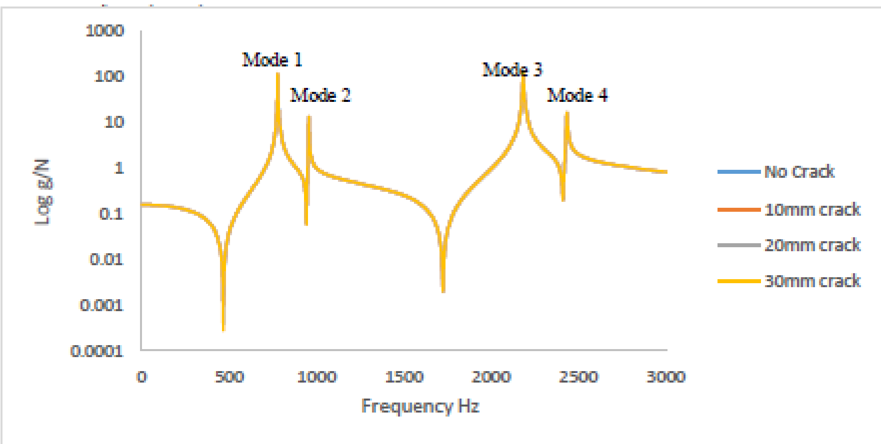


Figure 10: Comparison of the natural frequencies *Log* vs *Frequency* using FEA

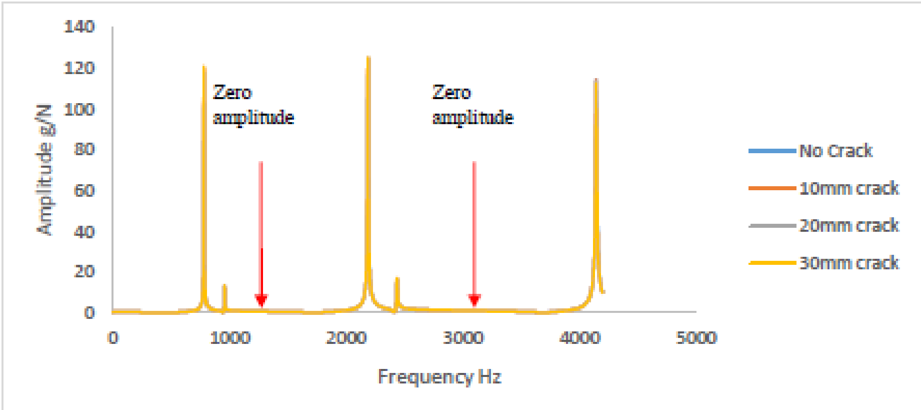


Figure 11: Comparison of the natural frequencies *Amplitude*vs *Frequency* using FEA

4.2 Natural Frequencies on the CSPStructure Using EMA

Figure 12 shows the comparison of natural frequencies on the CSP pipe using EMA. Based on the tabulation graph in Finite Element there are no significance differences in FRF for all FEM. Therefore, the calculated and theoretical FRF are unable to detect the crack of the pipe because all the FRF are almost similar. However, the crack shows some differences for the experimental modal analysis. It is thus recommended that a modal analysis was performed for fixed free boundary conditions.

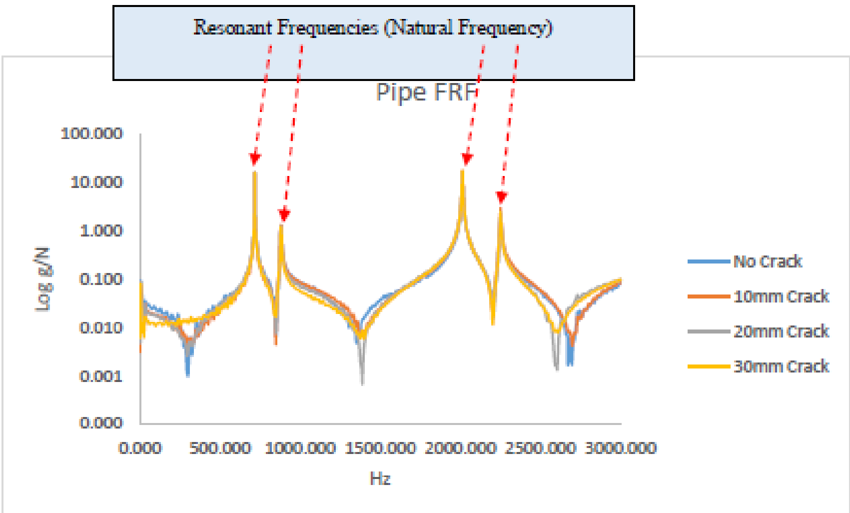


Figure 12: Comparison of natural frequencies*Log*vs *Frequency* using EMA

- Resonances - Peaks indicate the presence of the natural frequencies of the structure under test
- Damping - Damping is proportional to the width of the peaks. The wider the peak, the heavier the damping

The two methods (FEA and EMA) for obtaining the natural frequencies of the no crack and welded pipe with cracks yielded the results as shown in Figures10 and 12, respectively. Comparatively, both results showed strong resemblance (very much alike). However, the experimentalresults displayed wider differences compared to the calculated values of the frequencies. It can be assumed that the hammer tip on which the pipe was mounted for the experimental results caused vibration to occur. In all cases, the curves look alike. Based on the tabulation graph in EMA, the crack shows some differences for the experimental modal analysis in FRF for all EMA model.

4.3 Comparison of FEA and EMA Methods to Compte the Natural Frequencies

After obtaining the results from EMA, the results were then verified by thoseobtained from FEA. After comparing, it can be seen that the range of the natural frequency ranges from 700 Hz to 3000 Hz with the errors between the two techniques are less than 10%.

$$\text{Percentage Error } (\%) = [\text{Accepted Value (FEA)} - \text{Experimental Value(EMA)}]/[\text{Accepted Value (FEA)}] \quad (3)$$

The results in Table 3 show that the least error % is in Mode 4 for no crack area which is about 7.471% while at the other extreme, the result in Table 6 shows the maximum error % occurred in Mode 2 for 30 mm length of the crack which is about 8.336%.

The identification of natural frequencies of the structure has always been a challenging task and difficult. In this study, the measured data for natural frequencies of no crack and cracks pipe structure will be compared with the predicted result which is through FEA to confirm the accuracy of the model. Tables 3 to 6 show the results of the natural frequencies obtained from the experiment (EMA) and predicted (FEA) by comparing the results of the the no crack and cracked pipe structures.

The results in Table 3 show the comparisons of the measured data and predicted results based on the natural frequencies that were obtained from the no crack pipe structure. It can be seen that atotal percentage error of 31.617% (no crack**)** which is the least total error compared to others shown in Tables 4 to 6. On the other hand, a total percentage error of 31.920% isregistered for the highest error as depicted in Table 6 with reference to the 30 mm crack length on the pipe structure.

Table 3: Errors from comparing results by EMA with FEA for no crack

Mode	EMA (Hz), ω	FEA (Hz), ω	Error (%)
1	718.850	780.53	7.902
2	878.125	956.93	8.235
3	2012.500	2187.73	8.009
4	2253.125	2435.07	7.471 (Least error)
Total error (%)			**31.617**

Table 4: Errorsfrom comparing results by EMA with FEA for 10 mm crack

Mode	EMA (Hz), ω	FEA (Hz), ω	Error (%)
1	718.742	780.19	7.876
2	877.250	956.51	8.286
3	2012.240	2186.84	7.984
4	2252.250	2434.49	7.485
Total error (%)			31.631

Table 5: Errorsfrom comparing results by EMA with FEA for 20 mmcrack

Mode	EMA (Hz), ω	FEA (Hz), ω	Error (%)
1	718.650	780.17	7.885
2	877.110	956.42	8.292
3	2011.500	2187.1	8.028
4	2251.143	2434.37	7.526
Total error (%)			31.730

Table 6: Errorsfrom comparing results by EMA with FEA for 30 mmcrack

Mode	EMA (Hz), ω	FEA (Hz), ω	Error (%)
1	717.750	779.99	7.979
2	876.230	955.92	8.336 (Most error)
3	2010.500	2186.86	8.064
4	2250.125	2433.75	7.544
Total error (%)			**31.920**

From the graphs in Figures 13 and 14, it is found that nature of the pattern of the natural frequency change is increasing similarly for every mode though for FEA it is relatively higher than the values obtained in the EMA counterpart. In all cases, the trend of the curves seems almost similar.

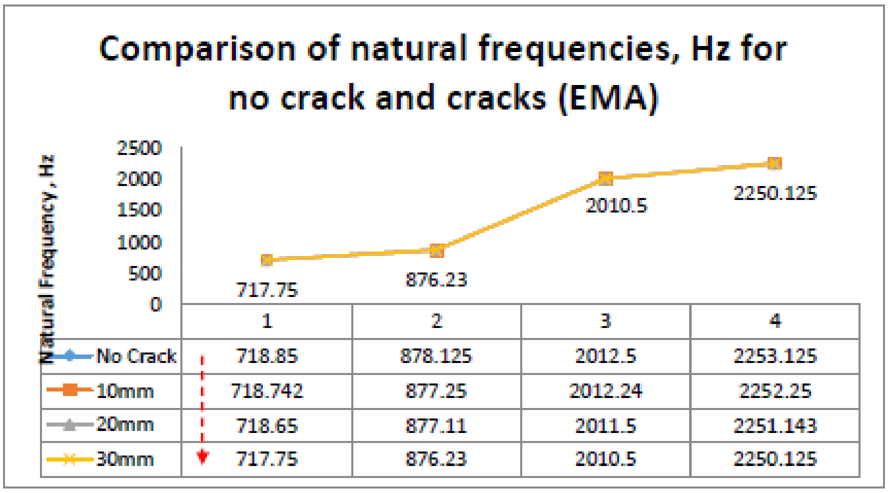
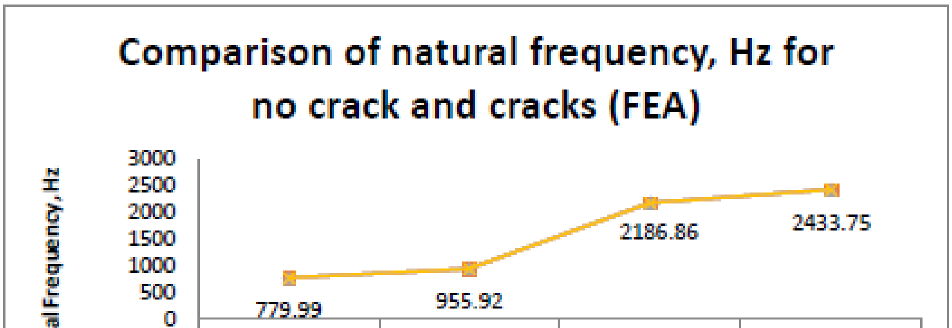


Figure 13: Comparison of natural frequencies for no crack and with cracks (EMA)



	1	2	3	4
No Crack	780.53	956.93	2187.73	2435.07
10mm	780.19	956.51	2186.84	2434.49
20mm	780.17	956.42	2187.1	2434.37
30mm	779.99	955.92	2186.86	2433.75

Figure 14: Comparison of natural frequencies for no crack and with cracks (FEA)

From the results shown in Tables 3 to 6, the least error was found in Mode 4for every case while the highest error was in Mode 2,also for every case. On the other hand, it clearly shows the changes in the natural frequencies of the no crack and cracked pipe structure. The changes in the natural frequencies achieved from the measured data indicate the presence of cracks in the pipe structure. It has been observed that the natural frequency changes substantially due to the presence of cracks depending upon the length of the crack variation. Since crack areas have lower stiffness compared to the no crack region, it causes the dominant vibration to occur in this severely cracked region.

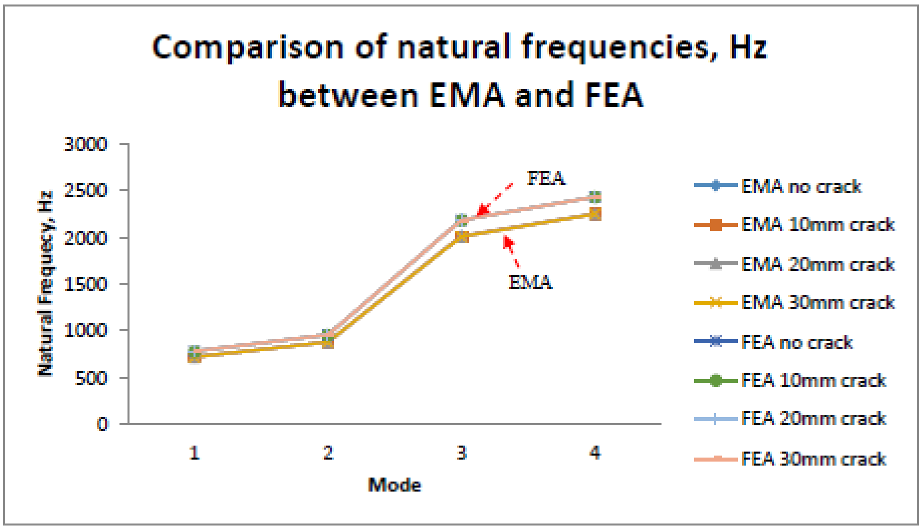


Figure 15: Comparison of natural frequencies, Hz between EMA and FEA

According to Figure 15, it shows that the identification of damage based on frequency response function (FRF) data has been successfully and accurately obtained using the proposed technique with guidance from the predicted data. In all the cases, the FEA analysis and the experimental results were close enough to infer that minimum errors were present during the experimental exercise. The effect of the crack length on the natural frequency seems to suggest that as the crack length increases the frequency is correspondingly decreased. This may be largely attributed to the stiffness reduction due to the presence of the crack on the welded pipe.

5.0 CONCLUSIONS

The results of the various analyses in the study showed that both methods of analyzing the modal frequencies of a physical body can be used. However, the limitations of each method in describing the overall real-life situation must be taken into consideration The FE analysis and experimental results were close enough to deduce that minimum error prevailed during the experiments for all cases. When the position of the crack is at the point where amplitude of vibration is zero there is no changes in the natural frequency in spite of the changes in crack length. Natural frequency drastically changes when a crack is present at the point where the amplitude of vibration is maximum. From this work, the following conclusions may be drawn:

1. Both methodsused in the study to detect the natural frequency of the pipe crack propagation are fast and efficient.
2. The natural frequency is decreased if the crack length is increased and is shown both experimentally or numerically. For example, in EMA, the natural frequency for no crack in Mode 1 is 718.85 Hz, whereas the natural frequency for the 30mm crack length in Mode 1 is 717.75 Hz. The percentageerror in the discrepancy is about 0.15%.
3. There is a possibility to detect the presence of crack in the pipe by using sensors to measure the natural frequency as mentioned earlier and that the generation of the crack reduces the vibration. From the early detection of the crack, it may lead to appropriate corrective action taken before causing a major problem at a later stage.
4. A crack with longer crack length imparts greater reduction of error in the natural frequency than that of the smaller crack length. Hence, the accuracy of results improves as the crack length increases.
5. A comparison was made between the analytical results from *HyperMesh Version 13.0* with the experimental results, in which the total maximum percentage error is found to be 31.62% forthe 30 mm crack length while the total minimum percentage error is 31.92% for the no crack condition.

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