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Transverse crack analysis in rotodynamic system

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ABSTRACT

The topic of the present work has been one of the most important research topics in the predictive maintenance field. This area has a good research potential in view of the field requirements for the smooth operation of critical machinery and equipment. Detection of the shaft crack in a rotating machine is one of the most challenging problems in equipment predictive maintenance. In the available literature, various crack detection methods have been applied to study the dynamic behavior of a cracked shaft.

The initiation and propagation of a shaft crack is a complex process that arises from machining imperfections. The concept of the approach is based on the fact that the development of a shaft crack or notch results in a distorted strain field within the component. The work involves vibrational and shaft dynamic analysis of the virtual rotodynamic system to describe the experimental results concerning effect of a crack in a rotating shaft.

The main aim of the project is to utilize the active vibration control technique to determine vibration amplitude at fundamental natural frequency in rotating shaft system with crack generation & subjected to varying loading conditions. The results from the cracked shafts were compared with that of an intact shaft.

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I. Introduction

A. *Importance of crack detection*

The diagnosis of shaft cracks in rotating machinery has been a research challenge for both industry and academia for several decades. Such cracks can cause total shaft failure and enormous costs in down time. Accordingly, owners of critical plant machinery are particularly interested in early detection of symptoms that can lead to in-service failure of machinery and equipment. Safe and reliable operation of equipment relies on proactive maintenance aided by newly emerging diagnostic technologies [1].

B. *Crack detection techniques*

Shaft crack detection techniques adopted in the literature can be broadly grouped into two methods: vibration-based and model-based methods.

The former relies on detecting changes in vibration signals as a crack in a structure tends to modify its dynamic characteristics such as the natural frequencies and mode shapes. Conversely, through monitoring the trend changes in measurements of the natural frequencies and mode shapes of a rotating shaft over time, a crack present in the shaft could be predicted. The stiffness of a shaft is reduced by a crack and consequently the shaft's Eigen-frequencies decline. Measuring these changes can help with identifying an early stage crack. Unfortunately, the available indicators cannot reliably differentiate a cracked shaft from other problems that create similar vibration spectra and waveforms, such as a misaligned or unbalanced shaft. Thus, to develop more reliable diagnostic methods, a thorough understanding of periodical stiffness of a cracked shaft is necessary.

The model-based methods are based on analytical or numerical models to simulate the behaviour of cracked shafts during rotation. In model-based identification, the fault-induced change in the rotor system is taken into account by equivalent loads in the mathematical model. These equivalent loads are virtual forces and moments acting on the linear undamaged system to generate a dynamic behaviour identical to that measured in the damaged system. However, the approximations and assumptions used in the model-based approaches could lead to large errors for the analysis of cracked shaft dynamic behaviour. Specifically in consideration of cracked shaft stiffness, the stiffness parameters used in some of the models do not really reflect its periodic change at different rotation angles [2].

C. *Causes of cracks*

There are two stages of crack development in rotating shafts: crack initiation, and crack propagation. The first is caused by mechanical stress raisers, such as sharp keyways, abrupt cross-sectional changes, heavy shrink fits, dents and grooves, and/or metallurgical factors, such as fretting and forging flaws. The second stage can accelerate the growth rate under certain conditions, viz., (i) operating faults like sustained surging in compressors; (ii) negative sequence current or grounding faults in generators and coupled turbines; (iii) the presence of residual and thermal stresses in the rotor material; and (iv) environmental conditions such as the presence of a corrosive medium. Also, from the physical morphology of a cracked rotor, cracks can be classified based on their geometries as follows: (i) transverse cracks that are perpendicular to the shaft axis; (ii) cracks parallel to the shaft axis known as longitudinal cracks; (iii) slants cracks that are at an angle to the shaft axis; (iv) open and close cracks when the affected part of the material is subjected to tensile stresses and stress reversals (breathing cracks); (v) gaping cracks or notches that always remain open; and (vi) surface cracks and subsurface cracks [3].

Crack breathing is one of the popular approaches for studying the dynamics of a cracked shaft by many researchers. During each revolution, the crack opens and closes gradually, in other words, it breathes during shaft rotation [4].

At a certain angle, when the stresses on a crack surface are compressive, the crack remains closed and the shaft has almost the same stiffness as an intact shaft. When the stress becomes extensive, the crack will open, in which case the stiffness of the shaft is reduced significantly.

In large industrial turbine-generator rotors, static deflection often dictates shaft vibration patterns. If any cracks are present in this kind of rotor, the crack will open and close according to the shaft rotation. Crack breathing behaviour lead to changes in one of the shaft mechanical properties stiffness. An intact shaft's stiffness normally remains the same value at different angles of rotation. However, when a shaft has a crack, the shaft stiffness will change periodically at different rotational angles.

II. EXPERIMENTAL SET UP

Fig. 1 Experimental set up

Material used for shaft & disc was C 40. Diameter of shaft is 25 mm, with length 350 mm (distance between bearing). Shaft crack was developed at mid of bearing support by wire cut EDM.

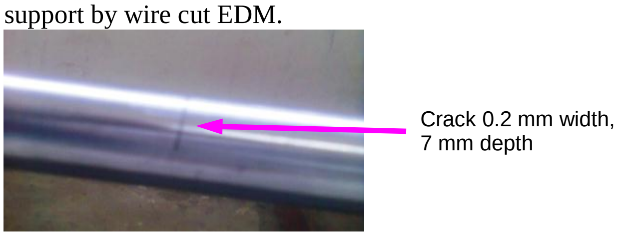

Fig. 2 Cracked shaft

III. RESULTS

Experiment was carried out on both intact & cracked shaft.

A. *Vibration signature on FFT*

Following figures shows amplitude pattern of intact & cracked shaft for different loads & speeds.

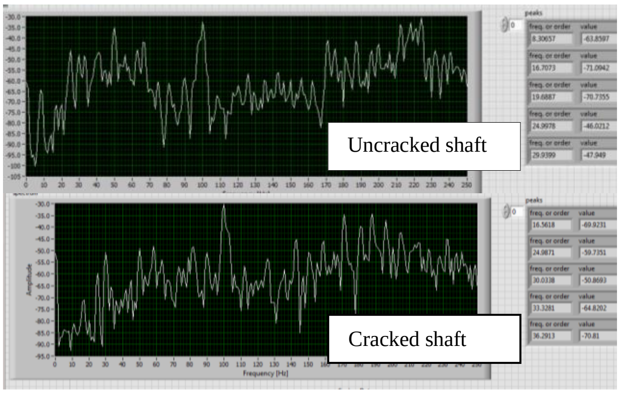

Fig. 3 No load (500 rpm)

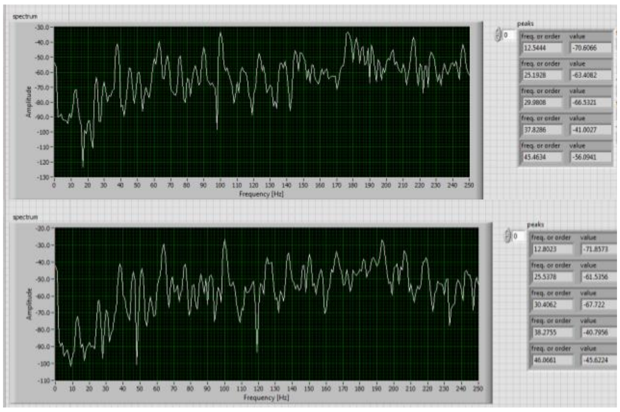

Fig. 4 No load (750 rpm)

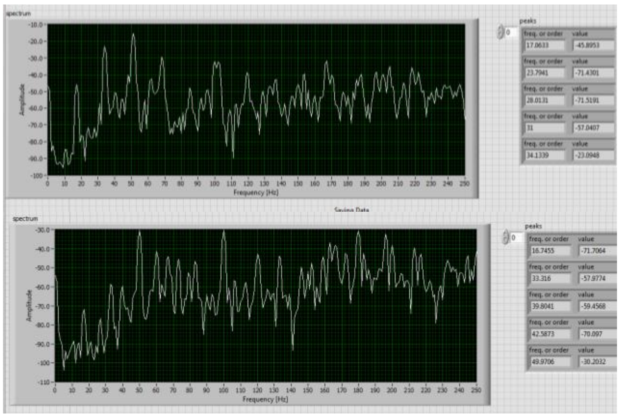

Fig. 5 No load (1000 rpm)

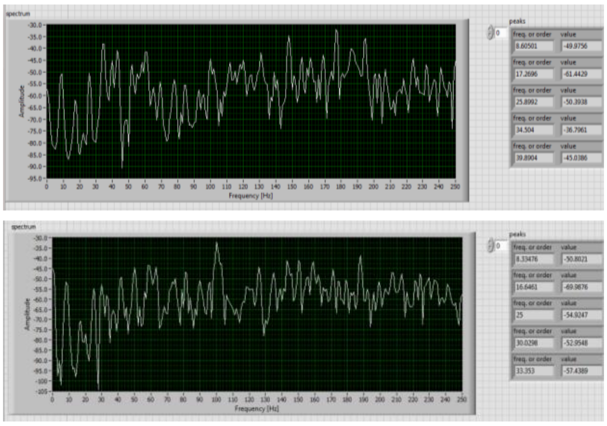

Fig. 6 0.25 kg load (500 rpm)

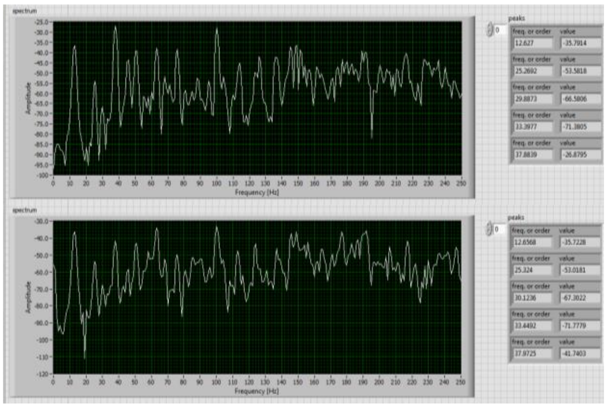

Fig. 7 0.25 kg load (750 rpm)

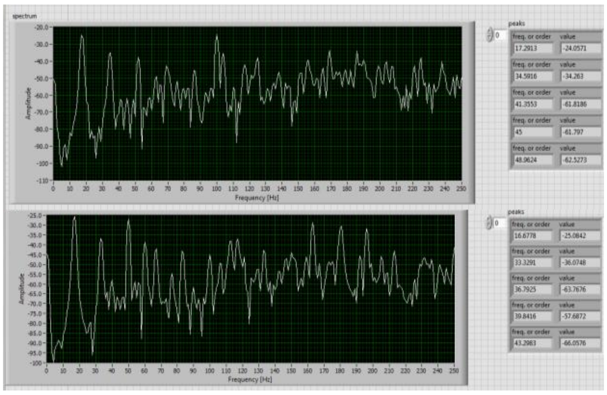

Fig. 8 0.25 kg load (1000 rpm)

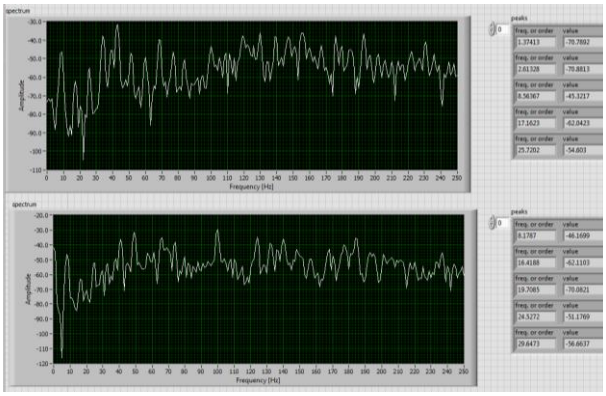

Fig. 9 0.5 kg load (500 rpm)

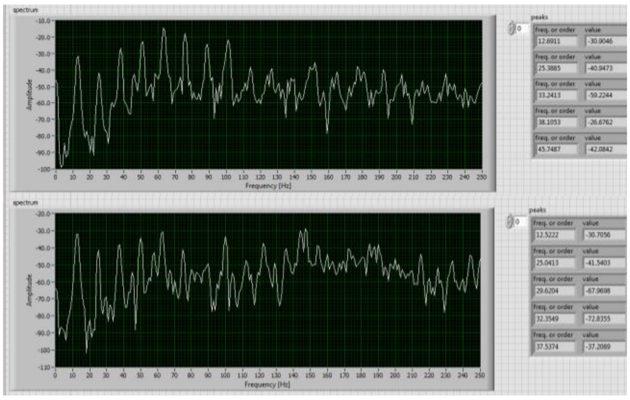

Fig. 10 0.5 kg load (750 rpm)

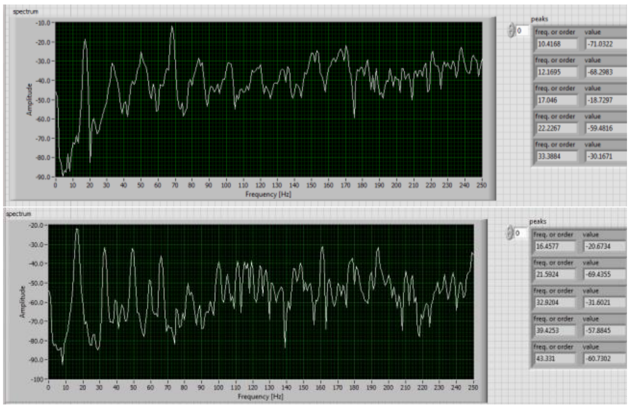

Fig. 11 0.5 kg load (1000 rpm)

B. Amplitude values of intact & cracked shaft at first four fundamental frequencies

TABLE I
EXPERIMENTAL AMPLITUDE VALUES of INTACT SHAFT

	Amplitude values :Uncracked shaft			
	Load (kg)	**500 rpm**	**750 rpm**	**1000 rpm**
First fundamental frequency	**0**	**63.85**	**70.60**	**45.89**
	0.25	**49.97**	**35.79**	**24.05**
	0.5	**70.78**	**30.90**	**71..03**
	0.75	**45.60**	**28.79**	**17.35**
	1	**42.15**	**26.30**	**72.97**
	1.25	**47.18**	**28.13**	**17.95**
	1.5	**44.68**	**29.30**	**17.90**
	1.75	**50.60**	**36.05**	**24.43**
	2	**69.41**	**58.90**	**49.72**
Second fundamental frequency	**0**	**71.09**	**63.40**	**71.43**
	0.25	**61.44**	**53.58**	**34.26**
	0.5	**70.88**	**40.94**	**68.29**
	0.75	**61.65**	**38.04**	**70.66**
	1	**63.47**	**28.68**	**69.10**
	1.25	**58.42**	**39.38**	**34.71**
	1.5	**62.93**	**48.92**	**58.96**
	1.75	**71.52**	**57.33**	**33.08**
	2	**69.24**	**64.89**	**56.27**
Third fundamental frequency	**0**	**70.73**	**66.53**	**71.51**
	0.25	**50.39**	**66.58**	**61.81**
	0.5	**45.32**	**59.22**	**18.72**
	0.75	**71.84**	**60.85**	**72.71**
	1	**46.07**	**71.09**	**63.14**
	1.25	**45.46**	**67.47**	**56.10**
	1.5	**47.73**	**64.92**	**53.30**
	1.75	**54.21**	**60.80**	**63.32**
	2	**53.66**	**65.07**	**69.51**
Fourth fundamental frequency	**0**	**46.02**	**41.00**	**57.04**
	0.25	**36.79**	**71.38**	**61.79**
	0.5	**62.04**	**26.67**	**59.48**
	0.75	**61.73**	**67.82**	**74.25**
	1	**51.21**	**61.87**	**51.75**
	1.25	**56.24**	**63.38**	**53.65**
	1.5	**51.63**	**61.12**	**54.48**
	1.75	**56.63**	**36.57**	**63.49**
	2	**53.60**	**58.49**	**19..87**

TABLE II
EXPERIMENTAL AMPLITUDE VALUES of CRACKED SHAFT

	Amplitude values :Cracked shaft			
	Load (kg)	**500 rpm**	**750 rpm**	**1000 rpm**
First fundamental frequency	**0**	**69.92**	**71.85**	**71.70**
	0.25	**50.80**	**35.72**	**25.08**
	0.5	**46.16**	**30.90**	**20.67**
	0.75	**43.12**	**27.29**	**67.19**
	1	**65.51**	**27.77**	**16.53**
	1.25	**42.76**	**26.93**	**16.04**
	1.5	**49.19**	**30.87**	**19.69**
	1.75	**49.34**	**34.56**	**22.94**
	2	**73.12**	**62.12**	**52.70**
Second fundamental frequency	**0**	**59.73**	**61.53**	**57.97**
	0.25	**69.98**	**53.01**	**36.07**
	0.5	**62.11**	**41.54**	**69.43**
	0.75	**64.77**	**72.50**	**18.08**
	1	**46.08**	**33.77**	**57.78**
	1.25	**58.99**	**70.59**	**59.87**
	1.5	**54.01**	**48.00**	**36.86**
	1.75	**69.24**	**55.60**	**66.98**
	2	**56.40**	**57.52**	**52.23**
Third fundamental frequency	**0**	**50.86**	**67.72**	**59.45**
	0.25	**54.92**	**67.30**	**63.76**
	0.5	**70.08**	**67.96**	**31.60**
	0.75	**54.45**	**69.83**	**60.97**
	1	**67.64**	**65.47**	**61.35**
	1.25	**73.92**	**39.58**	**57.36**
	1.5	**50.07**	**66.71**	**65.75**
	1.75	**71.64**	**68.69**	**27.56**
	2	**56.23**	**65.33**	**67.38**
Fourth fundament	**0**	**64.82**	**40.79**	**70.09**
	0.25	**52.95**	**71.77**	**57.68**

al frequency	**0.5**	**51.17**	**72.83**	**57.88**
	0.75	**52.09**	**33.19**	**52.36**
	1	**73.98**	**36.79**	**60.98**
	1.25	**46.62**	**60.62**	**61.79**
	1.5	**60.15**	**31.83**	**55.63**
	1.75	**51.01**	**65.57**	**59.58**
	2	**51.24**	**31.36**	**31.17**

C. Comparison of vibration amplitude between intact & cracked shaft

Following figures shows comparison of vibration amplitudes between intact & cracked shaft for first four fundamental frequencies.

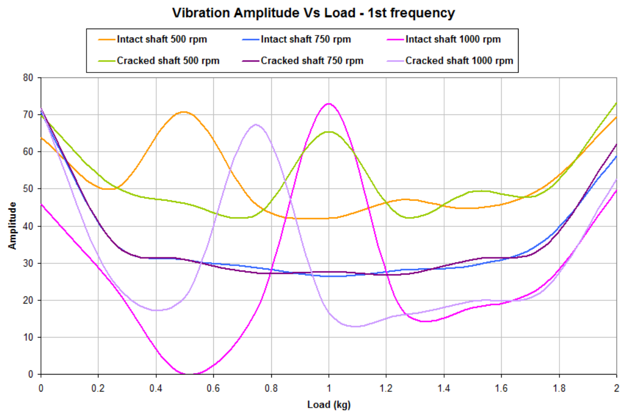

Fig. 12 Amplitude at first fundamental frequency

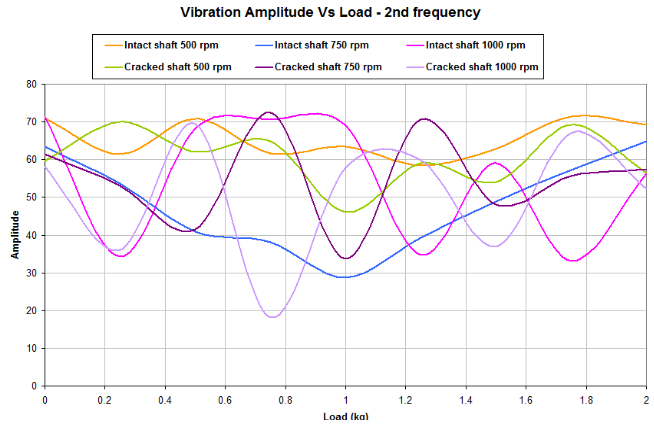

Fig. 13 Amplitude at second fundamental frequency

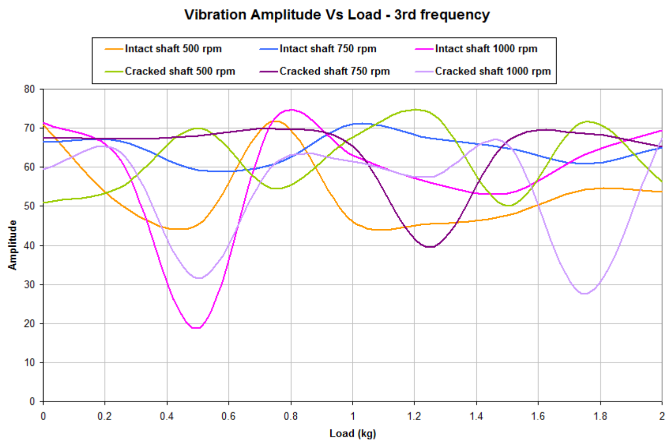

Fig. 14 Amplitude at third fundamental frequency

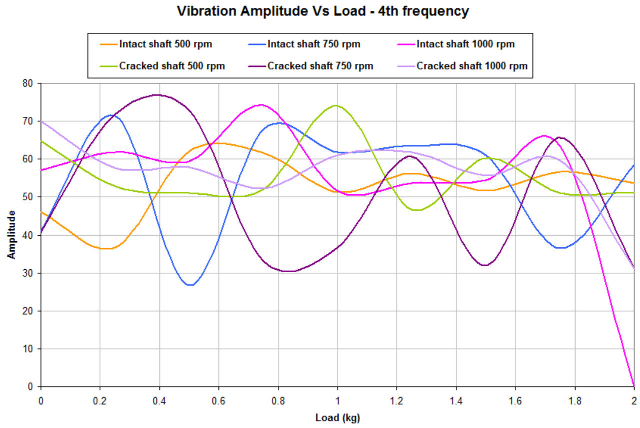

Fig. 15 Amplitude at fourth fundamental frequency

IV. SUMMERY

Vibration analysis of intact shaft & cracked shaft was done successfully for different loads. Amplitude peak of cracked shaft was higher than intact shaft. Such sudden change in amplitude gives significance of crack initiation & propagation.

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