# VIBRATION ANALYSIS AND IDENTIFICATION OF FAULTS IN A SPUR GEARED ROTOR SYSTEM INTEGRATED WITH ACTIVE MAGNETIC BEARINGS

## SHORT ABSTRACT

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# Abstract

Gearbox is widely used in industrial, transportation and military applications. The gearbox vibrations and noise caused by variation of contact forces often causes failure in the components of gearbox, which are then transmitted to the surrounding structures. The sources of error between the mating gears while in the operation are the gear mesh deformation, transmission error, and runout; resulting in dynamic forces, excessive vibration, and noise. To avoid any undesirable effect on the gear-pair and other supporting structures, it is essential to investigate these forced vibrations in time and frequency domain. The concept of active control of gearbox vibrations with piezoelectric actuators at mounting points of the gearbox is analysed earlier in several studies, then with certain limitations. The aim of this work is to investigate the feasibility of active vibration control with Active Magnetic Bearings (AMBs), being applied for supressing the transverse vibrations in a geared rotor system against transmission error excitations at the gear mesh. The AMBs are capable of suppressing the vibration of the system (transients as well as steady-state) by controlled electromagnetic forces considering the rotor vibrational displacement with a closed loop feedback system. A concept of active vibration control by Active Magnetic Bearings (AMBs) on the shaft of a spur gearbox has been introduced having conventional bearings as well. The AMB suppresses the response of the system by generating controlled electromagnetic forces based on the gear shaft vibration measurement. The AMB force is applied in two mutual perpendicular directions without any physical contact as opposed to mechanical forces in conventional bearings. Hence, an approach to monitor and control the transverse vibration of mating gears is presented with the help of AMBs. To understand the system dynamics and prediction of vibration responses, numerical models have been developed to carry out gear rotordynamic analysis of transverse vibration, transverse vibration with gyroscopic effect and coupled torsional-lateral vibration with geared rotor faults, like the mesh deformation, gear run-out, mass unbalance and asymmetric transmission error. The dynamic transmission error has been modeled as the sum of mean and varying components of error in two orthogonal transverse directions. With a feedback PID controller, the vibration amplitude is observed to get suppressed. The frequency domain analysis is done using a full spectrum, which shows that multiple harmonics of gear mesh frequency is minimized simultaneously.

Due to high service load, harsh operating conditions, faults may develop in gears. If the gear faults are not detected early, the health may continue to degrade, causing heavy economic loss or even catastrophe. Early fault detection and diagnosis is much needed for properly scheduled shutdowns to prevent any catastrophic failure and higher cost reduction. While focusing upon the dynamics based gearbox fault modeling, detection and diagnosis, identification algorithm has been developed to estimate the geared rotor fault parameters. Considering full spectrum analysis of the geared rotor system, from rotor vibration and AMB current information, estimation of system parameters, i.e. the equivalent mesh stiffness, mesh damping, gear runouts, the mean and varying transmission error magnitude and phase angles, and the current and displacement constants of AMBs has been performed. Gaussian noise in responses and modeling errors in mathematical models have been added to test the robustness of the proposed algorithm to comply with the experimental settings.

Based on the proposed model, an experiment test rig has been set up in the laboratory and the effectiveness of the proposed model is compared with and without the application of AMBs. The approach is based on an active control of the shaft transverse vibration with an electromagnetic actuator. The control forces are applied to the rotor shafts supported on conventional rolling element bearings by an eight-pole radial AMB, as an auxiliary component and a closed-loop linear output feedback control is employed for stable, reliable, and robust operation. A linear PD controller working on differential mode is used to generate the appropriate control signals and the experimental results are presented. Simulation and experimental results showed that there is considerable amount of reduction in the geared rotor vibration levels and correspondingly in overall measured gear noise levels.

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# 1 Introduction and Brief Literature Review

Gears play a crucial role in our daily lives right from the applications in industrial machineries, power transmission systems, electric vehicles, marine, aerospace, home appliances and so on. However, sometimes unwanted vibration and noise are inevitable during gear operations. These not only deteriorates the working environment, but also reduces the durability and reliability of the machine.

Usually the vibration excitations occur due to the resultant varying amplitude of contact forces between the gears. The relative displacement variation between the gears acts via the system dynamics to give a force variation resulting in vibration. Under normal driving conditions, a typical geared rotor system is subjected to large dynamic loads and the noise radiated from the gear transmission is directly related to the vibration level of the geared system (Smith, 1999). Gearbox noise emission can be either structure born or airborne. The majority of gear noise experienced in gear transmissions are classified into two distinct categories: rattle and whine. Generally, gear whine is the main concern for acoustic comfort. Gear whine occurs when vibrations driven by small fluctuations in rotation caused by the tooth profile or manufacturing error are transmitted via the bearings that support the gear shaft to the housing, resulting in vibration on the surface of the housing. These fluctuations in rotation are due to errors in the rotational angle of the gear teeth as they get meshed, that is known as transmission error. The noise characteristics varies with number of teeth and shaft rotational speed. A whine noise is a high frequency noise and is mainly caused by small errors in the gear tooth profile and tooth stiffness.

Transmission error is considered as the main reason for the generation of gear noise. (Munro, 1990) briefly stated that TE is the deviation in position of the driven gear (for any given position of the driving gear), relative to the position that the driven gear would occupy if both the gears are geometrically perfect and undeformed.

Over the last few decades, many attempts have been made by numerous authors to set up mathematical and numerical models aimed at simulating the dynamic behaviour of gears. According to Özgüven and Houser (1988) the literature suggests that many different models have been developed following the physical laws, i.e. simple dynamic factor models, models with tooth compliance, models for gear dynamics, models for geared rotordynamics, models for torsional vibrations and so on. For simple geared systems generally lumped parameter dynamic models with springs, masses and viscous damping are used keeping low computational burden. For more complex models, i.e. which includes the gearbox casing etc., finite element modelling is often used. Eritenel and Parker (2012) developed a three-dimensional lumped-parameter model for a pair of helical gears considering the nonlinearity of the gear mesh due to partial contact loss of gear teeth. Velex et al. (2016) used a modular three-dimensional model of multi-mesh gears to theoretically analyze the relation between dynamic mesh excitations and transmission errors.

The analytical methods using finite element method include more complete models of the system components and geometry. Initially, the models were analysed consisting of only the teeth in mesh, but it is now becoming common to include the remaining teeth, gear body, shaft system, and bearings. In the research work carried out by Andrews (1991) the finite element method was used for predicting the fillet stress distribution experienced by loaded spur gears. To save the computation cost, Parker et al. (2000) proposed a combined element/contact mechanics model to investigate the non-linear dynamic response of a spur gear pair. Guangjian et al. (2017) presented theoretical formulas of no load transmission error (NLTE) and time-varying backlash, which can be used for double eccentric gear system, whose contact ratio is random. Literature published on the effect of varying contact conditions in gear tooth interactions through finite element method, on the perceived transmission error from gear pair models is quite sparse.

There are several gear parameters which needs to be addressed while performing the dynamics based modelling, fault detection and diagnosis of geared rotor systems.

Generally, four methods are applied to evaluate time-varying gear mesh stiffness for gear fault diagnosis: square waveform method, potential energy method, finite element method, and experimental method (Liang et al. 2018). Gear mesh stiffness is a periodic function for a healthy gear pair running at constant speed. The period of a square waveform is called mesh period, which equals to the time duration for one revolution divided by the number of teeth. Liang et al. (2014) used the potential energy method to analytically evaluate the mesh stiffness of a planetary gear set. Rincon et al. (2013) described an advanced model for the analysis of contact forces and deformations in spur gear transmissions. Kosarev (2003) concluded that the factors causing gear vibration can generally be eliminated by profile modifications, adjustment of contact ratio and high-precision manufacture of gears.

It was noted that TE may happen due to deviations in geometry of the combined tooth profiles from the ideal involute, elastic deformation of the teeth being load dependent, inertial as well as stiffness effects, and thus is speed and load dependent. There are several sources of TE. According to Smith (1983), TE results from three main sources: 1) Gear geometrical errors, 2) Elastic deformation of the gears and associated components and 3) Errors in mounting. The geometry errors are mainly from manufacturing and practical assembly of gears within systems that yield profile, lead, run-out and tooth spacing errors. The misalignment of gears and shafts during assembly is also another important contributor to the generation of transmission error stated by Athavale et al. (2001). There are a few types of transmission errors that are frequently referred to in the literature and they vary in small measures from one another. (1) Geometry transmission error (GTE) (2) Static transmission error (STE) (3) Kinematic transmission error (KTE) (4) Dynamic transmission error

Vibration monitoring is one of the most popular condition monitoring techniques practiced in rotating machineries. The vibration based analysis is classified into three main categories, i.e. the model and signal based, model properties based, and machine learning based. Different authors have used different methods to estimate the system level parameters. In the present work, the model based fault identification approach have been taken into account. According to Hiroaki and Nader (2012), the fault detection and diagnostic techniques based on vibration signal analysis are the ideal non-destructive machine health monitoring method, that can be applied in a minimally intrusive manner; i.e. by attaching an accelerometer on a gearbox casing. However, the dynamic interaction amongst the machine elements of a gearbox is often complex and the vibration signals measured from the gearbox is not easy to interpret. The diagnostic information that directly related to an emerging fault in a gear or a bearing is typically buried in the dominating signal components that are driven by the mechanisms of the transmission system themselves. For example, gear meshing signals.

While DTE is considered to be the most common factor for gear noise, it is of course the most difficult to obtain, either by analysis or measurement. However, it has been recognised that TE can be measured by phase demodulation of the signals of shaft encoders rigidly attached to each of the gears in mesh, i.e. the GTE at low speed and low load, the STE at low speed and higher load, and the DTE at higher speed and higher load. Since the dynamic transmission error is excited by the static transmission error, it is fruitful to reduce noise by addressing the static transmission error. The alternating component of the static transmission error is reduced by specifying tooth modifications that compensate the stiffness variation. Houser et al. (1994) showed that sound power measurements (sum of harmonics and sidebands) can be correlated well with predicted transmission error in the parallel axis arrangement. Loutridis (2006) proposed an energy-based feature for the gear fault prediction and diagnosis. Feng et al. (2012) summarized the spectral characteristics of planetary gear vibration signals for the fault diagnosis of planetary gearboxes.

In recent years, a great amount of work has been done on the application of active control. The main advantage of active control over passive control is the ease with which active control can adjust to varying loading conditions. Other advantages of active vibration control include the low weight, compact size, and versatile operating conditions.

Gembler et al. (1998) attached the inertial actuators to the gearbox strut system outside of the gearbox of helicopter. Sutton et al. (1997) had set up a helicopter gearbox support strut in the laboratory under realistic loading conditions to investigate the active control of longitudinal and lateral vibration transmission to a connected receiving structure.

Few researchers have introduced the concept of active vibration control of gear systems through piezoelectric actuators. Montague et al. (1994) were among the first few researchers to perform the active vibration control of gear transmission systems using piezoelectric actuators, experimentally. Wang et al. (2018) developed a built-in piezoelectric actuator to generate the control forces, which can be transmitted to the shaft through additional support bearings. A non-linear controller for an active vibration control of a single-stage spur gearbox was proposed by Dogruer et al. (2017), which can modulate the input torque acting on the driving gear that minimizes the dynamic transmission error and compensates the periodic changes in mesh stiffness.

The demand for the use of active magnetic bearings (AMBs) in condition monitoring of rotating machineries is increasingly growing for replacing the oil lubricated bearings as well as retaining the vibration level at minimum such that the undue stresses that causes catastrophic failures are minimum (Siva et al., 2018). The application of AMBs are very much demanding with emphasis on turbomachinery, blood pumps, centrifuges, machine drilling tools, energy storage flywheel, high-speed motors and generators. Schweitzer et al. (2009) have demonstrated the design and development of a variety of compact and simple structured AMBs and their control systems. Maslen (2000) presented the design and dynamic analysis of both the axial and radial magnetic bearings of rotors, and discussed the different elements along with control for the working of active magnetic bearing systems, such as the position sensors, controllers and power amplifiers. Knopse (2007) presented experimental results from two test rigs illustrating the potential of magnetic bearings for the active suppression of machining chatter. Zhong et al. (2014) utilized homo-polar type electro-magnetic (EM) actuators and employed proportional-derivative (PD) type controller for the position control by AMB. Kimman et al. (2010) presented the design and realization of a miniature milling spindle with AMBs. Mushi et al. (2011) presented the framework of a model-based control design to ensure efficient, reliable, and safe operation of turbomachinery on AMBs. Several methods have been described in the literature for identification of parameters on different types of AMB systems in both the time and frequency domains. Vázquez et al. (2001) presented the identification of a long flexible rotor with three magnetic bearing journals, experimentally. Li et al. (2006) presented a comprehensive modelling and identification method with individual mathematical modelling and identification of the subcomponents, followed by an overall identification of a closed loop transfer function. Ranjan and Tiwari (2020) developed an identification algorithm to execute high-speed balancing of a flexible rotor system supported on conventional bearings.

The literature suggests that AMBs has been chosen as an efficient component in vibration control and condition monitoring of flexible rotor-bearing systems. The proposed work involves the novel use of AMB technology not for geared rotor support but rather as an actuator for reduction of vibration and noise emanating from the system. The current study deals with application of AMBs for vibration suppression and identification of faults in geared rotor systems.

## 1.1 Shortcomings of the Present Literature

The above literature survey portrays that there exists a lot of different techniques to model the gear system dynamics. When considering the internal responses of the gearbox, forces generated by the mating gears between the gear teeth continually results in subsequent vibration and noise. The vibrations are transmitted from the gears to the shaft and through the bearings to the gear case. Sometimes, it becomes quite expensive to take out this damaged gearbox and replace it especially in offshore wind turbines, complex and large rotating machinery. As noted above, a number of factors needs be considered in order to reduce the transmission error in gears. The unmodified gear with less profile error provides better performance with regard to transmission error fluctuation when the load torque is low whereas the gear with a modified profile is better above a certain level of load torque. This shows how fluctuations in transmission error can be minimized by modifying the tooth profile to suit the load applied to the gear. So, usually tooth profile modification is suggested at the gear design stage or manufacturing stage to control the DTE (most important factor for gear noise) however this consumes time and is quite cumbersome. Evidently, gears are prone to failures and not much literature can be found on the identification of dynamic transmission error with experimental validation. For example, loaded transmission errors can be predicted by using software such as the LDP (Load Distribution Program) from Ohio State University's Gear Dynamics and Gear Noise Research Laboratory, (1994). Most transmission error analysis tools compute static transmission error. Additionally, TE is modelled in a single direction, which does not give the complete information, like its orientation and phase.

Somewhere researchers have used the vibration isolators/struts to reduce the vibration transmitted to the support structure. However, even with a well-designed isolator, there is always some residual vibration that is transmitted to the support structure. So, the concept of active vibration control of geared rotor systems with piezoelectric actuators was introduced by few researchers. Unfortunately, there are also few limitations with piezoelectric actuator technology, i.e. the structural vibrations intensify at frequencies close to the resonant frequency, so the positioning speed of piezo-based systems is limited by the lowest structural vibrational frequency, causing significant positioning errors. The major drawback of this actuation concept is that the slip rings configured to transfer electrical power to the rotating actuators are complex. Other practical limitations are the actuator's limited strength in tension, hysteresis in the movement and acceleration increasing exponentially with frequency, and the power dissipation stemming from the mass of the actuators increases significantly at higher frequencies. Furthermore, there are electrical limitations in piezoelectric actuators [26].

## 2 Objectives of the Present Work

The aim of the present study is to reduce the gear mesh vibrations by applying actively controlled electromagnetic forces with AMBs placed on the geared shafts and then identification of different types of geared rotor faults from the vibration responses of the proposed rotor system. The desired goal is achieved by undertaking the following objectives:

1. Develop the mathematical formulation for a single stage spur geared rotor system based on lumped parameter gear dynamic models devising various faults and integrated with Active Magnetic Bearings.

2. Conduct gear dynamic analysis of the proposed geared rotor-AMB system by taking the following cases:

(a) Rotor with gears at mid span of the shaft and integrated with AMB generating the vibrational displacement only in transverse direction.

(b) Rotor with gears placed slightly away from mid span of the shaft, integrated with AMB and creating the vibrational displacement in transverse direction along with gyroscopic effect.

(c) Rotor with gears placed slightly away from mid span of the shaft and integrated with AMB causing the coupled torsional-lateral vibrations along with gyroscopic effect.

3. Develop an identification algorithm from developed models using regression method for identification of various geared rotor faults, like the gear runout error, unbalance, variable transmission error with corresponding phases, AMB parameters like displacement stiffness and current stiffness factors, thereafter solve the inverse problem with least-squares technique. Since, the simulation does not have environmental noise interference. Hence, checking the robustness of the algorithm with addition of random noise and modelling error.

4. Design and fabricate the proposed geared-rotor AMB laboratory test rig for the experimental validation and investigation of active internal shaft vibration control caused by rotor unbalance, gear runout, transmission error, which usually resides within the gearbox.

5. Utilize the full spectrum responses obtained experimentally from the developed rotor AMB test rig as an input to the developed identification algorithm for prediction of the different rotor faults that were considered in the mathematical model.

## 3 Organization of the Present Work

The thesis is divided into seven chapters. The introduction and literature review are presented in Chapter 1. The mathematical modelling, numerical simulation for transverse vibration analysis of the geared rotor AMB system in time and frequency domain has been carried out in Chapter 2. Later, an identification algorithm based on mathematical model has been developed and geared rotor faults, transmission error and AMB parameters are predicted by undertaking the full spectrum of vibration responses. Chapter 3 discusses the mathematical modelling considering offset gears and numerical simulation of the proposed system is carried out for the transverse vibration analysis with gyroscopic effect. The identification algorithm is developed accordingly and faults, AMB parameters are identified. Similarly, in Chapter 4 the work is extended to numerical investigation of the coupled torsional-lateral vibration analysis with gyroscopic effect. Based on the mathematical model the identification algorithm is developed and parameters are estimated. The detailed description of the various components for design and fabrication of the laboratory test rig is given in Chapter 5. Furthermore, the numerical results of the proposed model are compared with that of the responses obtained from the experimental test rig. The practical design guidelines of the active control system of a magnetic bearing in terms of sensors, actuators, power amplifiers and real-time controller implementation is presented and its effectiveness in suppressing the gear induced housing vibrations and noise are explicitly described. The identification of various rotor-AMB parameters is experimentally obtained from the rotor test rig vibration responses and the developed algorithm is validated. In the end, the conclusions, limitations, and future scope of the current work is presented in Chapter 6.

## 4 Conclusions

The aim of this research work to reduce the gear mesh vibrations by applying actively controlled electromagnetic forces with AMBs placed on the geared rotor shafts has been done effectively. It has been envisioned that if the gearbox internal shaft transverse vibration can be controlled effectively with the help of active magnetic bearings, then the gears and the surrounding support structures can be prevented from failure due to vibrations. In addition, it is difficult to obtain the magnitude and phase information of varying transmission error, which is a major concern for the gear noise. Hence, an identification algorithm based on least-squares regression technique has been developed to quantify the transmission error values and other rotor fault parameters.

With this frame a transmission error based gear dynamic model was developed. Initially a 4 DOF model for the transverse vibration analysis of a geared rotor system with gear run-out and dynamic transmission error was done with help of lumped parameter model. A time varying mesh stiffness was considered in the form of transmission error for a single pair of teeth engagement. The DTE was modeled as an asymmetric dynamic transmission error and full spectrum was chosen for spectrum analysis.

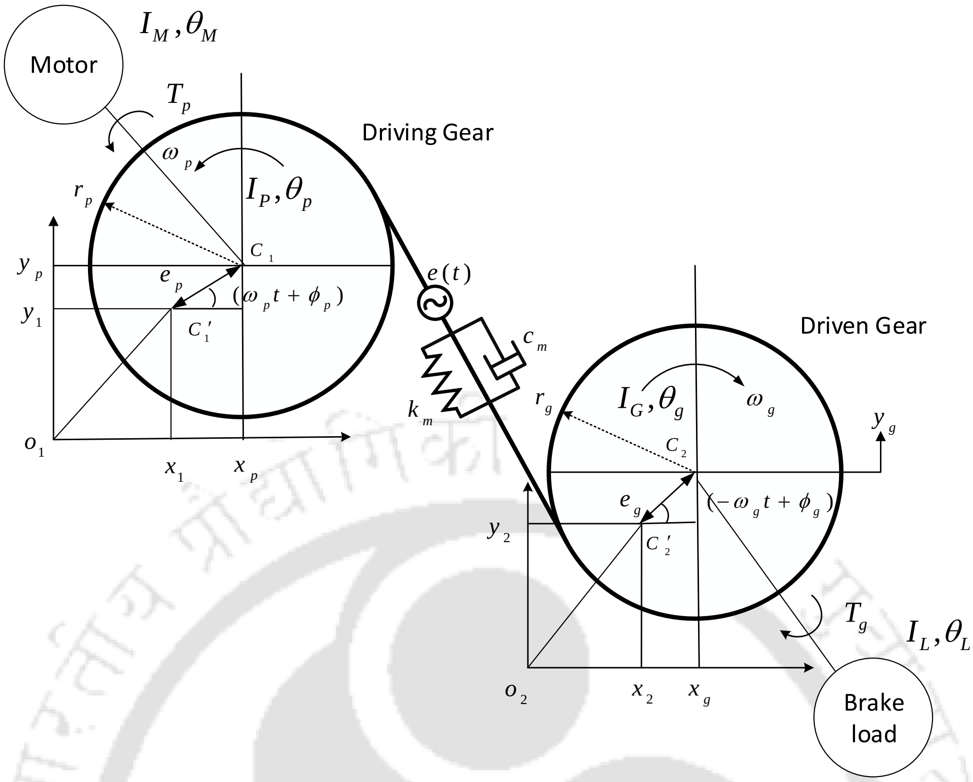



**Figure 1** Gear mesh model with co-ordinate system

A novel identification algorithm was developed using regression equations from the mathematical model which estimated the system fault parameters, i.e. the gear mesh stiffness, gear mesh damping, runout of input gear and phase, runout of output gear and phase, AMB displacement stiffness constant, AMB current stiffness constant, mean transmission error and phase, variable transmission error corresponding to different harmonics and respective phase angles.

In the next analysis, the gears were considered offset from central plane of the rotor. Here, the system configuration of geared rotor has 8 DOF model which includes the rotational displacement about the diametral axes, arising from gyroscopic effect due to offset gears. Since rotational displacements pose practical difficulty of accurate measurement, a dynamic reduction scheme was implemented to eliminate the rotational displacements in identification equations. For the identification procedure, regression equations were used to quantify the system fault parameters.

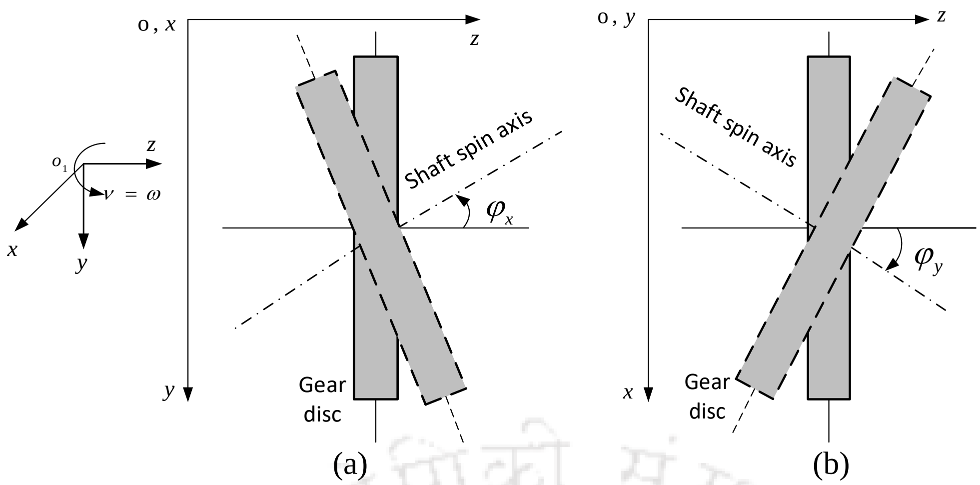
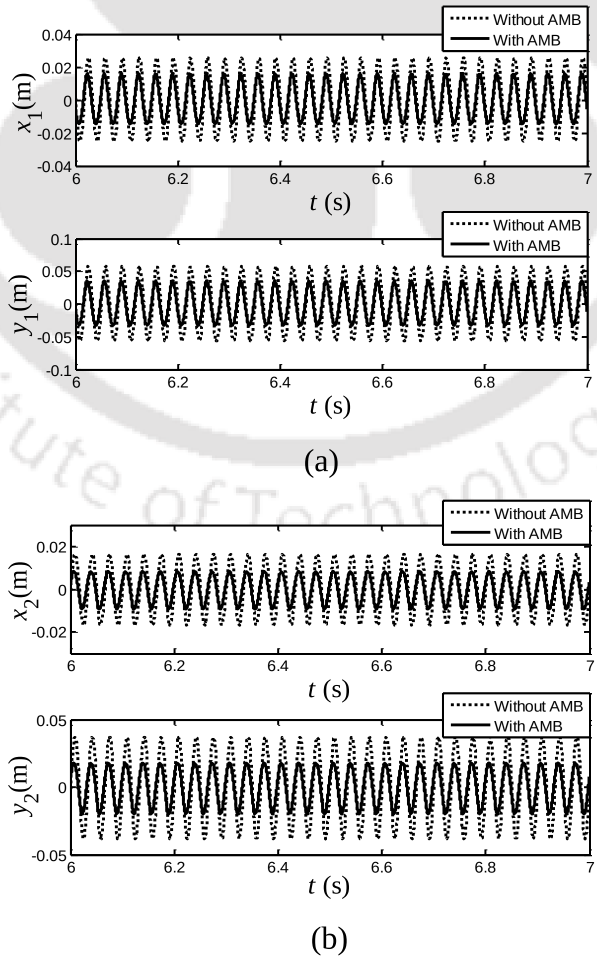
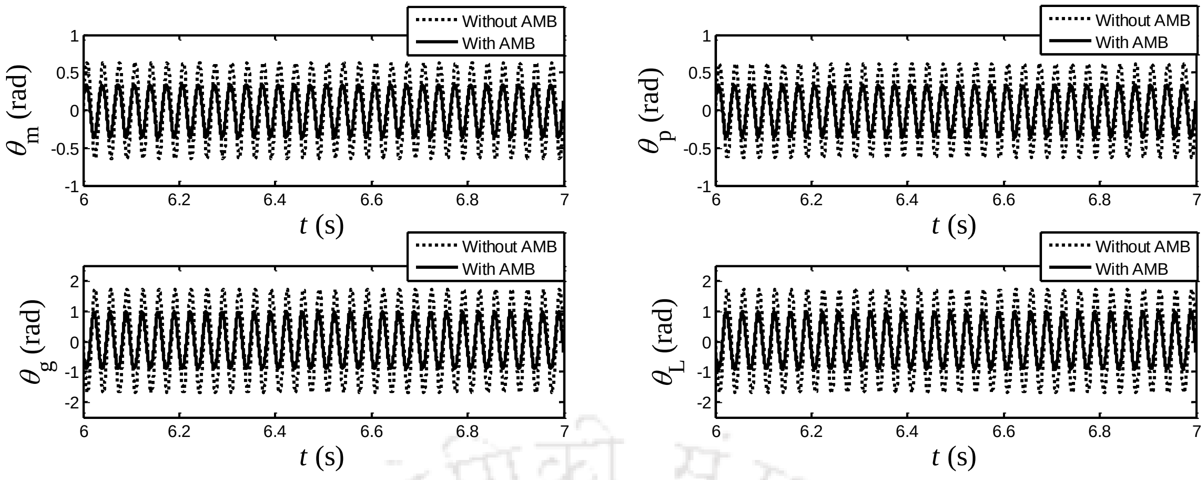



**Figure 2** Coordinate axes and positive conventions for rotational displacements due to gyroscopic effect (a) tilting of shaft axis *y*-*z* plane (b) tilting of shaft axis *z*-*x* plane

In third part, the coupled torsional-lateral vibration analysis was attempted with a desire to suppress the coupled torsional vibration along with transverse vibrations. Active magnetic bearings have been integrated for active control of gear-shaft coupled vibrations. The identification algorithm has been further extended by developing a mathematical model of coupled geared-rotor dynamics.






(c)

**Figure 3** Time domain response at $\omega_p = 60\text{Hz}$ , $\omega_g = 30\text{Hz}$ , $\omega_e = 1500\text{Hz}$ (a) x, y displacement of input shaft (b) *x*, *y* displacement of output shaft (c) torsional displacement of motor, pinion, gear, load respectively.

Thereafter, in fourth part the mathematical model developed and the numerical simulation of the proposed geared rotor AMB system was experimentally verified by a laboratory test rig.

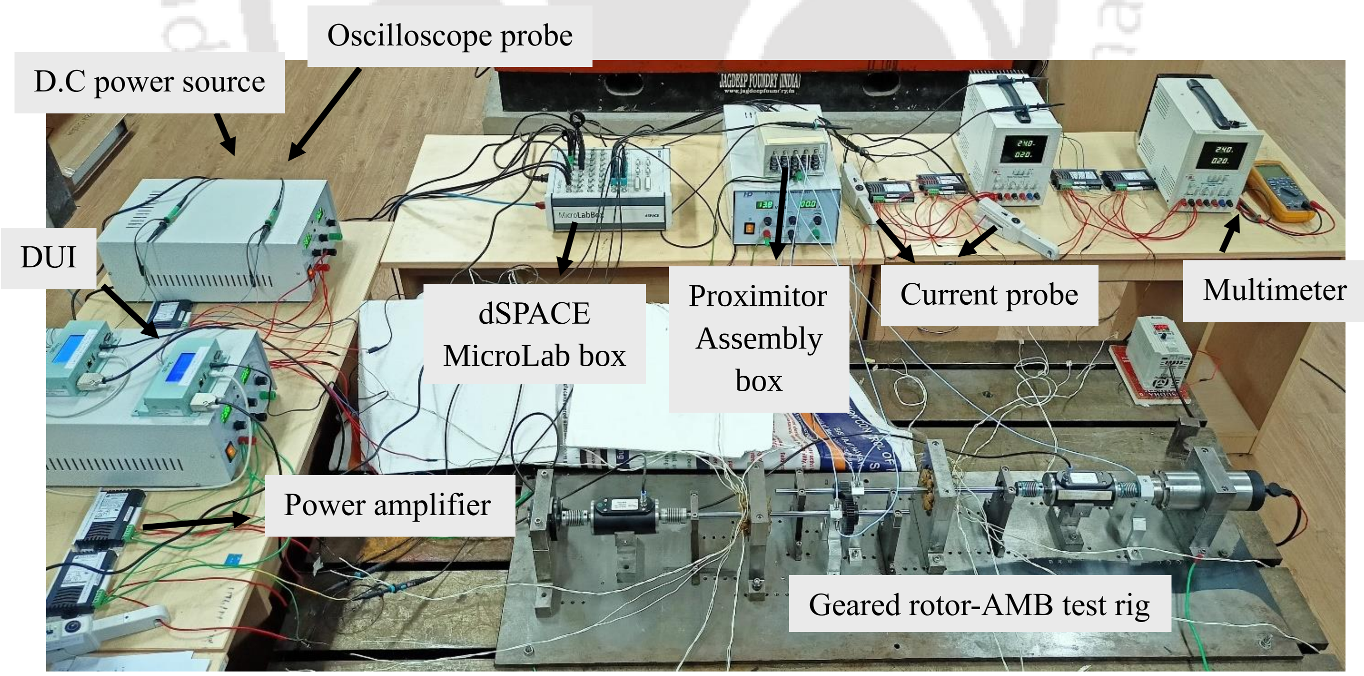



**Figure 4** Control Architecture of Experimental Rig

The experimental validations confirmed that the proposed transmission error based formulation is accurate and can account for identification of various fault and AMB parameters. During this experiments were conducted for suppressing the vibrations caused by variations due to gear meshing faults. A classical PD controller was used to achieve the desired control of the geared rotor by magnetic actuators working in differential driving mode. With a feedback of the displaced rotor position, the controller values were adjusted suitably to achieve the desired stiffness and damping characteristics of the AMBs.

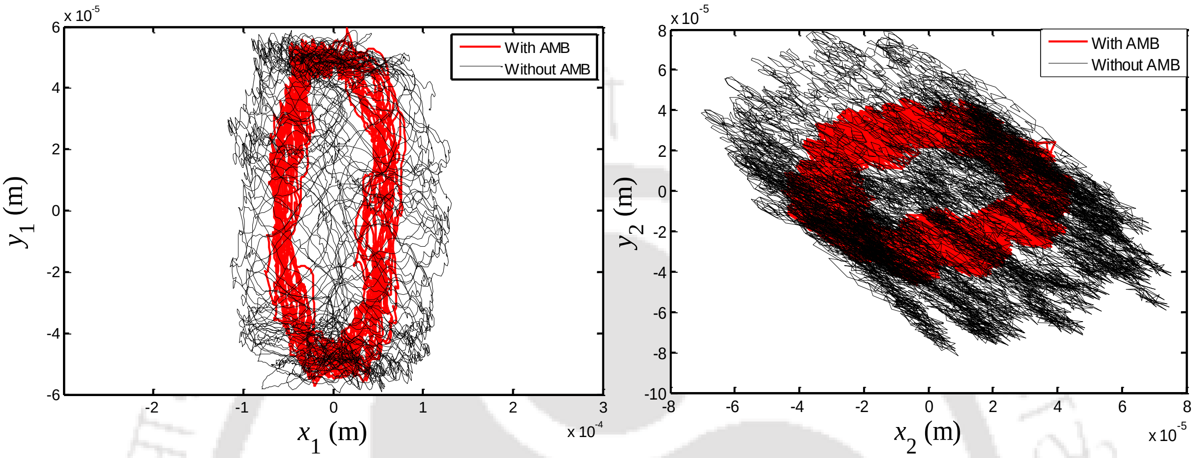



**Figure 5** Comparison of orbit plot after AMB control (a) Input end (a) Output end

Further, the experimental signals of rotor vibrational displacement and AMB current signals, were utilized to validate the numerical model of the identification algorithm. The fault parameters, such as mesh damping, eccentricity with phase, mesh stiffness, mean and variable transmission error with phase and AMB parameters associated with the test rig were estimated.

## 4.1 Main Contribution of the Research Work

1. Different Mathematical models of spur geared rotor system comprising of effects of gyroscopic moments, gear mesh deformation, runout error, dynamic transmission error integrated with active magnetic bearings was developed. Based on the proposed model, linear equations of motion have been derived using Lagrange's principle and the vibration analysis were conducted.

2. Transmission error was modeled as an asymmetric TE, which is the sum of mean and fluctuating value as a Fourier series function. This was useful to obtain the full spectrum responses containing both multiple forward and backward whirl frequency components and phase information.

3. With the help of active magnetic bearings significant amount of geared rotor transverse vibrational displacement are suppressed considering effects of unbalance, gear runout error and variable

transmission error. The active control was done quite effectively with a closed loop PID controller numerically and later demonstrated experimentally.

4. The transverse vibrational amplitude (m) versus gear mesh frequencies (Hz) plot using full spectrum was checked up to 5X gear mesh frequencies and from numerical simulation it was found to get attenuated at all the gear mesh frequencies.

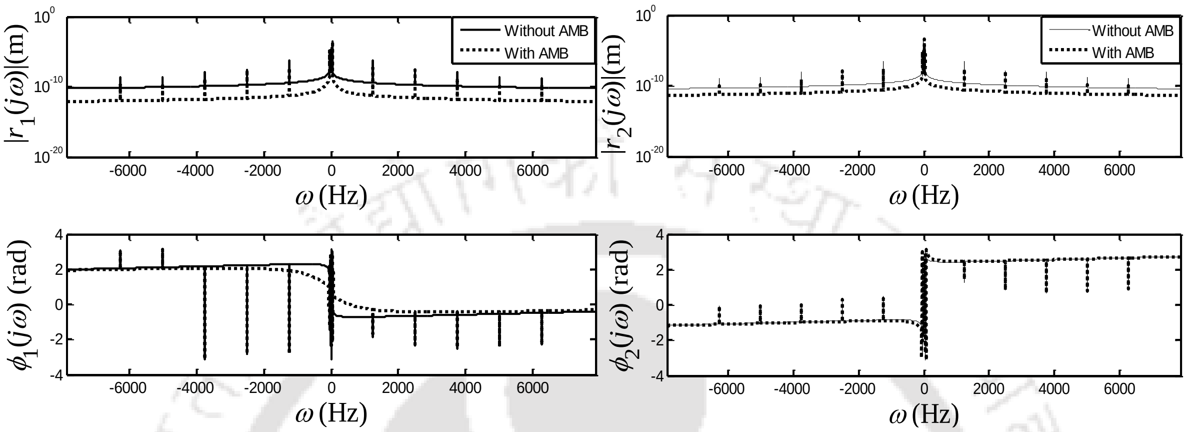



**Figure 6** Full spectrum response generated at $\omega_p = 60\text{Hz}$ , $\omega_g = 30\text{Hz}$ , $\omega_e = 1500\text{Hz}$ (a) Amplitude and phase of complex translational displacement for input shaft (b) Amplitude and phase of complex translational displacement for output shaft

5. Identification algorithm was developed using the regression method taking different types of forced vibration cases i.e., transverse, gyroscopic effect and coupled torsional-lateral dynamics in geared-rotor-AMB system and quantification of faults was done, such as the mesh damping, eccentricity with phase, mesh stiffness, mean and variable transmission error with phase and AMB parameters associated with the test rig. Measurement noise and modelling errors were added to check the robustness of the algorithm which gave favourable results.

6. A test rig was fabricated based on the proposed model to check the feasibility and practical implementation of the proposed model that can control the gear vibration and noise. The numerical results of the proposed model of geared rotor AMB system was compared with that of the responses obtained from the experimental test rig.

7. With a simple linear PD controller the maximum attenuation that could be attained was nearly 50% after fine tuning of the controller gains. Experimental full spectrum responses showed that the amplitude of vibration at the various gear tooth meshing frequencies were reduced quite efficiently except for few harmonics. The experimental results have also yielded about ~4 dB reduction in overall noise owing to vibrations by gear meshing.

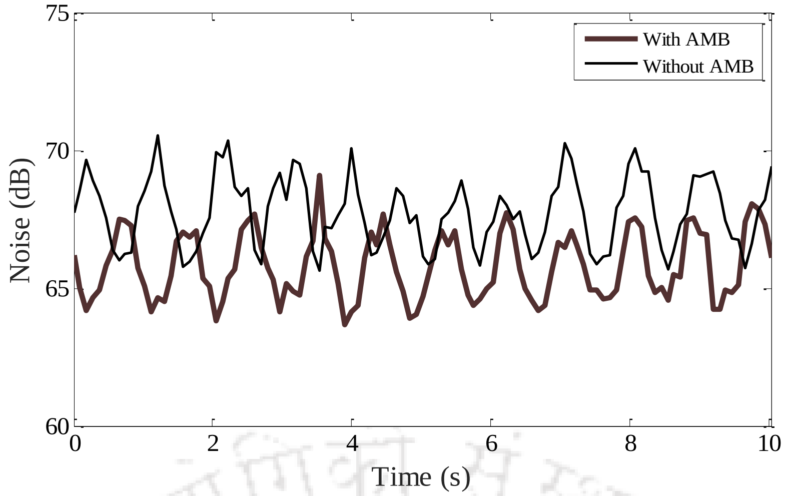



**Figure 7** Comparison of overall reduction in radiated gear noise levels after AMB control.

8. Experimental data collected from the geared rotor AMB test rig was used to validate the developed identification algorithm. It was seen that with the suppression of amplitude of vibration at various gear mesh frequencies the transmission error got lessened.

## 4.2 Limitation of the Present Work

1. Since a radial magnetic bearing acts in radial direction so there was not much effect seen on torsional vibration of the system numerically. The manual tuning process used in this work is cumbersome since separate adjustments has to be performed for different operating speed, and also operation was done under constant loading condition. An improvement can be made by deploying a more robust active control scheme involving an adaptive controller, which can be more effective for reducing the coupled vibrations irrespective of the speed and load variation.

2. The identification algorithms are model-based and developed using a linear mathematical model with constant mesh stiffness and damping. The non-linear factors like friction in meshing and backlash error were neglected. The rolling element bearings were considered rigid. The modelling parameters required in the identification needs to be considered accurately.

3. Due to inadequate sensors, the torsional vibrations could not be measured and the effect of AMBs on gear torsional vibration could not be comprehended experimentally. Due to which the numerical results obtained from the identification algorithm developed in case of coupled torsional-lateral vibration could not be validated experimentally.

4. All the identification algorithms require measurements in two orthogonal directions. In reality, the measurement locations on the shaft may not be accessible because of other mountings over the shaft.

## 4.3 Recommendation for Future Work

Some recommendations to extend the modeling approach and design of the experimental set up follow from the presented research:

1. In the current study simple modeling approaches were used for initial estimations. More advanced modeling of the geared rotor AMB system would be significant in simulating rotordynamic behavior. It is recommended to include nonlinearity like friction in meshing, backlash and examine time varying mesh stiffness, dynamic forces and so on.

2. Besides, an adaptation to operating conditions can be made by an adaptive active control scheme with AMBs in a multi gear transmission system under transient operating conditions with varying load and varying speeds.

3. In order to prepare a model to simulate the experimental setup the support structure should be included. In the present research, equivalent support models consist of springs and dampers depicting shafts, gears but bearing forces were excluded. It is suggested to investigate the whole system with a detailed finite element modeling and identification of support parameters to improve the accuracy of the model.

4. In the present research an experimental setup has been designed. As an improvement to the current experimental setup, the drive system and bearings that operate at higher speeds can be investigated. In this way gyroscopic effect on the stability of proposed geared rotor-AMB system at higher speeds can be examined experimentally.

5. Helicopter cabin noise reduction is a serious concern for designers. On-board noise measurements highlight that the prominent contributions of main are located in the frequency range of maximum human ear sensitivity (between 1000 Hz and 5000 Hz). With active control of gear mesh vibrations, the results can be used for active noise control which can have a great significance in reducing the helicopter cabin noise.

6. Under impact load conditions, an adaptive control method for dynamic load suppression based on torque compensation can be proposed. The key design parameters that influences the system dynamic performance such as stiffness of axles, inertia, etc., can be identified for further enhancement in vibration suppression and shock resistance.

7. Assembly or mounting errors like if the shafts are not perfectly parallel, misalignments arise and the contact zones between the mating teeth can be significantly altered. This can lead to substantial amount

of gear meshing error. Thus, the present analysis can be extended by considering the effect of different types of coupling misalignment on gear transmission error.

8. Other research topics may include determining gear teeth crack initiation points, crack propagation path, and evaluation of various fault growth indicators using laboratory vibration signals and comparing them with field vibration signals.

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# Publications

## Journal Publications

1. Majumder, G., Tiwari, R., " Transverse Vibration of Geared-Rotor Integrated with Active Magnetic Bearings in Identification of Multiple Faults. " **ASME Journal of Dynamic Systems, Measurement, and Control,** September 2021; 143(9): 091003.

2. Majumder, G., Tiwari, R., " Application of Active Magnetic Bearings in Control and Estimation of Geared-Rotor Faults in High Speed Offset Spur Gear Transmission System. " **Mechanical Systems and Signal Processing**, Vol. 176, 15 August 2022, 109113. ISSN 0888-3270,

3. Majumder, G., Tiwari, R., " Experimental Study on Vibration Control of Spur Geared Rotor System Using Active Magnetic Bearings. " **Journal of Sound and Vibration**, Vol. 532, 18 August 2022, 117005, ISSN: 0022-460X.

## Conference Publication

1. Majumder, G. and Tiwari, R., 2019, "Vibration Control of Spur Geared Rotor Systems with Transmission Errors by Active Magnetic Bearings". **ASME Power Transmission and Gearing Conference**, paper IDETC2019-97176, V010T11A017; 9 pages, Anaheim, CA, USA, Aug 18-21, 2019. Conference Paper Presented, 08/2019.