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Effect of Multiple Location Defects on the Dynamics of Draft Gear used in Freight Railway Wagon

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ABSTRACT:

The present work investigates the effect of crack location on the modal frequency of draft gear used in autocouplers of freight railway wagon for various orientations. First seven mode shapes of a healthy draft gear have been determined using finite element approach. Defect of semi-elliptical shape is modelled in the lateral as well as longitudinal direction of the draft pad which is a component of draft gear. Various damage scenarios have been simulated by considering multiple locations of the crack in the draft gear for different orientations. Effect of crack orientation and defective pads location on the natural frequency of draft gear is analysed. It is seen that for single defective pad as well as multiple defective pads, the natural frequency of draft gear is dependent on the dynamics of draft pad. It is also observed that defect in consecutive pads causes more change in frequency as compared to single defective pad. As far as the location of defective pad is concerned, it is seen that the draft gear frequency is more sensitive to defective pads located either near the housing base plate or top follower. This study provides a tool to diagnose crack defect in draft gear based on vibration characteristics.

KEYWORDS:

Draft gear; Draft pad; Natural frequency; Crack; Mode shape; Finite element method

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1. Introduction

The longitudinal dynamics of freight railway wagon largely depends on the dynamics of draft gear and consequently the draft pad. The draft pads are subjected to severe forces due to acceleration and braking in the longitudinal direction. These forces which play an important role in safe, efficient and stable train operations are repetitive in nature and tend to damage the draft pad. These draft pads fail under fatigue load which result in transmission of the longitudinal forces to the wagon and the safety of the laden goods is compromised. Fatigue failure of any mechanical component is dependent on the exciting frequency of the longitudinal force. Components are more prone to failure at resonance condition. The longitudinal in-train forces are responsible for several problems including broken draft gear and even causes railway wagons to be pulled off from the inside of curves [1]. Initial efforts by researchers were aimed at reducing longitudinal oscillations in passenger trains. Measurement and simulation of in-train forces were carried out to achieve reduction in longitudinal oscillations [2].

A mathematical model to calculate the transient responses of a coupler and to identify the coupling speed was developed [3]. Experiments to determine the occurrences of coupler impacts combined with pitching motions in the wagon body were also undertaken. These impacts were simulated using train-wagon interaction model in NUCARS and ADAMS/Rail [4]. The fatigue life of three different wagon connection coupling system was evaluated. The autocoupler systems had draft gear with and without self-locking features [5]. The effect of train braking delay time on longitudinal dynamics of train was studied for three different train forward velocities. Simulations were carried out for long, medium and short brake application time [6]. The stability of long and heavier trains is greatly affected by lateral force components and impacts from couplers. Modelling of coupler angles to normal longitudinal simulation was added for a comprehensive study of lateral components of coupler forces [7]. Dynamic behaviour of an individual draft pad and gear was determined and characterized with exciting frequencies and corresponding mode shapes. The vibration characteristics of individual draft pad are compared with draft pads that are part of draft gear [8].

This article concentrates on the effect of crack location and its orientation on the modal frequency of draft gear. The effect of crack in multiple pads is also analysed. First seven mode shapes of a healthy draft have been determined using finite element method (FEM). Crack of semi-elliptical shape is modelled in the lateral as well as longitudinal direction of the draft pad.

Different damage scenarios have been simulated by varying the orientation of the crack as well as location of defective pad(s) in the draft gear. The defect is also modelled in multiple pads. Effects of crack orientation, defective pad location and number of defective pads on the natural frequency of draft gear are analysed.

2. Modal analysis

Vibration characteristics of any system can be determined with modal analysis. For a structure it can be determined during the design process. Modal analysis has been used to determine the natural frequencies and mode shapes of a continuous structure like freight car wagon [9]. For a dynamic system, the general form of equation of motion is: $m\ddot{x}+c\dot{x}+kx=f(t)$. In finite element solution, the differential equation of motion is discretized into a number of finite element equations which form a system of algebraic equations to be solved using: $[K]\{u\}=\{F\}$, where $[K]$ is the stiffness matrix, $\{u\}$ is the nodal displacement vector and $\{F\}$ is the applied load vector. These equations are solved by finite element package ANSYS [10]. For a free vibration analysis, the natural frequencies (ω_i) and the mode shapes (ϕ_i) will be calculated using: $([K]- \omega_i^2[M])\{\phi_i\} = 0$ [11]. For evaluating mode shapes the material is assumed to behave linearly elastic neglecting nonlinearities.

As per the fundamentals of vibrations, for any mechanical system, its natural frequency (ω_n) is affected by two parameters, namely mass (m) and stiffness (K). The effect of these two parameters is defined in general by the equation:

$$\omega_n = \sqrt{K/m} \tag{1}$$

The natural frequency is directly proportional to the stiffness of the system. Thus any parameter that affects the stiffness of the system also affects its natural frequency. Hooke's law can also be used to correlate system stiffness with other parameters as,

$$\sigma = E\varepsilon \tag{2}$$

$$W/A = E\delta l/l \tag{3}$$

Thus, the stiffness for any system obeying Hooke's law can be written as:

$$K = W/\delta l = EA/l \tag{4}$$

It is seen that stiffness of any system is affected by its Young's modulus, cross-sectional area and thickness. These parameters thus have a similar impact on the natural frequency of the system. Presence of crack affects the cross-sectional area of the system as it tends to reduce it. Reduced area results in reduced stiffness and consequently reduces the natural frequency as seen from Eqns. (1) and (4).

While considering any crack, the variation in the area of a crack is realised by changing crack width or the crack aspect ratio. When crack width is maintained constant and the aspect ratio is varied. It is seen that area is function of a single parameter, i.e.

$$A = f(\text{depth of crack}) \tag{5}$$

Under such circumstances variation in area is linear. If the variation in area is effected by varying the crack width and maintaining the aspect ratio constant, then area is function of two parameters, viz., crack width and depth of crack. Thus,

$$A = f(\text{depth of crack} \times \text{crack width}) \tag{6}$$

Under such circumstances variation in area is parabolic. This reduction in stiffness will consequently reduce the natural frequency. Thus for a draft pad, the presence of crack should cause reduction in natural frequency in accordance to Eqns. (5) and (6).

3. Model for modal analysis

An accurate model is important for vibration-based analysis. Thus three dimensional models of draft pad and draft gear was created using Solidworks and exported to ANSYS environment for numerical analysis. The draft pad used in present study is illustrated in Fig.1. It is commercially available as 'Draft Pad RF-8' and conforms to 'Drg. No. WD-90076' of Indian Railways. The draft pad constitutes of a rubber compound sandwiched between two steel plates and perfectly bonded to them. Six such draft pads are used in a draft gear. Fig. 2 illustrates a partial section of draft gear (Miner RF-361) used in Indian Railways. The various components of the draft gear are draft pads (six) with top follower, shoes (three), and a wedge. All these components are assembled in housing with the three shoes arranged circumferentially around the wedge. The wedge and shoes operate between the top follower and the draft gear housing. The applied force reaches the draft pads through the wedge, shoes and top follower.

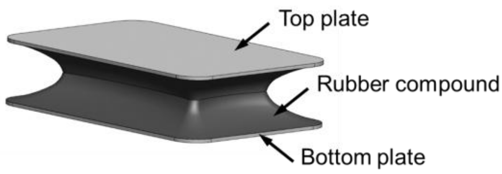

Fig. 1: Draft pad details

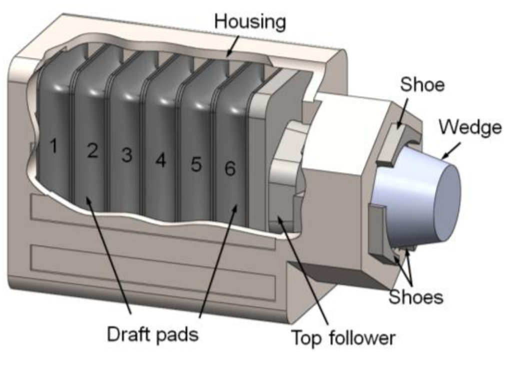

Fig. 2: Draft gear details

The material properties of steel are: Young's modulus: 200 × 10^9 N/m^2, Poisson's ratio: 0.30 and density: 7850 kg/m^3. For rubber compound the material properties are derived from experimental data and are: Young's modulus: 21.94 × 10^6 N/m^2, Poisson's ratio: 0.497 and density: 1220 kg/m^3. The boundary conditions are achieved by fixing all nodes at the bottom surface of the housing. Through site visits it has been observed that in most cases of failure, the crack is located on the minimum cross-section of draft pad. Fig. 3 illustrates the presence of crack in the lateral as well as longitudinal direction of the draft pad. The effect of crack on modal frequency is determined for two different locations which lie in the plane of the crack. The thickness of crack is not treated significantly as the natural frequency is a function of area. Fig. 4 illustrates the modelling of the crack in 3D CAD model along the width as well as length of the draft pad. A crack with semi-elliptical shape is considered. The dimension x defines the major axis of the ellipse and y defines the minor axis of the ellipse. The width of the semi-elliptical crack is defined by dimension x. The aspect ratio of the crack is x/y. For the cracks located in these two directions, the size (x) which defines the width is varied from 40 mm to 65 mm in step of 5 mm. The depth (y) of the crack is also varied to achieve aspect ratios of 0.4, 0.5, 0.6, 0.7 and 0.8.

Fig. 3: Crack location on draft pad - Lateral orientation (top) and Longitudinal orientation (bottom)

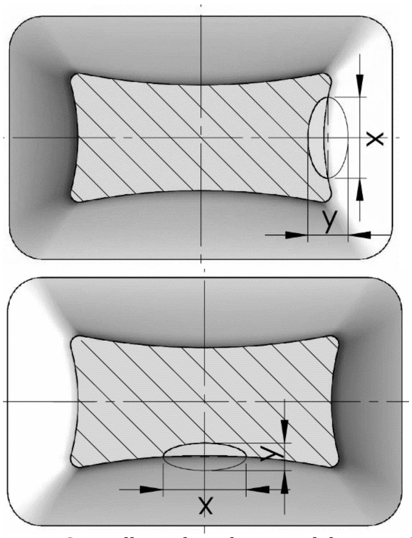

Fig. 4: Semi-elliptical crack - Lateral direction (top) and Longitudinal direction (bottom)

4. Results and discussions

The mode shapes are obtained using finite element method by considering the draft gear isolated from its actual environment. Initially the mode shapes have been obtained for healthy draft gear. Fig. 5 describes the first mode shape of a draft gear. It is seen that all the draft pads oscillate about the longitudinal (*x*) axis of draft gear. Each draft pad exhibit modal behaviour close to its first mode shape [8]. The draft gear housing is very stiff as compared to draft pad and thus has a very poor modal response in comparison to the latter. Hence it has been hidden in the illustration. Symmetry in modal behaviour is observed at the interface of third and fourth pad for all seven mode shapes of draft gear. Hence modal behaviour of the first three draft pads is presented in the illustrations. For the second mode of the draft gear shown in Fig. 6, a linear displacement of the interface between pad 3 and pad 4 in lateral (z) direction is observed causing the draft pads to exhibit modal behaviour close to its second mode shape [8]. The third mode illustrated in Fig. 7 shows linear displacement of the interface between pad 3 and pad 4 in vertical (y) direction causing the draft pads to exhibit modal behaviour close to its third mode shape [8].

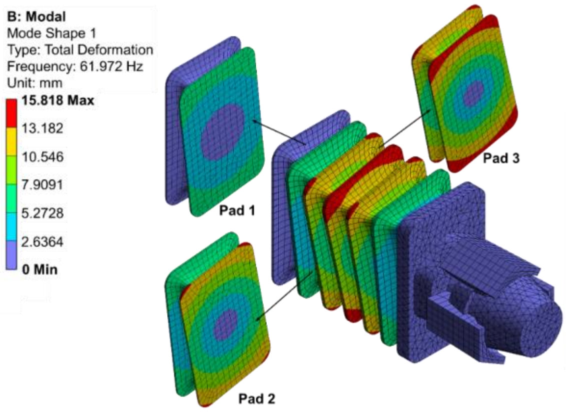

Fig. 5: First mode shape of draft gear

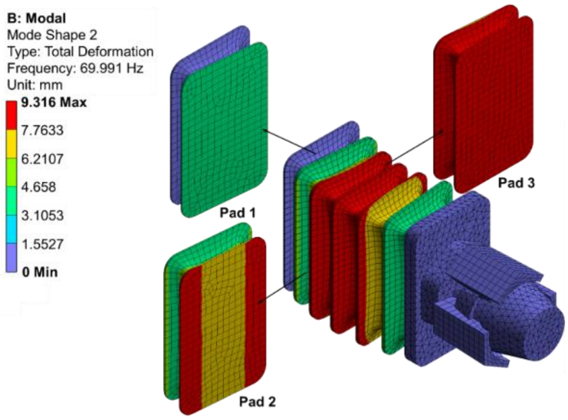

Fig. 6: Second mode shape of draft gear

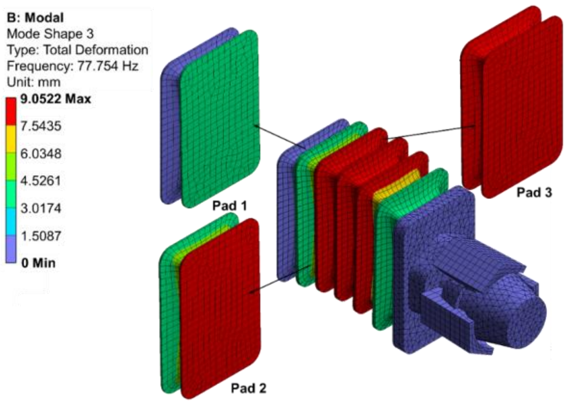

Fig. 7: Third mode shape of draft gear

For the fourth mode shape shown in Fig. 8, the interface between pad 3 and pad 4 remains fixed and the interfaces between pads 1 and 2, 2 and 3 and interfaces between pads 4 and 5, 5 and 6 oscillate about longitudinal (x) axis in opposite sense. As a result, modal behaviour corresponding to the first mode shape of draft pad is observed in some draft pads [8]. Fifth mode shape illustrated in Fig. 9 shows oscillation of the interface between pad 3 and pad 4 about vertical (y) axis. The result is that some draft pads exhibit fourth modal behaviour of individual draft pad. Remaining pads exhibit higher modal behaviour. Sixth mode shape illustrated in Fig. 10 shows oscillation of the interface between pad 3 and pad 4 about lateral (z) axis. As a result some draft pads exhibit third modal behaviour while some exhibit fifth modal behaviour of an individual draft pad. In the seventh mode shape shown in Fig.11, interfaces between pads 2 and 3, 4 and 5 remains fixed and interfaces between pads 1 and 2, 3 and 4, 5 and 6 oscillate about longitudinal (x) axis causing every single pad to execute motion in accordance to first mode shape. The oscillatory motion of interface between pads 1 and 2; 5 and 6 and pads 3 and 4 is opposed. Further, mode shapes of the draft gear have been obtained after incorporating semi-elliptical defect (Fig. 4) in draft pad. The defect is incorporated with different orientations of the crack on single draft pad and two adjacent draft pads. The defect is introduced on draft pad(s) and the same are located at various positions from either ends of the housing. The change in natural frequency for different orientations and locations has been summarized for each mode shape of draft gear with defective pad(s).

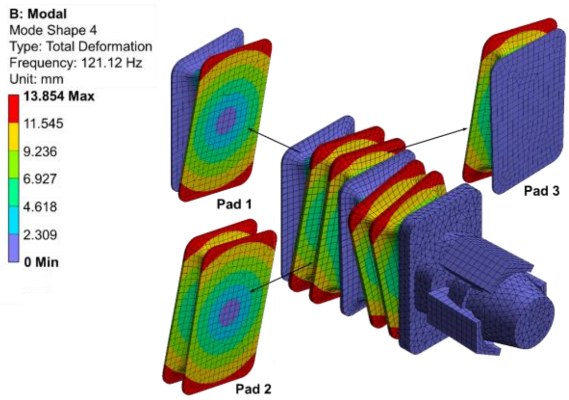

Fig. 8: Fourth mode shape of draft gear

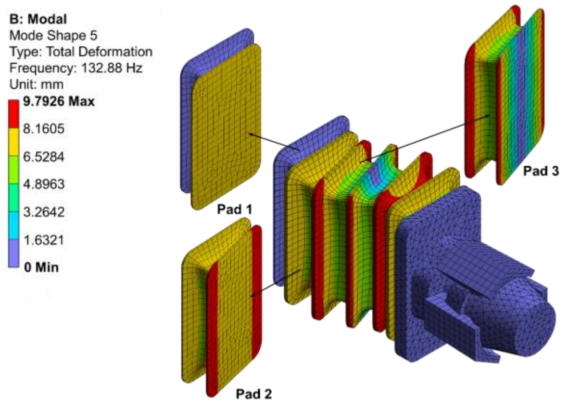

Fig. 9: Fifth mode shape of draft gear

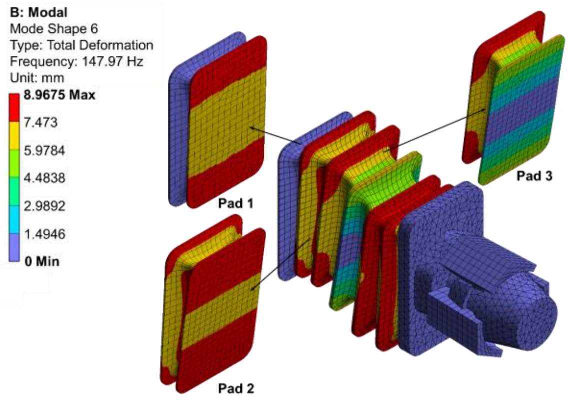

Fig. 10: Sixth mode shape of draft gear

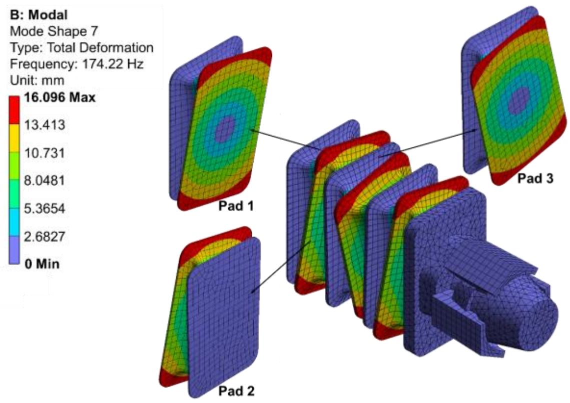

Fig. 11: Seventh mode shape of draft gear

For the first mode shape illustrated in Fig. 5 the orientation of the crack as well as position of defective pad(s) affect natural frequency of the draft gear as observed in Fig. 12. The lateral orientation of the crack has dominant effect on the frequency as compared to the longitudinal orientation due to the individual mode of the draft pad. All draft pads in this mode of draft gear have oscillating motion about longitudinal (x) axis of the draft gear and such mode is more sensitive to lateral orientation of crack. As far as location of crack on draft pads is concerned, it is seen that a single defective pad when located at positions 3 and 4 from either ends have least effect on the draft gear frequency. This insensitive natural frequency towards presence of crack can be attributed to the fact that the angular displacement of pads 3 and 4 in accordance to mode shape 1 is minimal. This same reason holds good for draft gear with two defective pads. The frequency shift is minimal in the presence of crack on pads 3 and 4 simultaneously. In general, frequency shift is seen to increase with increase in number of defective pads.

For the second mode shape shown in Fig. 6, it is seen that both, the orientation and location of the crack does not alter the natural frequency of the draft gear significantly except for location of crack in pads 1 and 6. However variation in frequency is observed only for longitudinal orientation of the crack as seen in Fig. 13. This is so because the motion of draft pads in draft gear corresponds to the second mode shape of draft pad which is insensitive to lateral orientation of the crack. At pad locations other than the extremes, displacement of draft pads is less and hence effect of crack on frequency shift is minimum for draft gear with single defective pad as well as two defective pads. Also, no considerable rise in frequency drop is observed for draft gear having multiple defective pads.

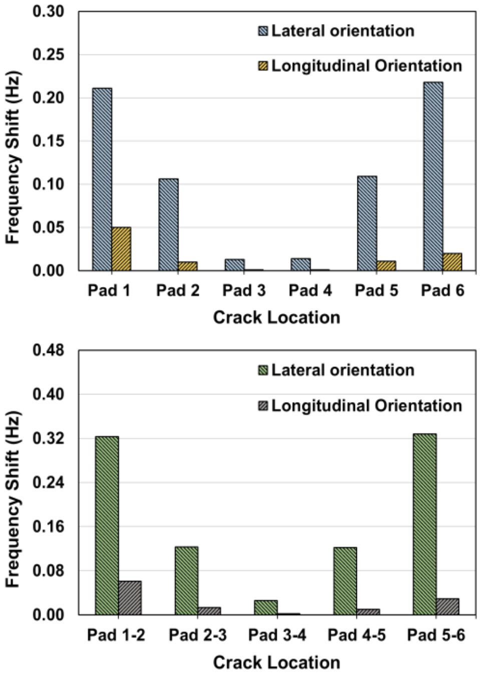

Fig. 12: Frequency drop in draft gear for first mode shape - single defective pad (top); two defective pads (bottom)

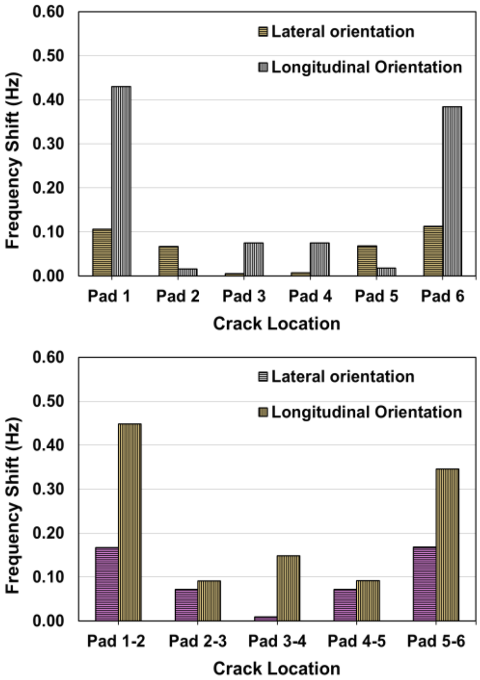

Fig. 13: Frequency drop in draft gear for second mode shape - single defective pad (top); two defective pads (bottom)

In case of third mode shape of draft gear, there is no significant change in frequency of draft gear in presence of single defective pad or two defective pads as seen from Fig. 14. However, the motion of pad is seen to be slightly more sensitive to lateral orientation as compared to longitudinal orientation of crack. As far as crack location is concerned their extreme positions are most sensitive for lateral as well as longitudinal orientations. For the fourth mode shape of draft gear shown in Fig. 8, draft pads 2 and 5 execute simple rotation about *x*-axis. All other draft pads exhibit oscillatory motion about longitudinal axis of draft gear which is same as the first modal behaviour of draft pad. From Fig. 15 it is observed that such modal behaviour is sensitive only to lateral orientation of the crack. As pads 2 and 5 execute simple rotational motion, presence of crack in lateral or longitudinal orientation hardly has any influence on the frequency of draft gear. Hence no frequency variation is observed in case of draft gear having crack on pads at these locations. Since the draft gear frequency is affected by presence of crack on pad 3 and pad 4, a similar influence of crack on natural frequency when present simultaneously on pads 3 and 4.

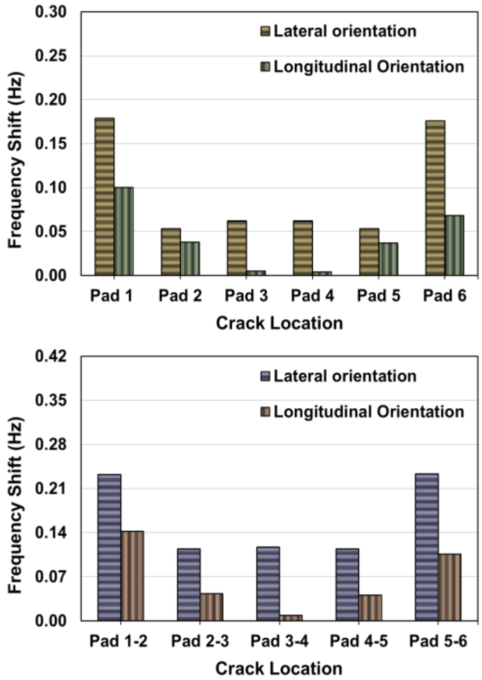

Fig. 14: Frequency drop in draft gear for third mode shape - single defective pad (top); two defective pads (bottom)

For the fifth mode shape of draft gear shown in Fig. 9, an oscillation of the interface between pads 3 and 4 about vertical axis is observed. The motion of pads is in accordance to fourth modal shape of draft pad. Fig. 16 shows that draft gear frequency is more sensitive to the presence of crack on the pad in longitudinal orientation as compared to lateral orientation. Defect present in pad positioned at location 1 cause’s frequency variation in both orientations. A similar behaviour pattern is observed for draft gear having two defective pads simultaneously. However, the frequency variation is more prominent. The sixth mode shape illustrated in Fig. 10 is defined by the oscillation of the interface between pads 3 and 4 about lateral axis of draft gear. The natural frequency of draft gear as a result of this motion is sensitive to lateral orientation of the crack as compared to its longitudinal orientation as seen in Fig. 17. This is because pad 2 and pad 5 exhibit modal behaviour in accordance to fifth mode shape of draft pad which is sensitive to lateral orientation of crack. Similarly, pad 3 and pad 4 exhibits third modal behaviour of draft pad which is equally sensitive to lateral and longitudinal orientation of crack on draft pad. For draft gear with two defective pads, the frequency is sensitive to lateral orientation of crack. For the seventh mode shape shown in Fig. 11, interfaces between pads 2 and 3, 4 and 5 remains fixed and interfaces between pads 1 and 2, 3 and 4, and 5 and 6 oscillate about longitudinal (x) axis. Although the oscillatory motion of interface between pads 1 and 2; 5 and 6 and pads 3 and 4 is opposed all pads exhibit modal behaviour in accordance to first mode shape of draft pad. It is thus obvious that the seventh modal frequency is most sensitive to lateral orientation of crack. This sensitiveness is more prominent in the presence of multiple defective pads.

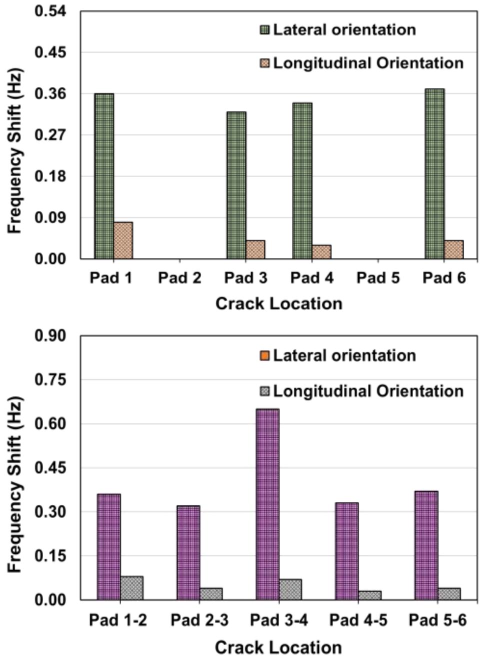

Fig. 15: Frequency drop in draft gear for fourth mode shape - single defective pad (top); two defective pads (bottom)

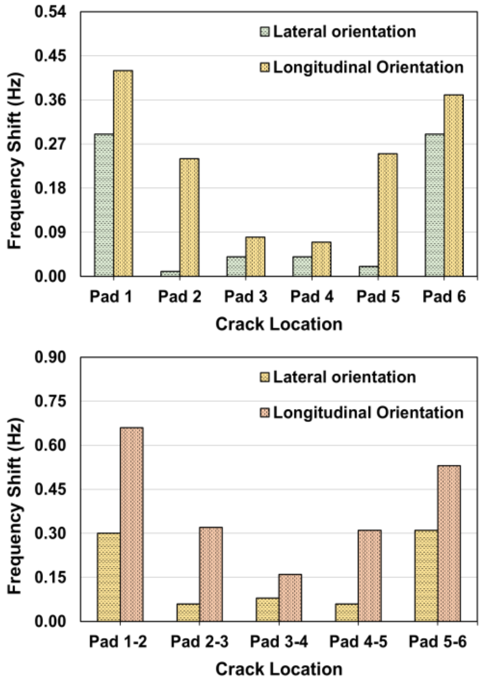

Fig. 16: Frequency drop in draft gear for fifth mode shape - single defective pad (top); two defective pads (bottom)

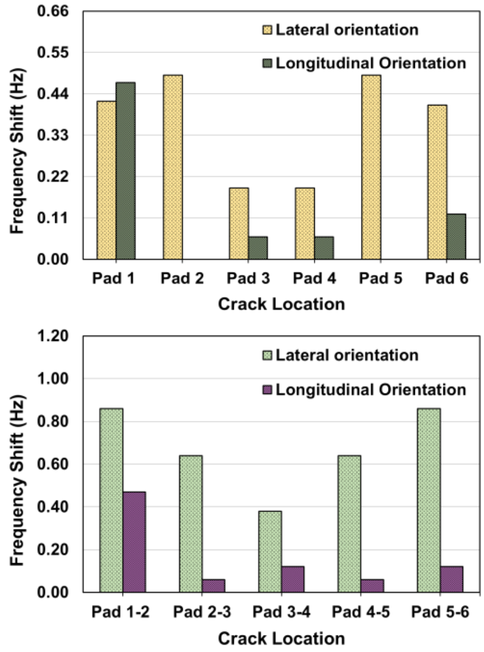

Fig. 17: Frequency drop in draft gear for sixth mode shape - single defective pad (top); two defective pads (bottom)

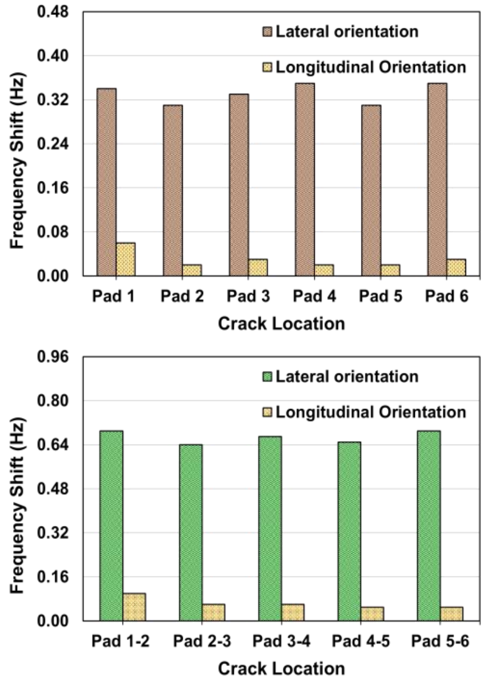

Fig. 18: Frequency drop in draft gear for seventh mode shape - single defective pad (top); two defective pads (bottom)

5. Conclusions

Modal analysis of a defective draft gear has been carried out. Defect of semi-elliptical shape with fixed crack width of 65 mm and aspect ratio of 0.8 has been considered in a single draft pad with different locations from the housing back plate. Same defect has also been considered in two draft pads and their locations varied with reference to the housing rear plate. Effect of crack orientation and defective pad location on the natural frequency of draft gear has been analysed. A critical examination shows that the modal frequency of the draft gear is affected by the crack because of its orientation as well as due to its location. The drop in modal frequency of draft gear due to presence of crack with different orientation of crack is totally depends on the modal behaviour of draft pad.

It is seen that the first modal frequency of draft gear is sensitive to lateral orientation of crack, whereas the frequency for second mode shape drops only when crack is present in first and sixth draft pad. No significant change in frequency of draft gear in the presence of single defective pad or two defective pads is observed for third mode shape of draft gear. However, the frequency of draft gear is seen to be slightly more sensitive to lateral orientation of crack as compared to longitudinal orientation of crack. The fourth mode shape of draft gear is sensitive only to lateral orientation of the crack. The fifth modal frequency of draft gear is more sensitive to the presence of crack on the pad in longitudinal orientation as compared to lateral orientation. The draft gear frequency for sixth mode shape is sensitive to lateral orientation of the crack as compared to its longitudinal orientation in case of single and multiple defects. The seventh modal frequency is sensitive to lateral orientation of the crack. As far as the effect of location of defective pad on natural frequency of draft gear is concerned, except for fourth and seventh mode shape, for all other modes the draft gear frequency drops when defective pad is located adjacent to the housing base plate and top follower. This study thus provides a tool to diagnose crack defect in draft gear based on its vibration characteristics.

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