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Sanjay Singh
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Recent Advances in Aerospace Engineering

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Preface

The 2nd International Conference on Modern Research in Aerospace Engineering (MRAE 2023), hosted on September 22nd, 2023, under the auspices of the Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, Noida, India. We are delighted to announce the forthcoming publication of our conference proceedings. This compilation, titled "*Recent Advances in Aerospace Engineering*," is set to be published by Springer Nature. It stands as a testament to the collective effort and dedication of our esteemed contributors, whose work has significantly enriched the landscape of aerospace engineering with innovative research and groundbreaking discoveries.

The MRAE 2023 conference provided a vibrant platform for scholars, researchers, and industry professionals from across the globe to convene and exchange ideas at the forefront of aerospace engineering. Covering a diverse array of disciplines, our conference explored the latest advancements shaping the future of aerospace technology and innovation.

From the foundational domains of aerospace propulsion and combustion systems to the cutting-edge frontiers of electric mobility and autonomous airborne systems, our conference sessions delved into a multitude of topics, including space research, aerodynamics, computational fluid dynamics, avionics, flight mechanics, aircraft control system and stability, structural analysis, composite materials, aircraft maintenance, airworthiness, and environmental issues, artificial intelligence, unmanned aerial vehicles, and air safety. Each presentation and discussion contributed to the rich tapestry of knowledge and insight that forms the basis of this publication.

The genesis of this book stems from our collective aspiration to encapsulate the wealth of knowledge and innovation shared during the MRAE 2023 conference. It serves as a testament to our commitment to disseminating groundbreaking research and fostering collaboration within the aerospace community. By consolidating diverse perspectives and expertise, this volume aims to serve as a definitive reference for scholars, practitioners, and enthusiasts alike, offering invaluable insights into the latest developments and trends shaping the aerospace industry.

We are confident that the contents "*Recent Advances in Aerospace Engineering*" will serve as a source of inspiration for upcoming generations of aerospace professionals,igniting their passion for innovation and excellence in the field. Furthermore, we believe that the knowledge and insights encapsulated within this volume will serve as a springboard for continued innovation and propel us towards a brighter future in aerospace exploration and technology.

We extend my heartfelt gratitude to all the authors, presenters, reviewers, and organizers whose tireless efforts have made this publication possible. We extend my sincere appreciation to the editorial board, for their diligent efforts in shaping this book into its current form.

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Guwahati, India — Dr. Sachin Singh Gautam
Adama, Ethiopia — Dr. Perumalla Janaki Ramulu

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Dr. Andrew Ooi, The University of Melbourne, Australia
Dr. Huang Weimin, NTU Singapore
Prof. Rajamohan Ganesan, Concordia University, Canada
Dr. Perumalla Janaki Ramulu, Adama Science and Technology University, Ethiopia
Dr. Parvathy Rajendran, University Sains Malaysia, Malaysia
Dr. Dinesh Bhatia, Glasgow University, Scotland
Dr. Bhargav Akkinepally, Yeungnam University, South Korea
Dr. A. K. Ghosh, Conceptual Design, Tata Aerospace and Defense, Bengaluru, India
Dr. Om Prakash, UPES Dehradun
Dr. Sachin Singh Gautam, IIT Guwahati

It would not have been possible to organize a conference without the unwavering support and expertise of these outstanding researchers and leaders.

The Conference Chair Dr. Sanjay Singh takes this opportunity to thank Patron-in-Chief Dr. Ashok K. Chauhan, Hon'ble Founder President, RBEF, and Chairman, AKC Group of companies, Patron Dr. Atul Chauhan, Chancellor, Amity University Uttar Pradesh, India and President, RBEF. Co-patron: Prof. (Dr.) Balvinder Shukla, Vice Chancellor, Amity University Uttar Pradesh, Organizing Chair: Dr. Rajesh Kumar Saluja, Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, India, Joint Organizing Chair: Dr. Neeraj Kumar Gahlot and Dr. H. Jeevan Rao, Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, India, and Financial Chair: Dr. Basant Kumar Agrawal and Dr. Narender Singh, Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, India, for their support and guidance. We also extend our gratitude to the expert Technical Chair: Dr. A. K. Ghosh, Head, Conceptual Design, Tata Aerospace and Defense, Bengaluru, India, and Dr. V. R. Sanal Kumar, Amity Institute of Aerospace

Engineering, Amity University Uttar Pradesh, India, Chairing Technical Committee. Further, we also thank the members of review committee for their valuable contributions that improved the quality of papers and made MRAE 2023 a resounding success. We would like to express deep gratitude to our publication partner Springer. No conference would be successful without excellent papers and inspiring presentations. We thank all authors, presenters, and delegates for their contribution in making MRAE 2023 a grand success.

Contents

About the Editors

Dr. Sanjay Singh completed his Ph.D. in Aerospace Engineering from the Indian Institute of Technology Kanpur in 2008. He is currently a professor and director of Amity Institute of Aerospace Engineering, Amity University Uttar Pradesh, India. His research area includes flight vehicle system identification and parameter estimation, neural networks, UAV/MAV, flight and wind tunnel testing, flight dynamics, and control. He has authored several articles published in reputed journals and conferences. He is the member of review committee of many national and international journals of Aerospace field. He has supervised more than 50 UG and PG projects and dissertations. Currently, he is supervising four Ph.D. students. Dr. Sanjay Singh is currently involved in the design and development of autonomous high endurance fixed-wing UAV.

Dr. Perumalla Janaki Ramulu is the associate professor in the Department of Mechanical Engineering and acting as a director of center for Advanced Manufacturing Engineering at Adama Science and Technology University, Adama. His research interest primarily includes advanced metal joining techniques, sheet metal forming, tailor welded blanks, modeling simulation of metal forming process, material characterization, welding technologies, and different metal forming processes analysis. He specialized in experimental and modeling simulation of sheet metal with different formability tests. He has published more than 180 papers in international journal, book chapters, and conferences. He has guided 36 UG and 30 PG projects, two Ph.D., and guiding 8 Ph.D. Teaching methods have been enhanced by providing and recording the video lectures in the recent years.

Dr. Sachin Singh Gautam is currently an associate professor in the Department of Mechanical Engineering, Indian Institute of Technology Guwahati. His research interest is in computational mechanics specifically isogeometric analysis, contact problems, and GPU computing. Recently, he has started to explore machine learning applications in finite elements especially contact problems. He has published one book, 35 journal papers, five are in various stages of review, 20 books chapters, and made more than 70 conference presentations. Currently he is co-authoring a textbook on finite elements with Prof. P. M. Dixit (Ex-Professor, IIT Kanpur). He has supervised five Ph.D.s, 22 master students, and many bachelor students. Currently he is supervising five Ph.D. students and three master students. Dr. Gautam is currently involved in development of contact and isogeometric modules for FEAST® software being developed by VSSC, ISRO.

Analytical Model of Spur Gear Tooth Crack for Evaluating the Effect of Crack Propagation Angle on Vibration Response

Ami Barot and Pravin Kulkarni

Abstract Vibration-based health monitoring is considered as an important tool since any anomaly present in the system is manifested through its own vibration signature. This vibration signature is unique in nature. This uniqueness is very well established and being utilized in industry effectively for obtaining vibration response of industrial gear boxes and this forms the basis of diagnosis of the extent to which the gears are working at the intended level of accuracy. In this study, the mathematical model is developed and based on eight degrees of freedom governing differential equations are formed consisting time varying meshing force. Further, this time varying mesh force is diffused in terms of time varying mesh stiffness. The eight degrees of freedom are four rotational and four translational. During mesh in spur gear pair, the load sharing is variable with respect to time along the line of contact and it also depends upon the number of teeth pair in contact. Different faults in gear can be enlisted as crack, spalling, pitting, etc., each contributing adversely on the system characteristics, mesh stiffness being one of those. A cracked gear tooth is attributed by many features such as crack depth, crack length, initiation zone of crack and crack propagation angle. Amidst these, the study associated with the influence of crack propagation angle on gear tooth vibrations has been undertaken and the results are presented in this paper. Time varying mesh stiffness equations are formulated based on potential energy theory and it is solved by using a MATLAB code. TVMS plot is generated to investigate the influence of propagation angle on TVMS.

Keywords Cracked tooth · Crack propagation angle (CPA) · Degrees of freedom · Differential equations · Dynamic model · MATLAB · Time varying mesh stiffness (TVMS) · Vibration

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1 Introduction

Rotating machineries are widely used in various industrial applications. Gears, shaft and bearings are the important components of rotating machinery. Failure of any rotating component causes the failure of machinery as a whole [1]. This can be avoided by replacing the components before its failure. For reliable working of mechanical systems, fault diagnosis of rotating element is the most important and crucial task [2, 3]. Vibration-based condition monitoring is a reliable method for fault identification in rotating machinery [4]. Each and every component have its unique vibration signal which is known as vibration signature. With the development of faults in rotating components, there is a change in this vibration signature and it is very conveniently used for identification of faults. Experimental-based gearbox vibration monitoring is very important in industry for maintenance. Gear faults can also be identified by developing a dynamic model of gear vibration [5, 6]. Cracks, pitting and spalling are different faults present in the spur gear pair and the pair is subjected to dynamic loading condition. Fault identification and fault severity can be detected or diagnosed by vibration-based condition monitoring. Gear tooth crack at the tooth root or fillet occurs due to fatigue load and high impact loading on gear tooth. Breakage occurs on the tooth when unexpected heavy loads are applied on the tooth. When two gears are in mesh, mesh compliance and related time varying mesh stiffness (TVMS) is an important parameter. Substantive information regarding the working state of the gears can be effectively assessed by comparing graphical impressions of earlier obtained TVMS of healthy gears. Mesh deflection of gears in mesh with rack was calculated and presented based on theoretical study [7]. While modelling mesh stiffness of gears based on analytical approach, the nature of load is assumed as concentrated load and/or uniformly distributed load based on Hertzian elastic contact theory [8–10]. The study related to the interaction of mesh stiffness and contact ratio for gear pair was presented [11]. There are different aspects of mesh stiffness in a gear pair. The effect of torsional mesh stiffness on overall TVMS was considered by Jia et al. [12]. A comprehensive study on dynamic analysis of effect of progressive crack and variation in centre distance on vibration of spur of gears is presented by Barot and Kulkarni [13]. In dynamic conditions, there are multiple ways in which the fatigue load may cause initiation of crack and further maturity of the developed crack. There is a definite sense of uncertainty involved in the overall impact which can be described as crack initiation point (at the tooth root or tip), extent of crack depth, crack length throughout the tooth width or partial (these results are presented in the earlier study [13] undertaken by the authors) and crack propagation angle (towards the tooth rim or along the tooth thickness).

In this study, the effect of crack propagation angle on the vibration response of spur gears is undertaken. The crack initiation is assumed at the tooth root and successively encompassing towards the rim. Taking into account, these considerations have ensured inclusion of all possible uncontrollable variations of crack propagation in the study.

Subsequent paragraphs, however, are indented.

2 Mathematical Model of Vibration of Spur Gear Pair in Mesh

For investigating the vibration response of a geared system, mathematical modelling is an important tool which takes into consideration several gear parameters along with working of gears under the influence of the operating conditions. The accuracy of the model is dictated by considering various aspects such as degrees of freedom (single to multi DOF), prediction of the form of the vibration pulse due to the presence of defects, incorporation of nonlinearity of elements, time varying mesh stiffness altogether or few in the model.

The purpose of designing and developing a mathematical model for vibrations of spur gear pair is to obtain, understand and analyse the response of the mechanical system to forces caused by moving parts in the machines [the forces acting along the line of action and it gives response in terms of vibration that can be displacement or velocity or acceleration]. The fatigue loading in spur gear causes development of cracks with passage of time. This will cause the nonlinear response of the machine to the forcing function. The forcing function contains frequency 1X only. However, in the nonlinear mechanical structure of the machine, the resulting vibration response will occur at 1X and multiples of this. The extent and magnitude of the harmonic content of the vibration gauges the nonlinearity of the machines. Interestingly, the internal interaction of the response occurring at 1X and its higher order harmonics (2X, 3X and so on) results in the generation of distinct sum and difference frequencies which are altogether new frequencies in the form of sidebands found in the spectrum of the defective gear pair. Remarkably, these frequencies in the response were not present in the forcing function. In case of gears, the rpm will modulate the gear mesh frequency resulting in sidebands. Modulation is always a nonlinear process.

In most of the gear pair systems, the coupling between the torsional vibration modes is controlled by mesh stiffness; therefore a 2-degree-of-freedom semi-definite mathematical model representing only the torsional vibration may yield a quite accurate result in most practical cases [14]. Zhang et al. [15] established the mathematical model of the nonlinear translational-torsional motion of spur gears using the Lagrange equation and analysed the meshing stiffness and vibration characteristics of gears and their transmission system based on gearbox. Jie et al. [16] developed a 6 degrees of freedom gear system dynamic model based on lumped parameter method to analyse the fault on vibration response.

In the present study, a nonlinear lateral-torsional model of spur gear pair with flexible support of gear pair is proposed. The model under investigation consists of two gears on two shafts, which are connected to a prime mover and an actuator. The model includes four inertias namely prime mover, pinion, gear and actuator. The torsional compliances of shafts and the transverse compliances of bearings combined with those of shafts are included in the model. Both bearing and shaft damping are also considered in the dynamic model. Lumped parameter method is used to analyse the vibration response including the effect of defects like cracks, pitting, spalling or broken tooth. Assumptions in the mathematical model are: Mass and inertia of shaft

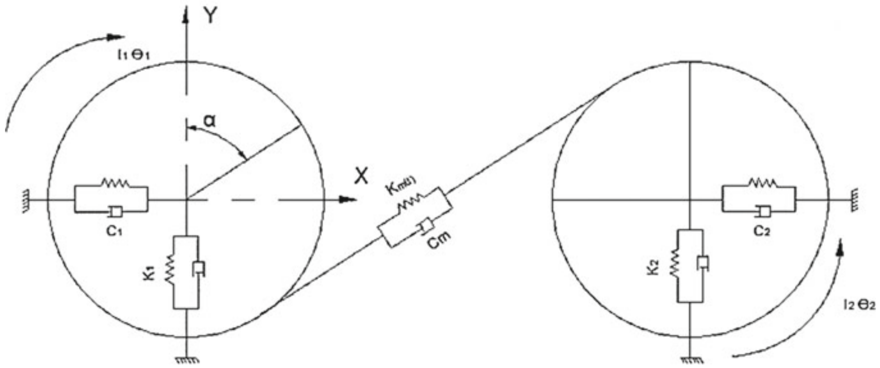

Fig. 1 8-DOF vibration model of a pair of gears meshing

are connected on the gear without considering friction between the gears and resonance of the gear. For the basic deflection of the tooth, bending, shear and compressive effects of the force components are considered and crack is throughout the length of the tooth, having uniform thickness and propagation starts at the root.

The model constitutes 8 degrees of freedom (Eqs. 1–8) which are four rotational and four translational. Rotational DOF is of the prime mover, pinion, gear and actuator. Translational are components along *x* and *y* axis of the resultant along the line of action for pinion and gear. Other important considerations in the model are inertia of prime mover and load, time varying mesh stiffness, mesh damping, torsional compliances of pinion and gear shafts, material damping in shafts (viscous), bearing compliances and damping (viscous), transverse compliances of shafts, drive torque and actuator torque (Fig. 1).

The governing equations of motion for the vibration model depicted can be written as follows:

$$I_p\ddot{\theta}_P + C_{s1}\left(\dot{\theta}_P - \dot{\theta}_1\right) + K_{s1}(\theta_P - \theta_1) = T_p \tag{1}$$

$$I_1\ddot{\theta}_1 + C_{s1}\left(\dot{\theta}_1 - \dot{\theta}_P\right) + K_{s1}(\theta_1 - \theta_P) = -F_m R_1 \tag{2}$$

$$I_2\ddot{\theta}_2 + C_{s2}\left(\dot{\theta}_2 - \dot{\theta}_A\right) + K_{s1}(\theta_2 - \theta_A) = F_m R_2 \tag{3}$$

$$I_A\ddot{\theta}_A + C_{s1}\left(\dot{\theta}_A - \dot{\theta}_2\right) + K_{s1}(\theta_A - \theta_2) = -T_A \tag{4}$$

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 = -F_m\sin\alpha \tag{5}$$

$$m_1\ddot{y}_1 + c_1\dot{y}_1 + k_1y_1 = -m_1g + F_m\cos\alpha \tag{6}$$

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 = F_m \sin\alpha \quad (7)$$

$$m_2\ddot{y}_2 + c_2\dot{y}_2 + k_2y_2 = -m_2g + F_m \cos\alpha \quad (8)$$

where

T_P = Input torque of prime mover.
T_A = Output torque of actuator.
α = Pressure angle.
m_1 and m_2 = Mass of pinion and gear, respectively.
k_1 and k_2 = Bearing stiffness of pinion and gear, respectively.
c_1 and c_2 = Damping coefficient of pinion and gear, respectively.
r_1 and r_2 = Base radius of pinion and gear, respectively.
x_1 and x_2 = Displacement of pinion and gear along x axis, respectively.
y_1 and y_2 = Displacement of pinion and gear along y axis, respectively.
I_p, I_1, I_2 and I_A = Polar MoI prime mover, pinion, gear and actuator, respectively.
K_{s1} and K_{s2} = Torsional stiffness of pinion and gear shafts, respectively.
C_{s1} and C_{s2} = Viscous damping coefficients of pinion and gear shafts respectively.
θ_P, θ_1, θ_2 and θ_A = Angular displacement of prime mover, pinion, gear and actuator, respectively.

In the above equations, F_m is the time varying meshing force along the line of action and its components are considered along the X and Y direction. Time varying mesh stiffness is considered as a main influencing parameter. F_m can be expressed as,

$$F_m(t) = C_m\dot{\delta} + K_m(t)f(\delta) \quad (9)$$

where

C_m = Meshing damping of gears in NSm^{-1}
$K_m(t)$ = Time varying meshing stiffness in Nm^{-1}
δ = Relative displacement of gears along the meshing line in m.

Relative displacement of gears can be expressed as,

$$\delta = x_1 \sin\alpha - x_2 \sin\alpha + y_1 \cos\alpha - y_2 \cos\alpha + r_1\theta_1 - r_2\theta_2 \quad (10)$$

Differentiating above w. r. t., velocity is obtained as,

$$\dot{\delta} = \dot{x}_1 \sin\alpha - \dot{x}_2 \sin\alpha + \dot{y}_1 \cos\alpha - \dot{y}_2 \cos\alpha + r_1\dot{\theta}_1 - r_2\dot{\theta}_2 \quad (11)$$

By putting values of δ and $\dot{\delta}$ in Eq. (9), F_m is expressed as follows:

$$\begin{aligned} F_m(t) = {} & C_m\left[\dot{x}_1 \sin\alpha - \dot{x}_2 \sin\alpha + \dot{y}_1 \cos\alpha - \dot{y}_2 \cos\alpha + r_1\dot{\theta}_1 - r_2\dot{\theta}_2\right] \\ & + K_m(t)[x_1 \sin\alpha - x_2 \sin\alpha + y_1 \cos\alpha - y_2 \cos\alpha + r_1\theta_1 - r_2\theta_2] \end{aligned} \quad (12)$$

Time varying mesh stiffness (TVMS) is a periodic function caused by the change in number of contact tooth pairs as well as the contact positions of the gear tooth. Importantly, TVMS is one of the main sources of vibration in a gear transmission system.

3 Formulation of Time Varying Mesh Stiffness Equations

In this section, mesh stiffness formulation is presented for healthy gears and cracked tooth gears. This forms the comparative analysis for progressive condition of gears from healthy to progressive deterioration condition of gears.

3.1 Mesh Stiffness of Healthy Gears

Analytical approach has been used to calculate TVMS of two gears. Strain energy is a type of potential energy that is stored in a structural member as a result of elastic deformation. Potential energy based on theory of elasticity is considered to derive the expression of TVMS. During the transmission of forces, deformation energy in the tooth is calculated individually. Potential energy in general is given by the product of work done by gradually applied load and distance moved by it or deflection or deformation. Also, it is the product of average load and deflection.

During the evaluation of TVMS, the individual teeth is considered as cantilever beam supported at the dedendum circle with a variable cross section, where a force acts along the line of action. The deformation energy accumulated in the tooth is calculated individually for each tooth coming into an engagement. For a pair of spur gears with contact ratio lying in between 1 and 2, according to potential energy method [17–24], the total mesh stiffness K_m (in Eq. 9) can be expressed as follows:

$$K_m = \frac{1}{\frac{1}{k_h} + \frac{1}{k_{f1}} + \frac{1}{k_{b1}} + \frac{1}{k_{a1}} + \frac{1}{k_{s1}} + \frac{1}{k_{b2}} + \frac{1}{k_{a2}} + \frac{1}{k_{s2}} + \frac{1}{k_{f2}}} \tag{13}$$

subscripts 1 and 2 indicate the driving and driven gear, respectively.

where K_h = Hertzian mesh stiffness, K_a = Axial mesh stiffness, K_b = Bending mesh stiffness, K_s = Shear mesh stiffness and K_f = Fillet foundation mesh stiffness

3.2 Mesh Stiffness of Cracked Tooth Gears

For cracked tooth in a gear, crack developed at the root of tooth is considered for a single tooth of a gear. Initiation of crack takes place at the most heavily stressed section in the material. The path of crack propagation is observed as a smooth, continuous and tend to be a straight line with slight curvature [25]. Wu et al. [26] presented method to calculate TVMS of helical gear by considering fillet foundation stiffness within multi-tooth in contact and also by considering nonlinearity. Kong et al. [27] presented analysis of time varying mesh stiffness and dynamic response of gear transmission system with pitting and cracking coupling faults.

In this study, for modelling of crack on gear tooth, the crack depth is considered as a straight line and along the whole depth of the tooth. Crack starts at the root of the driven gear and propagate as shown in Figs. 2 and 3. The crack depth is represented as C_0 and it propagates in the straight line. h_c is the initial position of crack from the centre of tooth width. The crack is assumed to be extended for the whole width of the tooth. Then the crack propagation is towards the centre line of the tooth which is at an angle α_c. This propagation angle is important and have remarkable influence on the TVMS. For crack, maximum depth of the crack can be $C_{\max}$. The tooth profile remains unaltered and the foundation stiffness is not affected. For time varying mesh stiffness calculations for cracked tooth, the mesh stiffness equation values of K_h, K_a and K_f will remain unchanged. However, bending mesh stiffness and shear mesh stiffness undergoes change due to crack on the gear tooth.

Total mesh stiffness of a pair of spur gear with cracked tooth can be expressed as follows:

$$K_m = \frac{1}{\frac{1}{k_h} + \frac{1}{k_{b\_crack}} + \frac{1}{k_{a1}} + \frac{1}{k_{s\_crack}} + \frac{1}{k_{f1}} + \frac{1}{k_{b2}} + \frac{1}{k_{a2}} + \frac{1}{k_{s2}} + \frac{1}{k_{f2}}} \tag{14}$$

The effect of crack on gear tooth is realized in Eq. 14 as compared to Eq. 13 for healthy gear.

For cracked tooth in the spur gear, initial depth of crack is C_0**,** Therefore, for any crack width C, $C = C_0 \leq C_{\max}$.

Then the effective area moment of inertia and area of cross section at the position of Y can be calculated as:

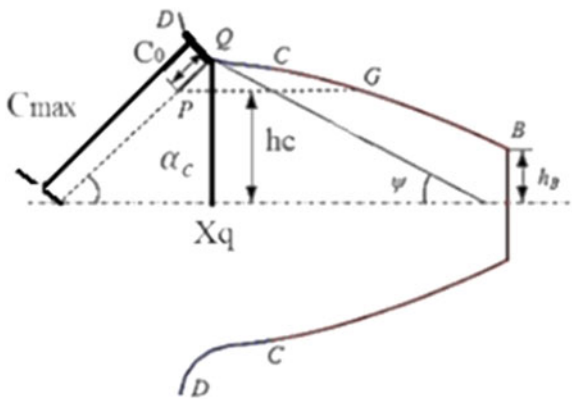

Fig. 2 Crack on spur gear

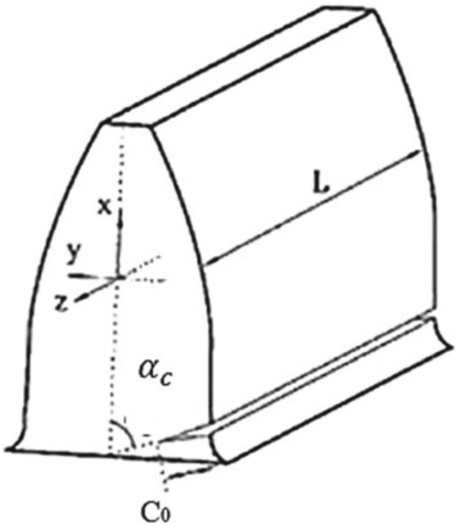

Fig. 3 Crack with constant depth

$$A = (H_c + x)L \text{ and } I = \frac{1}{12}(H_c + x)^3 L \tag{15}$$

4 Result and Discussion

As discussed in the previous section, time varying mesh stiffness (TVMS) is regarded as one of the most dominant indicators of the state of the gear under the influence of dynamic loading. For the calculation of time varying mesh stiffness of spur gear pair, analytical method is considered as an efficient and reliable method for spur gear. Depending upon the conditions of loading on a pair, the crack which is initiated at the root can propagate at an angle towards the centre of tooth thickness or rim. In following sections, results are presented for different angles of crack propagation. Based on this, significant conclusions can be drawn regarding healthy condition of gear. This is by the virtue of effect of variation of crack propagation angle on time varying mesh stiffness.

Initially, investigation of magnitude of TVMS is done for a gear tooth without crack. Successively, crack propagation angle is varied in steps and magnitude of TVMS is found for all the cases. However, variation of TVMS along the line of action is plotted graphically for some cases; healthy gear (without crack), CPA 70° and CPA 30° as shown in Fig. 4. The meshing action in a pair of gear tooth starts at the root of the driving tooth and tip of the driven tooth at the start of engagement. Successively, with the two gears rotating along their defined trajectory and the point of contact constrained to move along the pressure line at disengagement contact is at tip of driving tooth and root of driven tooth. In between these two events, some time is elapsed corresponding to the angle of action which indicates the angle for which a tooth of driver remains in contact with the driven tooth. Accordingly, discretization of the physical phenomena of the meshing is done by considering many data points from engagement to disengagement.

Table 1 in particular shows the magnitude of TVMS for three important positions which are start of engagement, middle and disengagement. Initially, at 1000 points, the same was computed. Magnitude of TVMS is presented for three instants (at start, at middle and at end of the engagement) and for different crack propagation angles. Figure 5 shows comparative analysis of TVMS for different CPA.

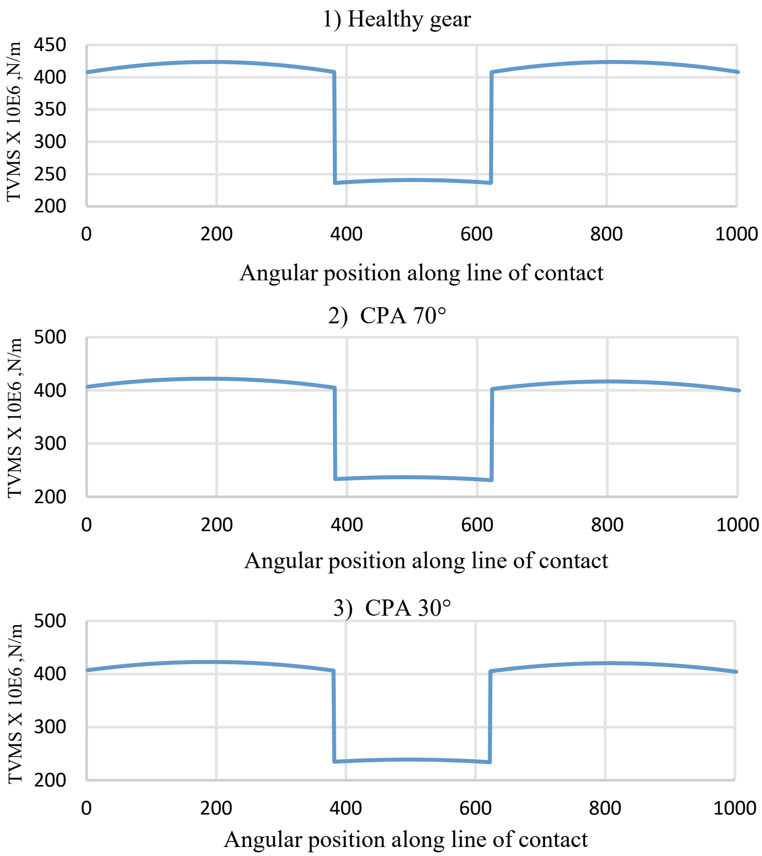

Fig. 4 Time varying mesh stiffness for healthy and crack propagation angle of 30° and 70°

Table 1 Effect of CPA on TVMS at start, middle and disengagement

CPA	Healthy	70°	30°	10°
Start	407,816,205	406,906,030	407,361,325	407,665,030
Middle	240,825,827	236,641,133	238,827,018	240,242,293
End	408,193,554	399,782,136	404,390,307	407,095,543

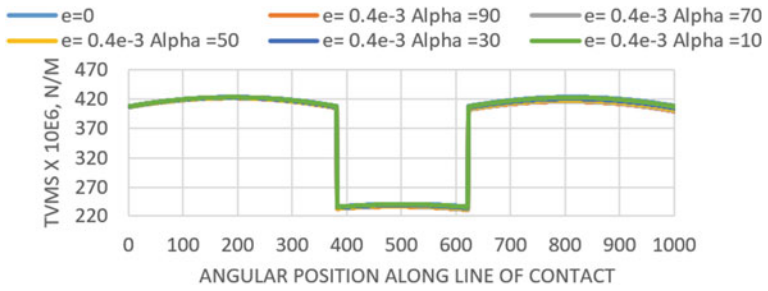

Fig. 5 Comparison of all crack propagation angle with TVMS values

5 Conclusion

As discussed in previous section, it is clear that for lower values of crack propagation angle, magnitude of TVMS is high and as angle increases, there is drop in TVMS. This indicates that drop in TVMS for higher values of crack propagation angle is associated with reduced load support. This happens due to the fact that at 90°, crack progresses towards the tooth thickness as compared to progression of crack at 10° which is the terrain of rim having massive material. This shows that, TVMS is an important indicator of development of crack on gear tooth. TVMS indicates the condition of tooth. It can be said that the way in which crack propagates on the gear tooth, have marked impact on TVMS. Moreover, it is observed based on the findings of earlier studies that the focus was on fixed crack propagation angle. This was the motivation for undertaking current study presenting results on varied crack propagation angles. The findings of this current study can be extended for evaluating the remaining life of the gear tooth with regards to variation of crack propagation angle.

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References

1. Tandon N, Choudhury A (1999) A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings. Tribol Int 32:469–480

2. Aherwar A (2012) An investigation on gearbox fault detection using vibration analysis techniques: a review. Aust J Mech Eng 10(2):169–184
3. White MF (1984) Simulation and analysis of machinery fault signals. J Sound Vib 93(l):95–l16
4. Patel VN, Tandon N, Pandey RK (2010) A dynamic model for vibration studies of deep groove ball bearings considering single and multiple defects in races. J Tribol 132:1–10
5. Randall RB (1982) A new method of modeling gear faults. J Mech Des 104:259–267
6. McFadden PD (1986) Detecting fatigue cracks in gears by amplitude and phase demodulation of the meshing vibration. ASME transactions. J Vib Acoustics Stress Reliab Des 108:165–170
7. Weber C (1949) The deformation of loaded gears and the effect on their load-carrying capacity. Sponsored Research (Germany). Department of Scientific and Industrial Research. London. Report 3
8. Chakraborti J, Hunashikatti HG (1974) Determination of the combined mesh stiffness of a spur gear pair under load. ASME paper 74 -DET-39
9. Terauchi Y, Nagamura K (1981) On tooth deflection calculation and profile modification of spur gear teeth. In: Proceedings of international symposium on gearing and power transmission, Tokyo
10. Arafa MH, Megahed M (1999) Evaluation of spur gear mesh compliance using the finite element method. Article ARCHIVE Proc Instit Mech Eng Part C J Mech Eng Sci 1989–1996:203–210
11. Dogan O, Karpat F, Kopmaz O, Ekwaro-Osire S (2020) Influences of gear design parameters on dynamic tooth loads and time-varying mesh stiffness of involute spur gears. Sådhanå 45:258. 15 pages
12. Jia SX, Howard I, Wang J (2003) The dynamic modeling of multiple pairs of spur gears in mesh, including friction and geometrical errors, Taylor & Francis Inc. Int J Rotat Mach 9:437–442
13. Barot A, Kulkarni P (2023) Dynamic analysis of effect of progressive crack and variation in center distance on vibration of spur gears. Mater Today: Proc 77:603–613
14. Ozguven HN, Houser DR (1998) Dynamic analysis of high-speed gears by using loaded static transmission error. J Sound Vib 125(1):71–83
15. Zhang L, Chen C, Liu J, Zhao S (2018) Dynamic characteristic of spur gear with flexible support of gearbox. J Vibroeng 20(3):1530–1543
16. Liu J, Wang C, Wu W (2020) Research on meshing stiffness and vibration response of pitting fault gears with different degrees. Hindawi. Int J Rotat Mach 2020, Article ID 4176430. 7 pages
17. Wu S, Zuo MJ, Parey A (2008) Simulation of spur gear dynamics and estimation of fault growth. J Sound Vib 317(3–5):608–624
18. Ma H, Zeng J, Feng R, Pang X, Wen B (2016) An improved analytical method for mesh stiffness calculation of spur gears with tip relief. Mech Mach Theo 98:64–80
19. Ma H, Zeng J, Feng R, Pang X, Wang Q, Wen B (2015) Review on dynamics of cracked gear systems. Eng Fail Anal 55:224–245
20. Tse DK, Lin HH (1992) Separation distance and static transmission error of involute spur gears. In: 28th joint propulsion conference and exhibit. Nashville. TN, U.S.A., 9 pages
21. Yang DCH, Lin JY (1987) Hertzian damping, Tooth friction and bending elasticity in gear impact dynamics. J Mech, Trans Auto Des 109(2):189–196
22. Chen Z, Zhang J, Zhai W, Wang Y, Liu J (2017) Improved analytical methods for calculation of gear tooth fillet foundation stiffness with tooth root crack. Eng Fail Anal 82:72–81
23. Yang DCH, Sun ZS (1985) A rotary model for spur gear dynamics. ASME J Mech Trans Auto Des 107:529–535
24. Sainsot P, Valex P, Duverger O (2004) Contribution of gear body to tooth deflections—a new bidimensional analytical formula. J Mech Des 126:748–752
25. Ma H, Song R, Pang X, Wen B (2014) Time-varying mesh stiffness calculation of cracked spur gears. Eng Fail Anal 44:179–194
26. Wu X, Luo Y, Li Q, Shi J (2022) A revised method to calculate time-varying mesh stiffness of the helical gear. MATEC Web Conf 355:01005
27. Kong Y, Jiang H, Dong N, Shang J, Yu P, Li J, Yu M, Chen L (2023) Analysis of time-varying mesh stiffness and dynamic response of gear transmission system with pitting and cracking coupling faults. MDPI, Mach 11(4)

Predicting Air Pollution: A Smart Step in Pollution Management

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Abstract The advancements in technology have introduced us to concepts like smart cities, smart devices, etc. A city can be considered as smart if it is liveable, inclusive, and sustainable. Other factors like building bold, strategic view for development, inclusive and accessible urban spaces, and services, having trust in government, proper waste management, and pollution management are some of the key factors which contribute significantly to making the city smart. Without oxygen, it is impossible to comprehend how humanity would survive. Modern human culture has had constant growth that has had a negative impact on the quality of the air. Daily transportation and home operations churn up dangerous pollutants in our surroundings. In the modern day, air quality monitoring and forecasting have become cumbersome tasks, particularly in developing nations like India. Managing pollution is becoming the need of the hour. This paper showcases how pollution management can be carried out with the help of machine learning techniques. A random forest algorithm has been applied to the sample data for predicting air pollution. It can be said that if air pollution is predicted at an earlier stage, it can contribute significantly to making the city smart.

Keywords Machine learning · Random forest · Air quality monitoring · Air quality index

1 Introduction

In the actions of modern humans, power consumption and its effects are unavoidable. The burning of fuel is a man-made source of air pollution, as are emissions from manufacturing facilities, automobiles, airplanes, and aerosol cans, among other

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things [1]. The health of people is impacted by the poisonous air that makes up air pollution. Humans are more susceptible to a wide range of dangerous illnesses brought on by air pollution, including asthma, cancer, types of heart illness, and bronchitis. Scientists have discovered that air pollution has the potential to have a negative impact on various historical sites. Atmospheric emissions from industries and power plants, as well as exhausts from agriculture, are to blame for the rise in gases like CO_2, NO2, and NH_3. The greenhouse gases have a negative impact on the climate, which in turn affects how quickly plants develop [2]. The major difficulty arises while monitoring a vast number of airborne particles and numerous injurious gases. Such gases are harmful to local residents. With rising automotive and industrial growth, monitoring and forecasting AQI has become an important and difficult undertaking, particularly in metropolitan regions. To track AQI, an intelligent air purifying model is required. Even though the engrossment of the deadliest pollutant, PM2.5, is shown to be multiplied in developing countries, the majority of air quality studies and research efforts focus on these nations.

Increasing air pollution is a threat to society. A lot of work is being done in different areas to keep a check on the increasing pollution levels. IoT and machine learning are the two sustainable solutions that are helping in curbing this menace. IoT analyzes the air quality index using sensors. Sensors are further used to measure PM 2.5 which helps in monitoring AQI. In this paper, we are trying to predict air pollution with the help of machine learning that can help in adapting preventive measures well in advance. With the help of preventive methods, we can protect the environment from hazardous gases.

The next section highlights the work done in the field of air pollution monitoring. The dataset under investigation, along with feature selection and preprocessing procedures used, is all described in Sect. 3. Through data visualization, Sect. 4 discusses finding hidden patterns in the dataset. The current work comes to an end in the last segment.

2 Literature Review

In the current section, a few similar works have been done already on-air pollution by different researchers with the help of ML techniques like KNN, SVM, and LR on varied datasets using accuracy, recall, AU-ROC, $f1$-score, and precision.

Neirotti [3] briefed about the idea of a smart city as a way of improving the quality of life of pupils has become more significant recently. With the development of a taxonomy of relevant application areas, including natural resources and energy, governance, economy and people, and many more, this article offers a thorough grasp of the concept of a smart city.

Siregar [4] discussed the need for ongoing surveillance of the pollution levels in the cities. This is crucial in the context of smart cities, where environmental concerns are crucial. Technologies can be created for a hybrid pollution surveillance system using Waspmote along with wireless sensors.

Peng [5] briefed about the prevention and management of the urban environment pollution has drawn significant attention from an increasing number of individuals. To assess the current state of environmental contamination, this system employs a variety of sensor and video monitoring interfaces, and it communicates the equipment it collects through a wireless network to a central server for evaluation and planning.

Toma [6] explained the objective is to reduce hazards to one's health and to increase the awareness of the negative consequences of exposure to air pollution. This study aims to examine the main problems of a problem-solving time pollution surveillance system. In the suggested IoT solution, security is given a lot of attention. Security is the central element that drives all other system components.

Agrawal and Mohan [7] discussed the potential ways to tackle the hazardous problem caused due to air pollution. The patterns in microscopic airborne particles that were observed throughout the past year across three Indian smaller towns are presented in this research. The results are significant for developing state and local policy for dealing with the issues of contaminants in the air in urban areas.

Kumar [8] briefed about the analysis and forecast of air quality using data from 2015 to 2020 from 23 cities in India. With and without the SMOTE resampling technique, machine learning-dependent AQI prediction is conducted. GNB, KNN, RF, SVM, and XGBoost were used to carry out the analysis process. Out of all these learning algorithms, XGBoost outperformed based on n-fold cross-validation techniques.

Murali [9] focus on the adverse impact of poor quality. In this paper, the authors aim to monitor AQI in Kerala. In this paper, the authors worked on multiple regression techniques. The benefit of turning toxins into a valuable result for business sectors is examined in this investigation.

Israfil [10] illustrated unorganized growth in population, commercial garbage, and greater movement in vehicles are some of the primary factors leading to the growth in the AQI index. Of all airborne contaminants, particle size (PM) 2.5 is especially worrisome because it adversely affects people's health. With the help of the LR, the machine learning technique helps in predicting the level of PM2.5. Through the prediction, nations may reduce contaminants in the air levels to minimize the worldwide incidence of lung tumors, ischemic attacks, and chronic as well as acute respiratory diseases like bronchitis.

The literature review has helped in understanding how to improve the quality of air so the pupil can lead their life without any threat of inhaling poisonous gas. IoT and machine learning both are playing an important role in determining the quality of air prior, so preventive measures can be taken well in advance. LR clarified that there was a great need to close this gap by doing some research and AQI forecasting for India. ML models have been implemented to achieve the solution to the problem.