International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-3, January 2020

Operational Modal Analysis of Damage Gear

M. Aarif Amirza, M. Azhan Anuar, A.A.Mat Isa, Zamri A.R.

Abstract*: As natural frequencies and mode shapes are often a key to understanding dynamic characteristics of structural elements, modal analysis provides a viable means to determine these properties. This paper investigates the dynamic characteristics of a healthy and unhealthy condition of a commercially used helical gear using the Frequency Domain Decomposition (FDD) identification algorithm in Operational Modal Analysis (OMA). For the unhealthy condition, a refined range of percentage of defects are introduced to the helical gear starting from one (1) tooth being defected (1/60 teeth) to six (6) teeth being defected (6/60 teeth). The specimen is tested under a free-free boundary condition for its simplicity and direct investigation purpose. Comparison of the results of these varying conditions of the structure will be shown to justify the validity of the method used. Acceptable modal data are obtained by considering and accentuating on the technical aspects in processing the experimental data which are critical aspects to be addressed. The natural frequencies and mode shapes are obtained through automatic and manual peak-picking process from Singular Value Decomposition (SVD) plot using Frequency Domain Decomposition (FDD) technique and the results are validated using the established Modal Assurance Criterion (MAC) indicator. The results indicate that OMA using FDD algorithm is a good method in identifying the dynamic characteristics and hence, is effective in detection of defects in this rotating element.

***Keywords* : Defected Helical Gear, Frequency Domain Decomposition (FDD), Modal Assurance Criterion (MAC), Operational Modal Analysis (OMA), Singular Value Decomposition (SVD).**

I. INTRODUCTION

Failure or defect in a rotating mechanical structure has become a major issue that affect the operating condition. This requires attention from the engineer(s) to solve the issue where a Condition-Based Monitoring (CBM) or Structural Health Monitoring (SHM) need to take place. In the area which involves continuous moving members such in the operation of machines, SHM and Vibration-Based Maintenance are becoming more demanding due to its usefulness and not interrupting the machines operation. Many different techniques have been introduced in SHM to monitor the condition of structural elements and to detect the present of any possible damage. Using so-called global technique, namely, vibration-based damage detection, SHM usually indicates its signs of structural health condition through modal properties such as the changes in natural frequencies, damping loss factor and mode shapes [1].

Helical gears are widely employed to transmit motion and machine power in the design of present-day machineries. It provides more stable performance and moreover the noise produce is lower [2]. Helical gears are commonly used as a power transmission element and widely applied in the industries such as wind turbines application, motor vehicles, marine power trains and helicopters transmission. Due to its high criticality in these applications, health monitoring of helical gears has attained central research focus in recent years. Studies shows that tooth surface wear is one of the most common failure modes in many transmission systems which usually occurs after a long service life. This surface wear has substantial undesirable effect in the dynamic and vibration behavior of the gear train which affecting the response[3], [4].

Breethe et. al [4] developed a more efficient method of analysis to monitor the condition of a helical gearbox from its dynamic response. A numerical model was developed to monitor the tooth surface wear under varying degrees by examining the dynamic forces variations and its effect on vibration responses. This model was simulated using time-varying mesh stiffness (TVMS) coupled with EHL frictional model and tooth wear characteristics, as a basis to achieve higher degree of accuracy in gear diagnostics.

There was a study implemented to look on the TVMS model of helical gears where the influences of two factors namely tooth spalling and the effect of local breakage were considered [2]. In this study, the faults were incorporated using combination of three methods such as slicing, potential energy and discrete integral prior to a parametric investigation.

A four-degree of freedom dynamic model was developed to detect crack fault in a gear for both gear profiles under interest that are symmetric and asymmetric [5]. This model was developed in order to recognize the error on the gear system especially on its dynamic transmission instigated by the cracks occur along the tooth thickness of the gear.Jiang et. al [6] studied the effects on the dynamic characteristics of the helical gears after two changes were applied; (1) change at the pitch plane (both sides) and (2) An existence of tooth spalling defect that produce the change of contact stiffness.

Revised Manuscript Received on January 30, 2020.
* Correspondence Author

Mohammad Aarif Amirza, INTEKMA Engineering and Services Sdn. Bhd, D17-03&03A, Menara Mitraland No. 13A, Jalan PJU5, Kota Damansara, Selangor Malaysia.,
Muhamad Azhan Anuar*, Faculty of Mechanical Engineering, Universiti Technologi MARA, UiTM Shah Alam, 40450 Selangor, Malaysia.
Ahmad Azlan Mat Isa, Faculty of Mechanical Engineering, Universiti Technologi MARA, UiTM Shah Alam, 40450 Selangor, Malaysia,
Zamri Abdul Rahman, Faculty of Mechanical Engineering, Universiti Technologi MARA, UiTM Shah Alam, 40450 Selangor, Malaysia,

The results, however, showed that there was no real good solution to indicate any significant change of the dynamic characteristics due to poor modelling and to calculate the internal excitation for a case with spalling defect.

This study presents the investigation of healthy and unhealthy helical gear using Operational Modal Analysis (OMA). This technique is carried out to provide a much needed tool for the determination of the dynamic characteristics of large and complex structures or mechanisms especially when input forces cannot be directly controlled or measured [7].

OPERATIONAL MODAL ANALYSIS TECHNIQUE

In Operational Modal Analysis (OMA), there are many algorithms typically used to decompose the modal parameters such as Stochastic Subspace Identification (SSI), Enhanced Frequency Domain Decomposition (EFDD) and Frequency Domain Decomposition (FDD). However in this study, only FDD will be used to extract the modal parameters from the specimen, and the MAC criterion will be used for validity of mode shape comparison.

A. Frequency Domain Decomposition (FDD)

Frequency Domain Decomposition (FDD) is a non-parametric method extended from the Basic Frequency Domain (BFD) technique [8]. It does not depend on any type of curve fitting from parametric modelling and was well explained by [7], [9]. It was shown to be very good technique in the study on the turbine wind where excellent results for natural frequencies and mode shapes were obtained.

B. Modal Assurance Criterion

The mode shapes between healthy and unhealthy condition of the structure is compared based on the value of Modal Assurance Criterion (MAC). Any differences in the obtained mode shapes especially the large differences are revealed in the MAC values and it offers a good statistical indicator to show the consistency of mode shapes under consideration. In addition, is essential to use a separate frequency assessment, in combination with the calculated MAC values in order to decide the correlation of modes between both conditions.

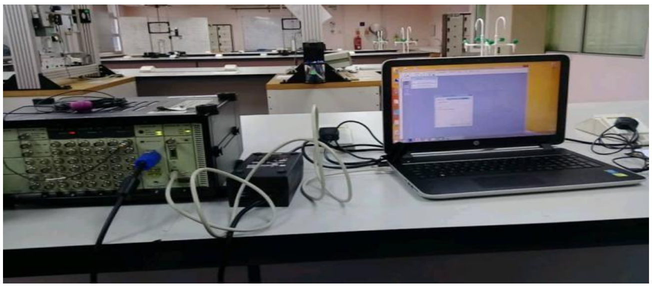
To ensure the consistency mode shapes comparisons, mode shape pairs derived from analytical models with the one obtained from testing are often used. Being simple and direct, any estimation of the system matrices are not required in MAC. The MAC values are indicated in the range of 0 to 1, with totally consistent mode shapes is presented as 1. Note, however the MAC values only show consistency and does not indicate validity or orthogonality. The mode are not consistent if the indicate value close to 0 [10].

Ideally, the MAC matrix indicates the relation of each mode obtained from two sets and how they are associated t each other. The MAC is a permutation matrix and the larges entries of it matrixes are not in the leading diagonal anymore if any two vectors are switched in one set. One of the disadvantage of MAC is inability to distinguish between local discrepancies and systematic errors and especially for cases of orthogonal or incomplete vectors, where it has problems to identify the difference [11], [12].

III. SPECIMEN AND METHODS

In this study, the Bruel&Kjaer PULSE^{TM} Multi-Analyzer System is used as the Data Acquisition Systems (DAQ) and the specimen used is a commercially available helical gear having 60 teeth. Post processing of the random acceleration signal data obtained from measurement is exported into the Ambient Response Testing and Modal Identification Software (ARTeMIS^{TM}) and required for Fourier transform of the correlation function in order to estimate Power Spectral Density (PSD) matrix as illustrated in Fig .1.

Fig. 1.The Bruel&Kjaer PULSETM Multi-Analyzer



System connected to a computer with The Bruel&Kjaer PULSETM Multi-Labshop software and ARTeMISTM software

Fig. 2 and Fig. 3 show both conditions of the specimen that had been used for this experiment which were healthy (no defect on the gear structure) and non-healthy (different amount of defects).

Fig. 2.The healthy condition of the commercially used helical gear

Fig. 3.The unhealthy condition of the commercially used helical gear

For this study, 20 accelerometers were used with only one data set to represent 20 DOFs.

The structure was excited randomly by tapping continuously with acceptable amount of energy in order to excite all frequencies of interest. Bruel&Kjaer PULSE^{TM} Multi-Labshop Software was used to set up the hardware, create the geometry, assign measurement points and perform the test. All the raw data which consists of geometrical values and series of measurements were then directly exported to the ARTeMIS^{TM} software for signal processing calculation and modal extraction. Frequency Domain Decomposition (FDD) was performed for both healthy and unhealthy gear conditions after all data were exported.

IV. RESULT AND DISCUSSION

The specimen, which is the helical gear is a part of rotating element in an automotive transmission gearbox which creates a thrust load on the teeth when they mesh in the gearbox.

The main concern of this study is to identify the effectiveness of OMA method in detecting the present of defect on the helical gear structure and whether or not it would produce acceptable range of flexural mode shapes and natural frequencies. From the results obtained, it indicates that this method implied a good and significant modal data for further application.

In order to do peak-picking, there were two parameters depicted, namely the natural frequency and mode shape. Fig.4 to Fig.8 show the Peak-Picking performed using Frequency Domain Decomposition (FDD) technique where Fig.4 illustrates the peak-picking for healthy gear while Fig.5 to Fig.8 are for the unhealthy gear with different percentage of defects.

From the results obtained using FDD technique for all gear conditions, there were only several real natural frequencies that imply relevant mode shapes. From the SVD plots obtained, it might seem to have several dominant peaks that appeared on the plot but some of it are actually in a complex mode which may be due to certain external disturbance such as noise and etc.

This requires a manual peak-picking process instead of automatic peak-picking.

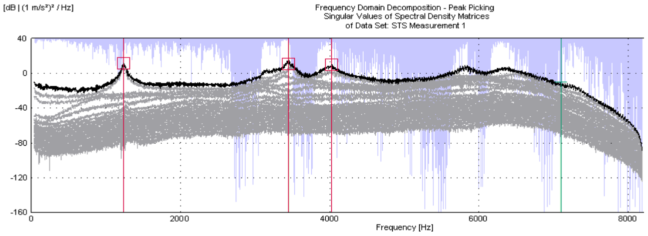


Fig. 4.FDD Peak Picking SVD Plot (Healthy Gear)

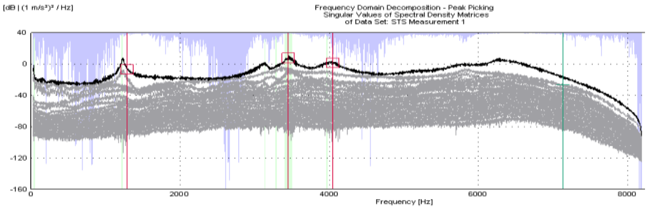


Fig. 5.FDD Peak Picking SVD Plot (1/60 Teeth Defect)

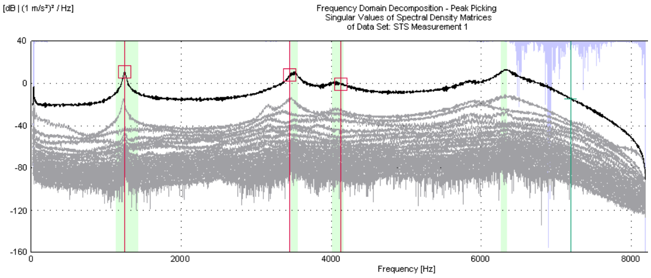


Fig. 6.FDD Peak Picking SVD Plot (3/60 Teeth Defect)

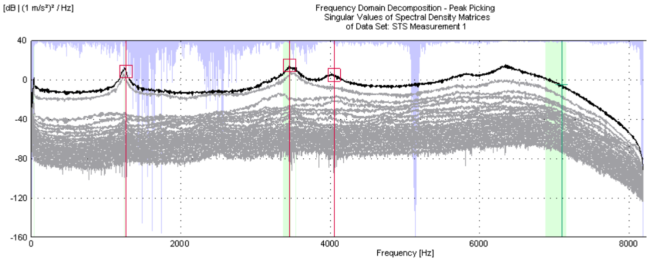


Fig. 7. FDD Peak Picking SVD Plot (5/60 Teeth Defect)

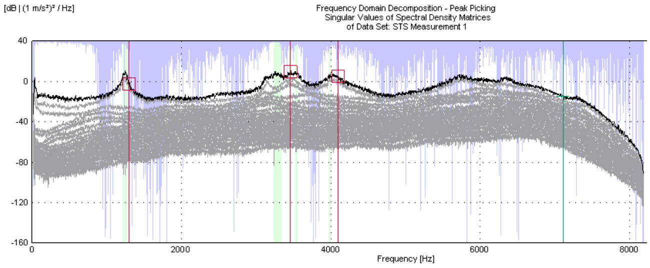


Fig. 8. FDD Peak Picking SVD Plot (6/60 Teeth Defect)

The natural frequencies and mode shapes for both conditions of the gear; healthy and unhealthy were obtained as shown in Table-I. For the unhealthy helical gear, some defects were introduced to the gear teeth accordingly where the percentage of defect(s) was based on the number of teeth of the helical gear being defected. For the first unhealthy gear, 1/60 tooth was grinded off to see whether OMA technique can detect the defect on the gear. Then, the percentage of defects were increased up to 5% (3/60 teeth defect), 8.3% (5/60 teeth defect) and 10% (6/60 teeth defect). As illustrated in Table-I, the natural frequencies obtained from the FDD are basically in the range of 1237Hz to 7197Hz. It can be seen that the first natural frequencies of the first mode shape of healthy and first unhealthy gear condition which are 1237 Hz and 1284 Hz while for the second, third and fourth unhealthy gear conditions are 1246 Hz, 1262 Hz and 1296 Hz, respectively. Comparing each unhealthy condition with the healthy one, it shows that the natural frequencies have an increasing value when chipping off a small portion of the helical gear which indicate that the mass effect is more dominant than stiffness effect.

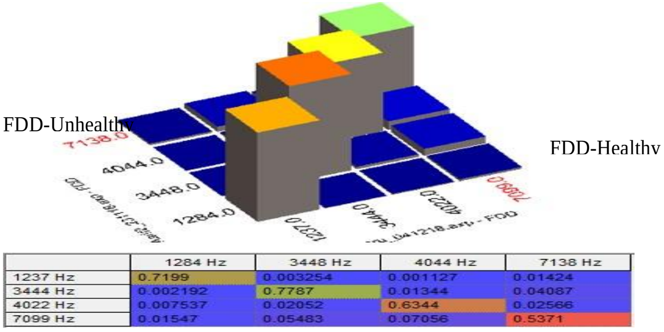
Table-I: Natural frequencies and mode shapes for both healthy and unhealthy gear condition from OMA technique.

Gear Condition	Mode Shape 1	Mode Shape 2	Mode Shape 3	Mode Shape 4
Healthy Gear	 $\omega_n = 1237$ Hz	 $\omega_n = 3444$ Hz	 $\omega_n = 4022$ Hz	 $\omega_n = 7099$ Hz
Unhealthy Gear 1, 1.7% defects (1/60 teeth defected)	 $\omega_n = 1284$ Hz	 $\omega_n = 3448$ Hz	 $\omega_n = 4044$ Hz	 $\omega_n = 7138$ Hz
Unhealthy Gear 2, 5% defects (3/60 teeth defected)	 $\omega_n = 1246$ Hz	 $\omega_n = 3447$ Hz	 $\omega_n = 4126$ Hz	 $\omega_n = 7197$ Hz
Unhealthy Gear 3, 8.3% defects (5/60 teeth defected)	 $\omega_n = 1262$ Hz	 $\omega_n = 3454$ Hz	 $\omega_n = 4052$ Hz	 $\omega_n = 7102$ Hz
Unhealthy Gear 4, 10% defects (6/60 teeth defected)	 $\omega_n = 1296$ Hz	 $\omega_n = 3461$ Hz	 $\omega_n = 4095$ Hz	 $\omega_n = 7113$ Hz

OMA method is sensitive enough in detecting defect(s) on this heavy structure of helical gear. For the second, third and fourth unhealthy gear conditions, the same pattern of increasing frequencies are obtained in this testing when compared with the healthy condition. Every frequency obtained representing different pattern of mode shapes and the trend of mode shapes obtained are almost similar. This indicates that good modal parameters were successfully obtained.

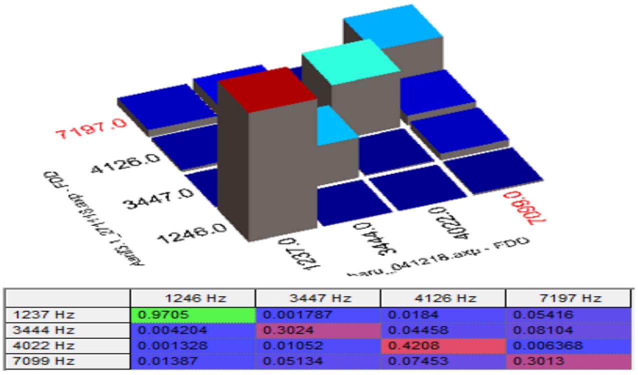
Since this study only focuses on one of the non-parametric algorithm in OMA which is the FDD, the Modal Assurance Criterion (MAC) was used as a statistical indicator for mode validation to indicate the correlation between mode shapes which provides additional confidence factor in the evaluation of a modal vector.

Modal Assurance Criterion (MAC) values plotted in Fig.9 to Fig.12 indicate good correlation across all 4 significant modes.



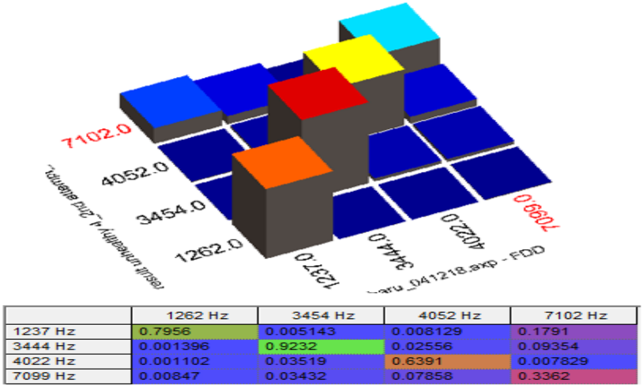
	1284 Hz	3448 Hz	4044 Hz	7138 Hz
1237 Hz	0.7199	0.003254	0.001127	0.01424
3444 Hz	0.002192	0.7787	0.01344	0.04087
4022 Hz	0.007537	0.02052	0.6344	0.02566
7099 Hz	0.01547	0.05483	0.07056	0.5371

Fig. 9.FDD-Healthy and Unhealthy Gear (with 1/60 Tooth Defect) MAC Comparison



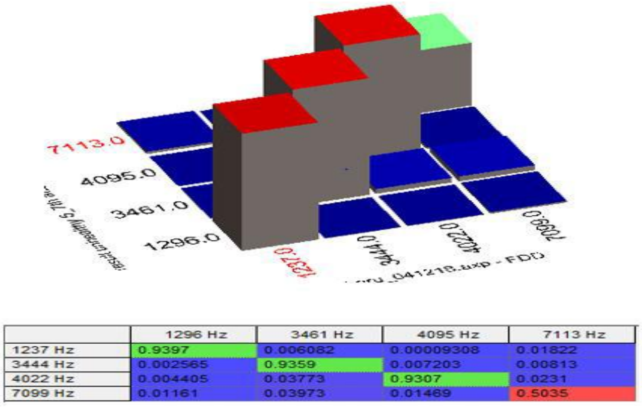
	1246 Hz	3447 Hz	4126 Hz	7197 Hz
1237 Hz	0.9705	0.001787	0.0184	0.05416
3444 Hz	0.004204	0.3024	0.04458	0.08104
4022 Hz	0.001328	0.01052	0.4208	0.006368
7099 Hz	0.01387	0.05134	0.07453	0.3013

Fig. 10. FDD-Healthy and Unhealthy Gear (with 3/60 Teeth Defect) MAC Comparison



	1262 Hz	3454 Hz	4052 Hz	7102 Hz
1237 Hz	0.7956	0.005143	0.008129	0.1791
3444 Hz	0.001396	0.9232	0.02556	0.09354
4022 Hz	0.001102	0.03519	0.6391	0.007829
7099 Hz	0.00847	0.03432	0.07858	0.3362

Fig. 11. FDD-Healthy and Unhealthy Gear (with 5/60 Teeth Defect) MAC Comparison



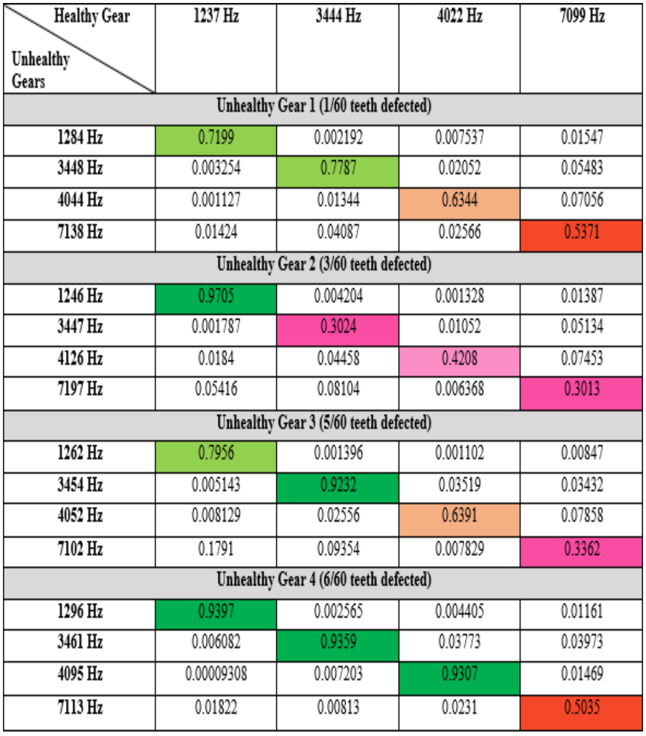
	1296 Hz	3461 Hz	4095 Hz	7113 Hz
1237 Hz	0.9397	0.006082	0.00009308	0.01822
3444 Hz	0.002565	0.9359	0.007203	0.00813
4022 Hz	0.004405	0.03773	0.9307	0.0231
7099 Hz	0.01161	0.03973	0.01469	0.5035

Fig. 12. FDD-Healthy and Unhealthy Gear (with 6/60 Teeth Defect) MAC Comparison

MAC values provide better understanding of the mode shape for each unhealthy gear condition when compared to healthy ones. It compares the degree of consistency between mode shapes.

Table-II shows that for each of the unhealthy gear conditions when compared with the healthy gear, the MAC values are acceptably high especially on the first mode which is in the range of 0.7 to 0.9 where they are very close to 1.All MAC values obtained for other mode shapes are still within an acceptable range between 0.4 to 0.7 except for the case of 'Unhealthy Gear 2' (at 3447 Hz and 7197 Hz) and 'Unhealthy Gear 3' (at 7102 Hz). These are among the least MAC values obtained in this study which might be caused by the complexity of the modes.Therefore, although the mode shapes for each condition of the gear look quite similar, it needs to be validated with the MAC values as it compares all vectors for each coordinate, thus is more accurate in providing information of the mode shapes.

Table-II: Overall Comparison of Modal Assurance Criterion (MAC)



Healthy Gear / Unhealthy Gears	1237 Hz	3444 Hz	4022 Hz	7099 Hz
Unhealthy Gear 1 (1/60 teeth defected)				
1284 Hz	0.7199	0.002192	0.007537	0.01547
3448 Hz	0.003254	0.7787	0.02052	0.05483
4044 Hz	0.001127	0.01344	0.6344	0.07056
7138 Hz	0.01424	0.04087	0.02566	0.5371
Unhealthy Gear 2 (3/60 teeth defected)				
1246 Hz	0.9705	0.004204	0.001328	0.01387
3447 Hz	0.001787	0.3024	0.01052	0.05134
4126 Hz	0.0184	0.04458	0.4208	0.07453
7197 Hz	0.05416	0.08104	0.006368	0.3013
Unhealthy Gear 3 (5/60 teeth defected)				
1262 Hz	0.7956	0.001396	0.001102	0.00847
3454 Hz	0.005143	0.9232	0.03519	0.03432
4052 Hz	0.008129	0.02556	0.6391	0.07858
7102 Hz	0.1791	0.09354	0.007829	0.3362
Unhealthy Gear 4 (6/60 teeth defected)				
1296 Hz	0.9397	0.002565	0.004405	0.01161
3461 Hz	0.006082	0.9359	0.03773	0.03973
4095 Hz	0.00009308	0.007203	0.9307	0.01469
7113 Hz	0.01822	0.00813	0.0231	0.5035

V. CONCLUSION

In this study, the experimental approach using Operational Modal Analysis (OMA) was successfully carried out on a commercially used helical gear on both condition of the structure; healthy and unhealthy under free-free condition. The effectiveness of OMA is validated from the results obtained where OMA is sensitive to a slight change in the operating conditions. Four (4) distinct different mode shapes and natural frequencies were identified from FDD method. These dynamic characteristics were obtained for both condition of the specimen, healthy and unhealthy.

The modal parameters of this structure in the form of natural frequencies and mode shapes were successfully obtained. The non-parametric technique (FDD) was successfully employed in determining the modal parameters. It is clearly seen that in this case the mass effect is more dominant than the stiffness effect, which apparent through the fact that the mode shapes are much better and comparable as the mass decreases. On the other hand, the value of natural frequencies started to increase due to decrease in mass as the gear being defected (from 1/60 teeth defect to 6/60 teeth defect). Comparison of natural frequencies and mode shapes between each unhealthy and healthy condition gave satisfactory results and mostly in good correlation.

REFERENCES

1. R. M. Fadhil Shazmir, N. Ayuni Safari, M. Azhan Anuar, A.A. Mat Isa, Zamri, "Operational modal analysis on a 3D scaled model of a 3-Storey aluminium structure," Int. J. Eng. Technol., vol. 7, no. 4, pp. 78–82, 2018.
2. L. Han and H. Qi, "Influences of tooth spalling or local breakage on time-varying mesh stiffness of helical gears," Eng. Fail. Anal., vol. 79, pp. 75–88, 2017.
3. J. Wojnarowski and V. Onishchenko, "Tooth wear effects on spur gear dynamics," Mech. Mach. Theory, vol. 38, no. 2, pp. 161–178, 2003.
4. K. F. Brethee, D. Zhen, F. Gu, and A. D. Ball, "Helical gear wear monitoring: Modelling and experimental validation," Mech. Mach. Theory, vol. 117, pp. 210–229, 2017.
5. O. Doğan and F. Karpat, "Crack detection for spur gears with asymmetric teeth based on the dynamic transmission error," Mech. Mach. Theory, vol. 133, pp. 417–431, 2019.
6. H. Jiang, Y. Shao, and C. K. Mechefske, "Dynamic characteristics of helical gears under sliding friction with spalling defect," Eng. Fail. Anal., vol. 39, pp. 92–107, 2014.
7. M. Azhan Anuar, A. A. M. Isa, A. R. Zamri, and R. Brincker, "Critical experimental issues of cracked aluminum beam in operational modal analysis," J. Mech. Eng., vol. SI 5, no. 6, pp. 211-225, 2018.
8. M. Batel, G. S., M. N., and H. Herlufsen, "Ambient Response Modal Analysis on a Plate Structure," in Proceedings of 21st International Modal Analysis Conference (IMAC-XXI), 2003.
9. M.A. Anuar, L. Roslan, and A. Isa A., Mat, "Dynamic Parameter Identification Using Ambient Response Analysis and Ibrahim Time Domain Approach: A Case Study on a Steel Plate Structure," J. Appl. Mech. Mater., vol. 110–116, pp. 2395–2399, 2012.
10. M. Pastor, M. Binda, and T. Harčarik, "Modal Assurance Criterion," Procedia Eng., vol. 48, pp. 543–548, Jan. 2012.
11. D. Fotsch and D. J. Ewins, "Application of MAC in the frequency domain," in Proceedings of SPIE - The International Society for Optical Engineering, 2000, vol. 4062.
12. R. J. Allemang, "The Modal Assurance Criterion (MAC): Twenty Years of Use and Abuse," Proc. SPIE - Int. Soc. Opt. Eng., vol. 4753, pp. 397–405, 2002.

AUTHORS PROFILE

Mohammad Aarif Amirza is an engineer at INTEKMA Engineering and Services Sdn. Bhd. He attained his Degree in Mechanical Engineering from Universiti Teknologi MARA (UiTM), Shah Alam, Malaysia. His research interests include vibration, rotating machinery troubleshooting techniques and pipework analysis

Muhamad Azhan Anuar received his B.Eng. (Hons) Mechanical Engineering from University of Manchester Institute of Science and Technology (UMIST) United Kingdom and completed his Master's Degree in Mechanical Engineering from National University of Singapore (NUS), Singapore. He works as a senior lecturer at Faculty of Mechanical Engineering, Universiti Teknologi MARA (UiTM) Shah Alam, Malaysia. His research interests include, but not limited to the following area; vibration, modal analysis especially on Operational Modal Analysis (OMA) application, vibration control, instrumentation and signal processing, structural and rotor dynamics, fault analysis, artificial intelligent and IoT intelligent system.

He collaborates with local company in Malaysia and he is actively involves in industrial consultation projects related to vibration issues and activities both in experimental and analytical works. Vibration issues with rotating machinery and process pipework systems at the power plant and also both onshore and offshore, petrochemical and oil and gas plants in Malaysia are among the cases he studied using Operational Modal Analysis (OMA), Experimental Modal Analysis (EMA), Operational Deflection Shape (ODS), vibration data acquisition and analysis, Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA).

Ahmad Azlan Mat Isa is a Professor at Faculty of Mechanical Engineering, Universiti Teknologi Mara Shah Alam. His research interests include but not limited to the following area; dynamic, vibration, control and condition monitoring.

Zamri Abdul Rahman is an Associate Professor at Faculty of Mechanical Engineering, Universiti Teknologi Mara Shah Alam. His research interests include but not limited to the following area; dynamic, vibration, control and condition monitoring.