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Frequency Based Damage Detection and Localization of Propeller Shaft of a Ship Using Experimental Modal Analysis

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Abstract: *The whole ship is dependent on the propeller shaft for its movement, the vibrations produced from the shaft destabilizes the whole ship and may lead to accidents. With this objective in mind, in this paper, we describe a methodology to detect and locate the crack present in the intermediate simply supported shaft using experimental modal analysis. In the present work, 304 stainless steel material shaft is taken as the specimen as it is one of the most versatile and widely used steels in the world for making different shafts used in any machinery equipment like ships propeller shaft, engine shafts, motor shafts. Initially, analytical analysis is done on the simply supported shaft then numerical modal analysis using ANSYS 2019 R3 software. Results obtained from the numerical modal analysis are compared with the experimental modal analysis which is done using FFT analyzer. Finally, the first three natural frequencies are used as a tool to detect damage detection and location in the propeller intermediate shaft.*

Keywords*: Experimental Modal Analysis; FFT analyser; Natural Frequencies; 304stainless steel; ANSYS 2019 R3 software; propeller shaft.*

I. Introduction

The propeller shaft is one of the important parts of the ship after the ship's engine; as it is subjected to different torsional, lateral, longitudinal vibrations the propulsion may get affected. So for the safe voyage, the propeller shaft should be monitored very carefully. Any damage in the propeller shaft can lead to catastrophic failure which in turn puts everybody's life on the ship in danger. Here a methodology like experimental modal analysis is used to study different vibration characteristics like natural frequency, mode shapes. Based on these the damage in the propeller intermediate shaft can be detected.

RafalGradzkiet al.[1] Performed an experimental modal analysis to detect a crack presence in a beam. The method is based on a new diagnostic model of rotor signals and external disturbances. The model utilizes auto-correlation functions of the measured rotor's vibrations. By proper processing of the measured vibration data, the influence of environmental disturbances is completely compensated and reliable indications of the possible rotor fault are obtained. Here the Responses are measured on two separate time intervals, concluded that the proposed method is reliable for crack detection based on the results.**Z C Ong [2]** performed an experimental modal analysis to detect a crack present in a beam and also used a crack detection algorithm to identify and locate cracks based on the first and second natural frequencies. Did theoretical calculations using the sensitivity equation given by kim and stubs to locate the cracks, experimental analysis using Bentley Nevada RK4 rotor kit and the simulation of cracks is done using CNC machines. The numerical calculations were almost nearly the same as the experiential analysis results. Concluded that the accuracy of damage detection mainly depends on the mode shapes or the types of modes. **Meilong Chen [3]** proposed an analytical method by combining both Hamilton's principle and integral transform and compared the results with a lumped mass method, finite element method. **Aiko Furukawa et al. [4]** Identification of structural damage based on vibration responses of the cantilever beam. The frequency of the object is changed when the mass and stiffness is changed. The original values are compared with changed values of the object and find the damage location and severity. **Hyungsuk Han [5]** studied the lateral-torsional coupled vibration of a naval ship diesel engine propulsion system assuming it as a Jeffcott rotor, derived a non-linear equation and analysed by identifying and estimating the main cause for the unusual increase in the torsional vibration and finally gave a solution by changing the resilient support of the engine to fixed support.

II. Material Selection

Present work a simply supported shaft made of stainless steel 304 material with dimensions (30mm diameter and 1000mm length) is taken as the specimen. Mechanical and chemical properties of the material are shown in Table 1 and Table 2.

Table no 1 Chemical composition of AISI 304 Stainless Steel

Material	Carbon%	Manganese %	Sulphur %	Phosphorous %
304 Stainless steel	0.08	2.0	0.030	0.045

Table no 2 Mechanical properties of AISI 304 Stainless Steel

Tensile strength, Mpa	Yield strength, Mpa	Density, Kg/m^3	Young's modulus, Gpa	Poisson's ratio
505	215	8000	193	0.29

The line diagram of the simply supported shaft shown in figure 1

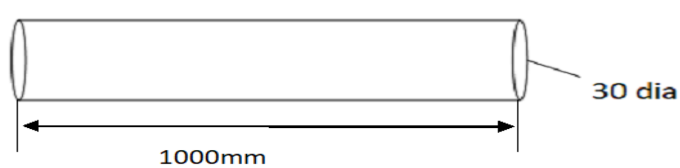


Fig 1 Line diagram of the shaft taken as specimen

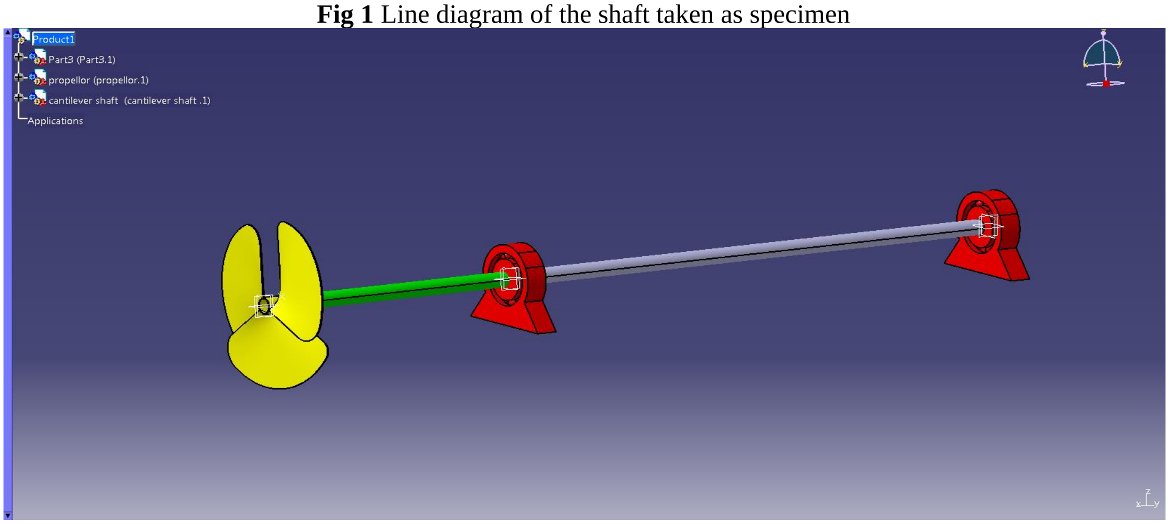


Fig 2 Model of ship's propeller shaft

The above Fig 2 depicts the model of the ship's propeller shaft.It has four parts and two different types of shafts namely:

1. Intermediate shaft (the shaft between two red coloured bearings)
2. Bearings (red coloured)
3. Tail shaft (the green coloured shaft)
4. Propeller (yellow coloured)

The intermediate shaft is simply supported and the tail shaft is cantilever type. In this paper, considering intermediate simply supported shaft and experimental modal analysis is done on this shaft.

III. Analytical Method

Using Euler's-Bernoulli's equation,

$$\boldsymbol{\omega_n = \alpha_n^2 \sqrt{\frac{EI}{\rho A L^4}}} \textbf{ Radians/sec}$$

$$f_n = \omega_n/(2\Pi) \text{ Hz}$$

For simply supported beam α_n= 3.142, 6.284, 9.425……. for first, second, third natural frequencies.

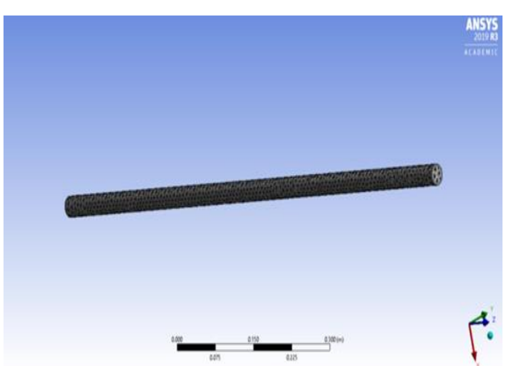
Table 3 Natural frequencies obtained by analytical method

Mode	Natural frequency of healthy shaft (Hz)
1	57.89
2	231.57
3	520.939

The table 3 indicates the first three natural frequencies found using analytical formula.

IV. Numerical Analysis Using ANSYS 19.1 R3 Software

Numerical modal analysis was done using modal analysis in ANSYS. Initially, the engineering data are given as an input and then shaft designed in CATIA is imported into ANSYS and modal analysis performed to get natural frequencies and mode shapes. The below fig. 3 and fig. 4 are the meshed shaft models.



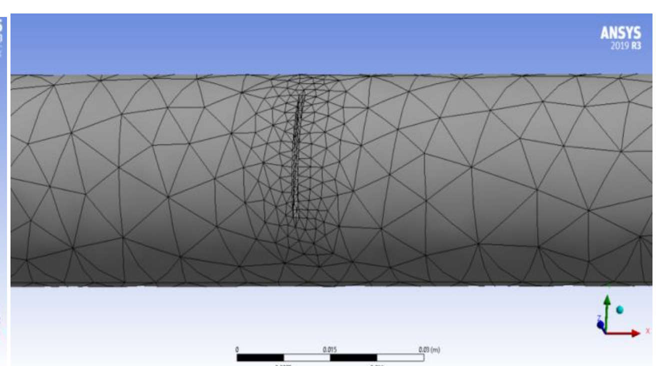


Fig 3 Meshed healthy shaft modelFig 4 Meshed shaft with transverse crack

The fig 5 represents the natural frequency results from ANSYS 2019 R3.

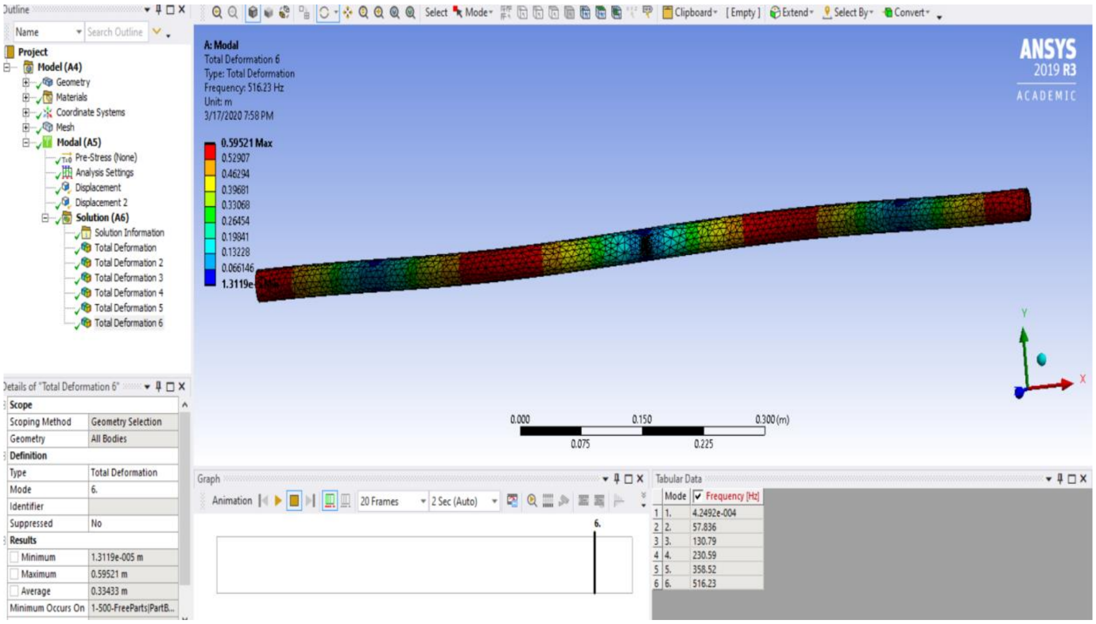


Fig 5 Natural frequency results from modal analysis in ANSYS 2019 R3.

The deformation of the shaft takes place with certain mode shape depending on the natural frequencies which is Shown in fig .6

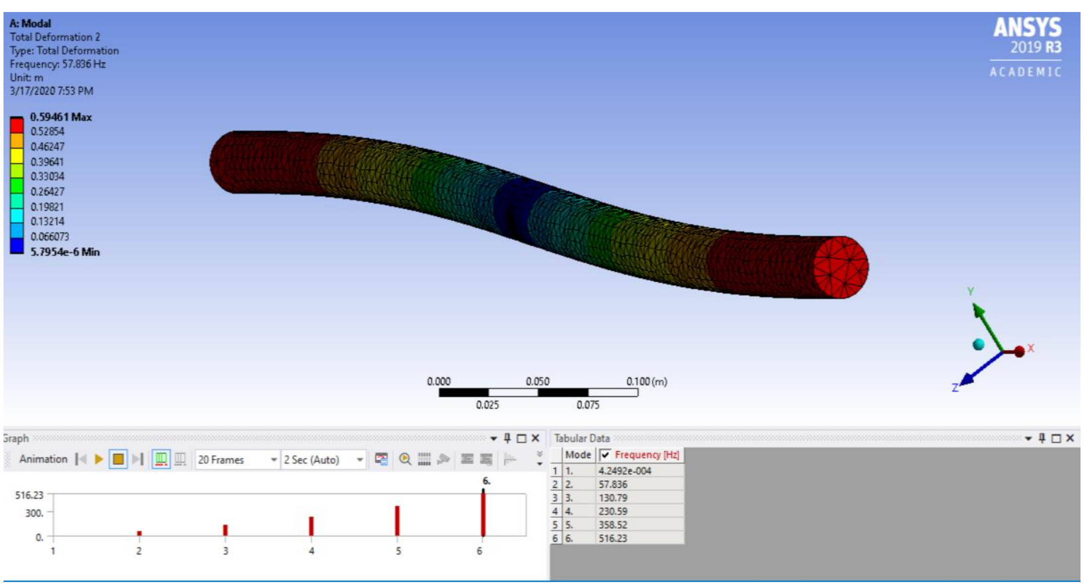


Fig 6 Deformation of the shaft model at first natural frequency

By varying eight different crack depths(1,2,3,4,6,8,10,12mm)at five different crack locations (100,200,300,400,500mm) forty different cracked shaft models are made and modal analysis performed . The below tables (4, 5, 6) give the natural frequencies of a shaft with varying crack depth and crack location. Particularly result of 2mm crack depth at 300mm crack location is considered as it is the actual crack that is considered for experimental modal analysis.

Table 4 First three natural frequencies of a simply supported shaft for various crack depths at 300mm location

Crack depth(d) in mm	First natural frequency (Hz)	Second natural frequency (Hz)	Third natural frequency (Hz)
1	57.834	230.62	516.17
2	57.823	230.61	515.93
3	57.508	230.59	515.5
4	57.776	230.56	514.84
6	57.687	230.46	512.81
8	57.546	230.3	509.64
10	57.334	230.08	505.17
12	57.06	229.76	499.05

Table 5 First three natural frequencies for various crack locations of 2 mm crack depth

Crack location (s) in mm	First natural frequency (Hz)	Second natural frequency (Hz)	Third natural frequency (Hz)
No crack	57.795	230.46	515.87
100	57.803	230.53	516.2
200	57.812	230.61	516.2
300	57.823	230.61	515.93
400	57.833	230.53	516.01
500	57.836	230.47	516.23

Table 6 ANSYS 2019 R3 Natural frequency results for various crack depths and crack location

Crack location from fixed end in mm	Crack depth in mm	First natural frequency in Hz	Second natural frequency in Hz	Third natural frequency in Hz
No crack	No crack	57.795	230.46	515.87
100	1	57.831	230.61	516.21
	2	57.803	230.53	516.2
	3	57.745	230.39	515.95
	4	57.68	230.17	515.7
	6	57.448	229.52	514.93
	8	57.085	228.51	513.77
	10	56.57	227.1	512.18
	12	55.864	225.24	510.11

200	1	57.832	230.62	516.22
	2	57.812	230.61	516.2
	3	57.777	230.59	516.16
	4	57.723	230.56	516.08
	6	57.555	230.46	515.87
	8	57.291	230.31	515.52
	10	56.913	230.09	515.03
	12	56.379	229.79	514.34
300	1	57.834	230.62	516.17
	2	57.823	230.61	515.93
	3	57.508	230.59	515.5
	4	57.776	230.56	514.84
	6	57.687	230.46	512.81
	8	57.546	230.3	509.64
	10	57.334	230.08	505.17
	12	57.06	229.76	499.05
400	1	57.836	230.6	516.18
	2	57.833	230.53	516.01
	3	57.828	230.39	515.7
	4	57.819	230.17	515.23
	6	57.795	229.51	513.77
	8	57.756	228.46	511.52
	10	57.66	226.96	508.38
	12	57.618	224.86	504.13
500	1	57.836	230.59	516.23
	2	57.836	230.47	516.23
	3	57.837	230.26	516.23
	4	57.837	229.93	516.23
	6	57.836	228.92	516.23
	8	57.836	227.34	516.22
	10	57.836	225.1	516.21
	12	57.836	222	516.19

V. Experimentation Using FFT Analyser

5.1 Preparation of the specimen which is to be tested

For experimental modal analysis, a simply supported shaft of 304 stainless steel whose both ends are simply supported using two ball bearings and has a circular cross-section of dimensions 30mm diameter x 1000mm length is considered. The below fig 7 is the image of the specimen for experiment prepared to perform the experimental modal analysis.

Fig 7 Image of the specimen for experiment

5.2 Fast Fourier Transformer

FFT means Fast Fourier Transformer, it is a device used to find the natural frequency of a specimen or object or body. It has an impact hammer and an accelerometer sensor.

Fig 8 FFT analyser along with impact hammer (on left side) and an accelerometer sensor (on right side).

5.3 Experimentation

Initially, the experimentation is done for the healthy shaft and then later an artificial crack is made on the shaft of known depth and location. Then this cracked shaft has experimented and the natural frequency data will be obtained from the frequency response graphs. The below fig 9 represents the experimentation of the shaft. The fig10, fig 11 represent the frequency response spectrum obtained from the healthy and cracked shaft using FFT analyzer

Fig 9 Image of experimentation on the shaft using FFT analyser

After experimentation these are the obtained frequency response graphs from the EDM software, from these graphs the natural frequencies of the shaft are obtained.

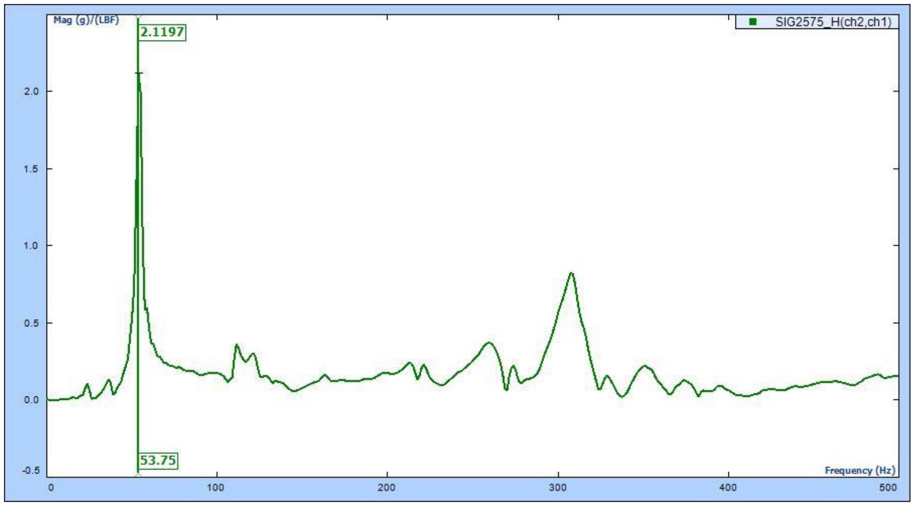


Fig10 Frequency response spectrum from FFT analyser for a healthy simply supported shaft

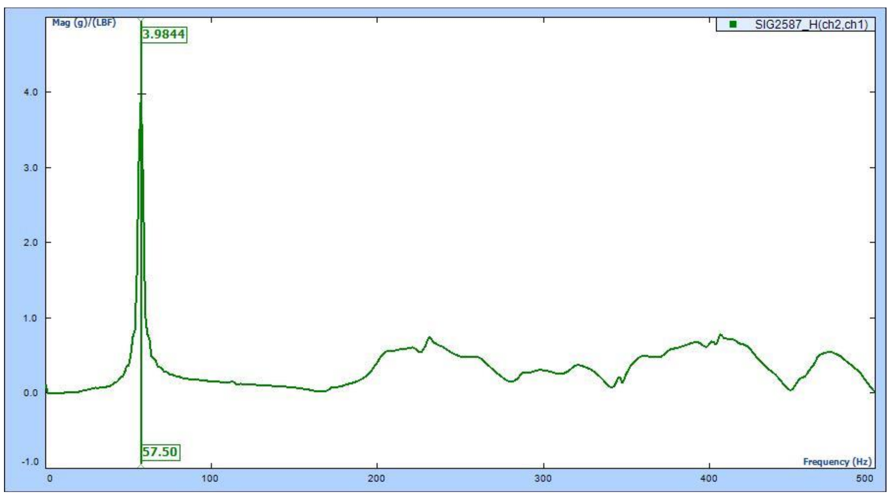


Fig11 Frequency response spectrum from FFT analyser for a cracked simply supported shaft

VI. Results and Discussion

Results from the all the three methods (analytical method, numerical method and experimental method) are compared and the percentage of error is calculated to prove that the proposed methodology is correct. Table 7 gives theNatural frequency results for analytical, numerical and experimental method. Since the percentage of error between Experimentalmodal analysis and Analytical method is from 3.58% to 7.15% and percentage of error between Experimental modal analysis andNumerical method is from 2.64% to 6.99%.The percentage of error is less than 10%, so the results are valid.

Table 7 Natural frequency results for analytical, numerical and experimental method

Mode	Natural frequency in Hz			Percentage of error between Experimental modal analysis and Analytical method (%)	Percentage of error between Experimental modal analysis and Numerical method (%)
	Analytical Method	Numerical Method-ANSYS2019 R3	Experimental Method		

1	57.89	57.79	53.75	7.15	6.99
2	231.57	230.46	221.14	4.50	4.04
3	520.93	515.87	502.23	3.58	2.64

6.1 Damage Detection and Localization

To locate the crack present in the shaft normalized natural frequency data is used. The formula for normalized natural frequency is given below. Initially, for our reference, a crack of 2mm is made at 300mm location from one end to estimate the geometric location.

Normalized natural frequency $(f_N) = \frac{\text{Modal frequency of damaged beam}}{\text{Modal frequency of healthy beam}}$

By using the above formula the normalised natural frequency results obtained from 2mm crack depth and 300mm crack location are 1.0004 at first mode, 1.0006 at second mode and 1.0001 at third mode. Now using these normalised natural frequency data contour plots are drawn in MINI TAB 15.0 software. By taking the above normalized natural frequency data and using MINI TAB 15.0 the contour plots for different normalized natural frequencies vs. crack depth and crack location are drawn. The below Fig(12,13,14) are the individual contour plots drawn against each normalised natural frequency.

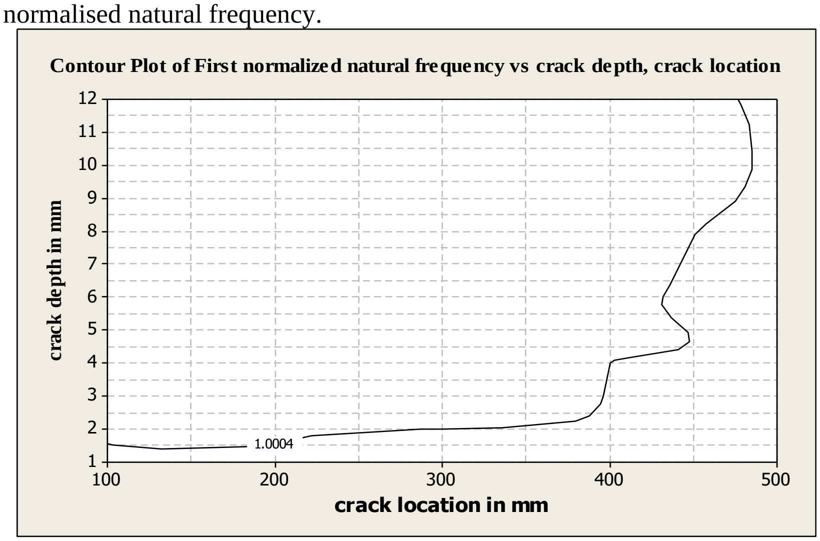


Fig12 Contour plot for first normalized natural frequency

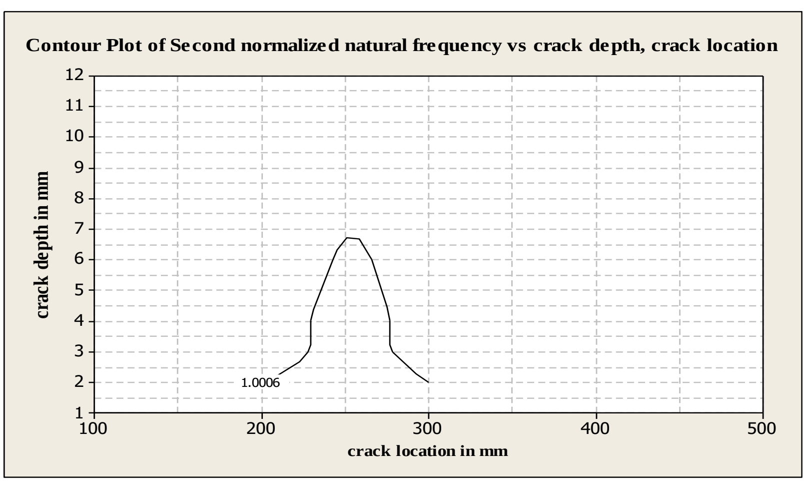


Fig13 Contour plot for second normalized natural frequency

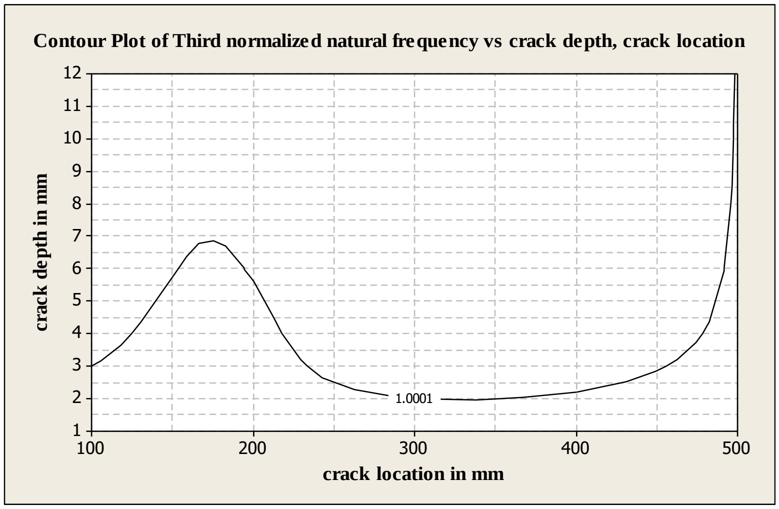


Fig14 Contour plot for third normalized natural frequency

The common point of intersection of all the three contour plots gives the crack depth and location of the crack. Here Fig 15 indicates that the crack depth is 2.0035mm and location is at 299.34mm.but if we see the actual crack depth is 2mm and location is at 300mm. The percentage of error is from 0.17% to 0.22% which is represented in Table 8 given below. Since it is less than 5% it is valid. This proves that the proposed methodology is correct.

Table 8 Comparison between actual and estimated geometric locations of the crack

Parameter	Actual geometric location of crack	Identified geometric location of crack using ANSYS 19.1 R3	Percentage of Error %
Crack location (mm)	300	299.34	0.22
Crack depth(mm)	2	2.0035	0.17

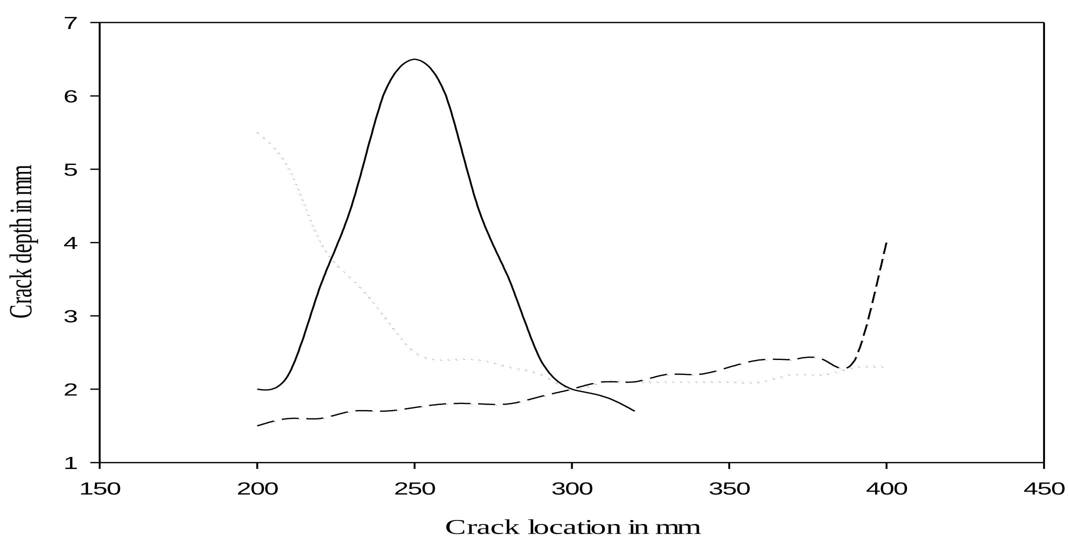


Fig15 Intersection of first three modes contour plot

VII. Conclusion

In this paper, a methodology is proposed to detect and locate the damage or crack present in the ship's propeller shaft. At the end of the work following observations are made.

- From the natural frequency results of healthy and cracked shaft we can conclude that the natural frequencies vary due to reduction of the material mass, stiffness of the shaft.
- The natural frequency results of all the three methods are compared and the percentage of error between Experimentalmodal analysis and Analytical method is from 3.58% to 7.15%, percentage of error between Experimental modal analysis andNumerical method is from 2.64% to 6.99%.since the percentage of error is below 10% it is acceptable.
- Estimated crack depth and crack location are within 5% error of the actual crack depth and crack location, hence the proposed methodology can be accepted and can be used to detect and locate the crack of propeller shafts and also can be used to solve real time problems.

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