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Dynamic Response Analysis of Misaligned Rotating Systems in Water Pumping Stations Under Uncertainty

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ABSTRACT

Rotating systems are essential components in various machinery and equipment, such as pumping stations, where precise alignment is crucial for optimal performance. Couplings, which connect motors to driven shafts, must balance rigidity and flexibility to meet dynamic operational demands. However, due to their flexibility, these systems are susceptible to vibrations and misalignments, often introduced during installation. This study addresses the uncertainty in the dynamic response of a rotating system composed of a motor, a pump, shafts, and two flexible couplings. The developed model includes three bearings and 12 degrees of freedom. The system's dynamic behaviour is analysed in both aligned and misaligned conditions to assess the impact of misalignment on vibration response. The robustness analysis is conducted in two phases: first, by evaluating the uncertainty associated with the alignment defect, and second, by examining the uncertainty in the torsional stiffness of the coupling.

To achieve this, the study employs the probabilistic Polynomial Chaos approach, validated using the Monte Carlo method. This combined methodology provides a comprehensive understanding of system uncertainties, enabling the development of strategies to mitigate potential issues and enhance overall reliability.

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INTRODUCTION

Rotating systems are essential components in various types of machinery and equipment, requiring high precision for optimal performance. This precision is often ensured through careful human intervention. Couplings play a crucial role in these systems, providing the necessary balance between rigidity and flexibility to meet diverse operational demands (Ramteke and Metha, 2021 and Tuckmantel, 2019). In applications such as pumping stations, couplings connect the motor to the driven shaft, offering mechanical adaptability that accommodates a certain degree of misalignment. This capability enhances system reliability and reduces the risk of mechanical failures caused by misalignment. Achieving and maintaining optimal shaft alignment is challenging due to multiple factors. Misalignments can result from manufacturing and assembly tolerances, the precision of metrology instruments, and operational deflections caused by thermal expansion and structural distortions. Additional contributing factors include foundation compliance, system vibrations, bearing wear, and operational forces (Klebanov, 2007). These various causes highlight why misalignment is widely recognized as the second most common source of faults in rotating machinery, as noted by Muszynska (2005). Despite its significance, research on the dynamic response of misaligned rotors remains relatively limited (Adams, 2009). Mancuso provides several explanations for this, emphasizing that the low cost of couplings, typically accounting for less than 1% of the total equipment cost, often leads to their undervaluation (Mancuso, 1999). The identification of shaft misalignment is consistent with findings from previous studies (Lee, 2021 and Ghorbel, 2021), which indicate that this defect amplifies vibrations and introduces a distinct harmonic component at twice the rotational frequency in the signal spectrum.

Understanding the nature of misalignment and its associated vibration signatures is crucial for model-based diagnostics. Bachschmid and Pennachi (2000) identified misalignment by minimizing the least squares difference between measured and theoretical bearing loads. Similarly, Bachschmid et al. (2002) applied this method to diagnose multiple faults in rotors, focusing on minimizing bearing displacements. Sekhar (2003, 2004) utilized a flexible coupling model, specifically designed for angularly misaligned shafts. Jalan and Mohanty (2009) also employed this model, incorporating the first two harmonics for restoring forces, while Li et al. (2009) considered only the second harmonic for forces and moments induced by transmitted torque. Regarding disc couplings, the available literature is relatively limited. Dewell and Mitchell (1984) developed a theoretical model to describe the moments in disc couplings and conducted experimental investigations to assess the effects of angular and parallel misalignments on the amplitudes of the first, second, and fourth harmonic frequencies. Redmond (2010) further expanded this research by accounting for the angular stiffness anisotropy of flexible couplings, selecting a value representative of a disc coupling. Numerous research works have explored the modelling and studying of flexible couplings, as documented extensively in the literature (Tadeo, 2011, Hammami, 2019 and Bouslema, 2022). To further enhance the understanding of misalignment effects, it is essential to incorporate uncertainty analysis into these studies. Uncertainty in parameters such as misalignment severity and torsional stiffness can significantly impact the dynamic response of rotating systems. By integrating methods like the deterministic Monte Carlo (MC) simulations (Papadopoulos, 2001 and Marseguerra, 2009) and Generalized Polynomial Chaos (GPC) expansions (Garoli, 2020 and Guerine, 2016), we can quantify the variability in system behaviour due to these uncertainties. This approach not only provides a more comprehensive understanding of system robustness but also helps in developing more reliable and resilient mechanical designs. Exploring these uncertainties allows for a better prediction of system performance under varying operational conditions, ultimately leading to improved maintenance strategies and reduced downtime.

This paper is structured as follows: Section 2 presents the dynamic model of the pumping station in detail, along with the characterization and modelling of parallel misalignment defects. Section 3 introduces the methods used to incorporate uncertainties into the developed model. The simulations and numerical results are discussed in Section 4. Finally, conclusions are drawn based on the obtained results.

PUMP STATION MODELLING

Model description

Pumping stations play a crucial role in distributing water from dams to populated areas. These systems consist of three interconnected subsystems working together to achieve this objective. The motor generates mechanical rotational energy, which drives the centrifugal pump through a flexible coupling transmission system. This system allows for motion transmission while accommodating potential misalignments. However, due to their operational characteristics, pumping stations are among the most vibration-prone facilities. To address this issue, we develop a model incorporating two flexible couplings, as illustrated in Fig. 1.

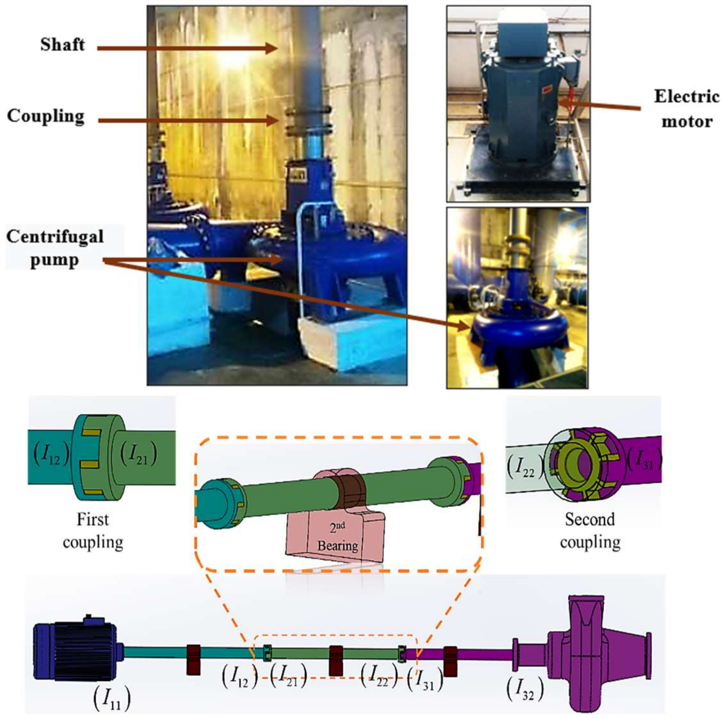

Fig. 1. Modelling of a pump station with coupling

The model is allocated across three blocks in the following manner: The first block is characterized both by the inertia of the rotating motor elements I_{11} and the first part of the first coupling I_{12}, while the second block includes the inertia of the second part of the first coupling I_{21} and the inertia of the first part of the second coupling I_{22}, respectively. The third block incorporates the inertia of the second part of the second coupling I_{31} together with the inertia of the centrifugal pump I_{32}.

The model has 12 degrees of freedom distributed as follows: two torsional degrees of freedom on each block - the first (θ_{11}, θ_{12}), the second (θ_{21}, θ_{22}), and (θ_{31}, θ_{32}) on the third, as well as two linear degrees of freedom in the x and y directions for each block bearing, as illustrated in Fig. 2.

Generally, a negligible mass is assumed for axes with torsional rigidity K_θ, which are supported by bearings. These axes exhibit linear displacements along the x- and y-axes due to a modelling approach based on springs. the linear stiffness of the bearings is modelled by K_x and K_y. The elastic coupling is represented using the Nelson and Crandall model (2019), which incorporates both translational stiffness (K_{xc}, K_{yc}) and torsional stiffness K_c.

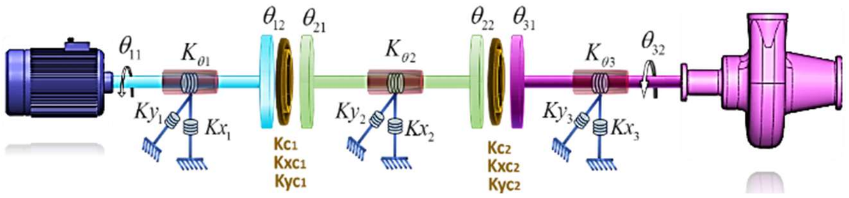

Fig. 1. Dynamic model of pumping station (12 *dof*)

Equation of motion

Using Lagrange's formalism, the equation of motion for the system, dependent on the generalized coordinate vector $\{q\}$ with 12 degrees of freedom (DOF), is expressed as follows:

$$[M]\{\ddot{q}\}+[K]\{q\}=\{F_{ext}\} \tag{1}$$

$$[M]\begin{Bmatrix}\ddot{\theta}_{11}\\ \ddot{\theta}_{12}\\ \ddot{\theta}_{21}\\ \ddot{\theta}_{22}\\ \ddot{\theta}_{31}\\ \ddot{\theta}_{32}\\ \ddot{x}_1\\ \ddot{y}_1\\ \ddot{x}_2\\ \ddot{y}_2\\ \ddot{x}_3\\ \ddot{y}_3\end{Bmatrix}+[K]\begin{Bmatrix}\dot{\theta}_{11}\\ \dot{\theta}_{12}\\ \dot{\theta}_{21}\\ \dot{\theta}_{22}\\ \dot{\theta}_{31}\\ \dot{\theta}_{32}\\ \dot{x}_1\\ \dot{y}_1\\ \dot{x}_2\\ \dot{y}_2\\ \dot{x}_3\\ \dot{y}_3\end{Bmatrix}=\{F_{ext}\}$$

The mass matrix [M] is derived from the inertial properties of various components and the mass of each individual block. The stiffness matrix [K] combines the torsional stiffness parameters of the shafts, as well as the x and y stiffness of the bearings, in addition to the stiffness of the coupling, whether it is torsional or translational. For the external forces vector $\{Fext\}$, it depends on the input torque from the motor, the output torque related to the centrifugal pump, as well as the force applied to each bearing resulting from the instantaneous displacements at the couplings due to misalignment defects.

The parameters values of the pump station with flexible coupling model are taken according to the model of Ghorbel et al. (2021). Table 1 define them.

Characterization and modelling of misalignment defect

Misalignment is one of the main causes of reduced equipment service life.

It occurs when either two shafts connected by a coupling or two bearings supporting the same axis are not perfectly aligned. This issue is as common and significant as imbalance. The causes of misalignment include improper mounting, thermal expansion, or shear forces on the bearings.

The two rotors can have angular misalignment at the coupling, radial misalignment (parallel), or a combination of both. In this paper, we focus on the modelling and study of radial misalignment. If the centerlines of the shafts are parallel but do not intersect, it causes a parallel misalignment fault. Figure 3 shows the movement estimation for this type of misalignment. In this scenario, the bearing of the receiving shaft undergoes compressive stresses in the (*xz*) plane and bending stress in the (*xy*) plane.

This article specifically focuses on the radial faults of the couplings related to the uncertainty surrounding the fault itself, as well as the uncertainty associated with the torsional stiffness of the coupling.

Parameters	Values
Rotational speed (RPM)	$N = 3000$
Torsional shaft stiffness (Nm/rad)	$K_\theta = 10^5$
Bearing stiffness (N/m)	$K_x=K_y=10^8$
Inertia of the coupling (Kg m^2)	$I_{c1}=I_{c2}=4.10^{-3}$
Mass of the coupling (Kg)	$m_{c1}=m_{c2}=4.5$
Coupling torsional stiffness (Nm/rad)	$K_{c1}=K_{c2}=352$
Coupling translational stiffness (N/m)	$K_{xc}=K_{yc}=462.10^4$

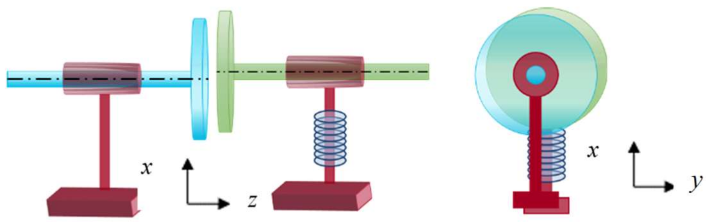

Fig .3. Road profile estimation

Misalignment results in external forces being exerted on the bearings. As a result, the stiffness of the bearings and the first coupling will be represented by a periodic variation in the (*xy*) plane. This variation is mathematically expressed by the equation k(t):

$$k(t) = k_0 + \Delta k \sin(2\omega t) \quad (2)$$

Δk represent the stiffness variation which depend on the amount of misalignment.

In this situation, the force applied by the bearing exhibits periodicity in the radial direction, occurring at a frequency double that of the rotation frequency of the 2ω motor shafts (Fig .4).

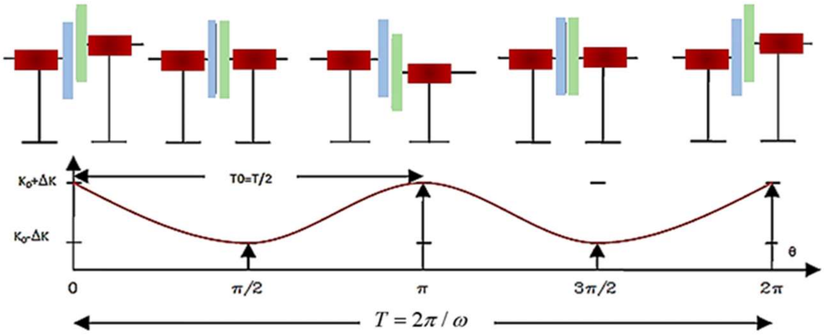

Fig 4. Bearings behaviour for parallel misalignment

UNCERTAINTY METHODS

Uncertainty analysis is a crucial aspect of evaluating the reliability and performance of engineering systems. It involves quantifying the impact of uncertain parameters and inputs on the system's behaviour.

The flowchart in Fig. 5 classifies the different methods used to propagate uncertainties in engineering and scientific research. These methods are grouped into four primary categories: Deterministic, Probabilistic, Possibilistic, and Experimental Design Method. Each category encompasses specific techniques that are suited to addressing various types of uncertainties and system behaviours.

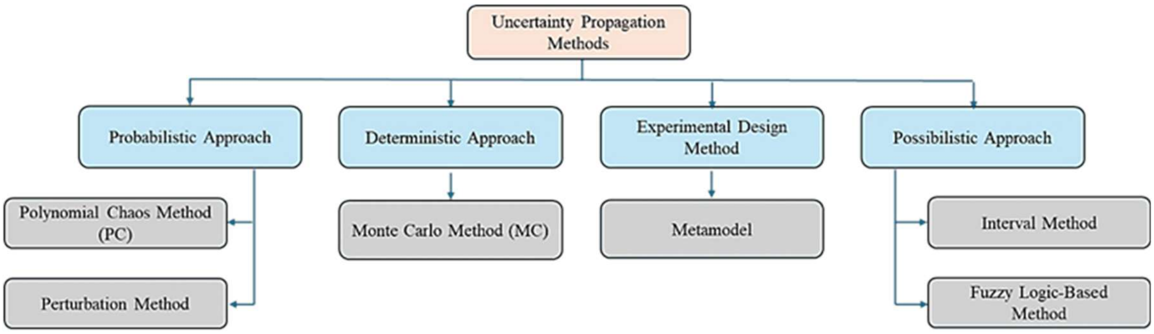

Fig 5. Uncertainty propagation methods

Monte Carlo (MC) and Polynomial Chaos (PC) are the most commonly used methods for probabilistic analysis, offering a robust framework for quantifying uncertainties. Possibilistic methods, such as Interval and Fuzzy Logic, are particularly useful when probabilistic information is either unavailable or insufficient. Experimental Design and Metamodeling techniques, on the other hand, help reduce computation time by providing useful approximations without the need for exhaustive simulations. The selection of the appropriate method depends on factors such as the complexity of the system, the type of uncertainty involved, and the computational constraints of the analysis.

In this study, we focus on two primary approaches to conduct uncertainty analysis: the probabilistic Generalized Polynomial Chaos (GPC) method and the Monte Carlo (MC) sampling method.

Monte Carlo method

The MC method is a stochastic technique that relies on random sampling to estimate the statistical properties of a system's response. By generating a large number of random samples of the input variables, the MC method simulates the system's behaviour under varying conditions. This approach is straightforward and versatile, capable of handling complex systems and nonlinearities. It does not require prior knowledge of the specific forms of the input distributions.

The MC method is effective for verifying results obtained from other analytical methods and for examining the extreme values and the tails of the distribution, which are critical for risk assessment and safety evaluations.

This approach involves functions of the following form (Hadj Kacem, 2022):

$$X = G(f) \tag{3}$$

where G indicates the model adopted, f is the vector of random variables (uncertain input parameters), and X is the vector of estimated out outs provided.

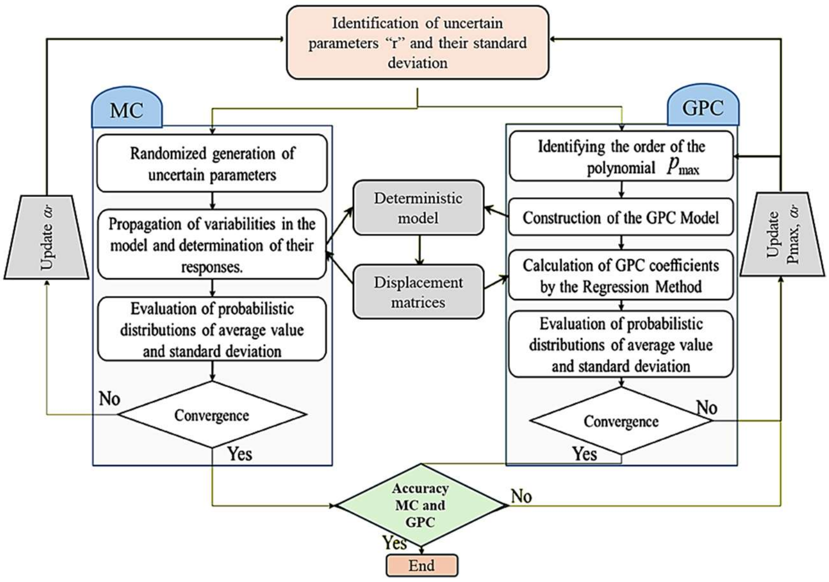

Fig 6. Flowchart of the numerical algorithm

Polynomial chaos method

The probabilistic method is based on the projection of random variables in the probability space according to Wiener's homogeneous chaos theory by a spectral expression, called generalized polynomial chaos (GPC) (Dammak, 2019). Generalized Polynomial Chaos theory (GPC) (Azrar, 2019) states that a second-order model V(ξ) can be decomposed into a convergent series of polynomial functions (mean-square terms) as follows:

$$Vi(x, \xi) = \sum_{j=0}^{\infty} \overline{v_j} \emptyset_j(\xi)\,; \quad \xi = (\xi_1, \xi_2, \dots) \tag{4}$$

where $\phi_j(\xi)$ refer to orthogonal polynomials inside the unrelated random factors ξ with a given random density of probability W(ξ).

$$\langle \emptyset_i | \emptyset_j \rangle = \int \emptyset_i \emptyset_j W(\xi) d\xi = \begin{cases} 0 & if \quad i \neq j \\ \langle \emptyset_i, \emptyset_j \rangle & if \quad i = j \end{cases} \tag{5}$$

In line with Askey's scheme, the use of Legendre polynomials is particularly suitable for capturing uniform uncertainties (Azrar, 2019 and Luo, 2018), Indeed, the random eigenvalues have uncertainties that are provided by:

$$V_i(x, \xi) = \sum_{j=0}^{Np} \overline{V}_{i,j}(x) \Phi_j(\xi) \;; \qquad \xi = (\xi_1, \xi_2, \dots)$$

(6)

A finite number Np is used which changes according to the order of the P=max(r_j) polynomial and the stochastic dimension which reflects the number of uncertain parameters. To determine the $\overline{V}_{i,j}$ coefficients, we employed the non-intrusive approach. This method is highly efficient because it only requires simulations for specific samples of random variables (Luo, 2018). One of the primary methods within the non-intrusive approach is the regression method, which was used in this paper (Cheng and Lu, 2018).

iscrepancy between the solution of the random model and its approximation in the Generalized Polynomial Chaos basis.

Numerical algorithm

This study outlines an innovative hybrid uncertainty analysis technique that combines Monte Carlo (MC) simulations with generalized polynomial chaos (GPC) techniques (Fig. 6). The approach addresses the computational challenges of traditional MC methods, which require many iterations to accurately capture uncertainty effects, making them expensive. By integrating GPC, which employs orthogonal polynomials to efficiently represent random variables, it enables a more effective handling of uncertainties. This hybrid approach proves particularly advantageous in modeling complex systems with dynamic behaviour and uncertainties, such as misalignment and torsional stiffness in pumping systems.

NUMERICAL SIMULATIONS

Dynamic behavior without uncertainties

Analyzing the dynamic behavior of a rotating system, such as a water pumping station, is of paramount importance for several reasons. First, this analysis helps to understand the vibrations and dynamic forces acting on the system, thereby aiding in the prevention of failures and extending the lifespan of its components. Through the early detection of imbalances or coupling faults, corrective measures can be implemented before these issues lead to costly production stoppages or major repairs. Additionally, understanding the dynamic behavior helps optimize the energy efficiency of the station, ensuring the system operates harmoniously and without unnecessary overloads. Finally, a thorough study of dynamic behavior is indispensable for ensuring the reliability and efficiency of the system.

In this study, the simulations were carried out using a parallel misalignment value of $DE = 5.10^{-3} m$.

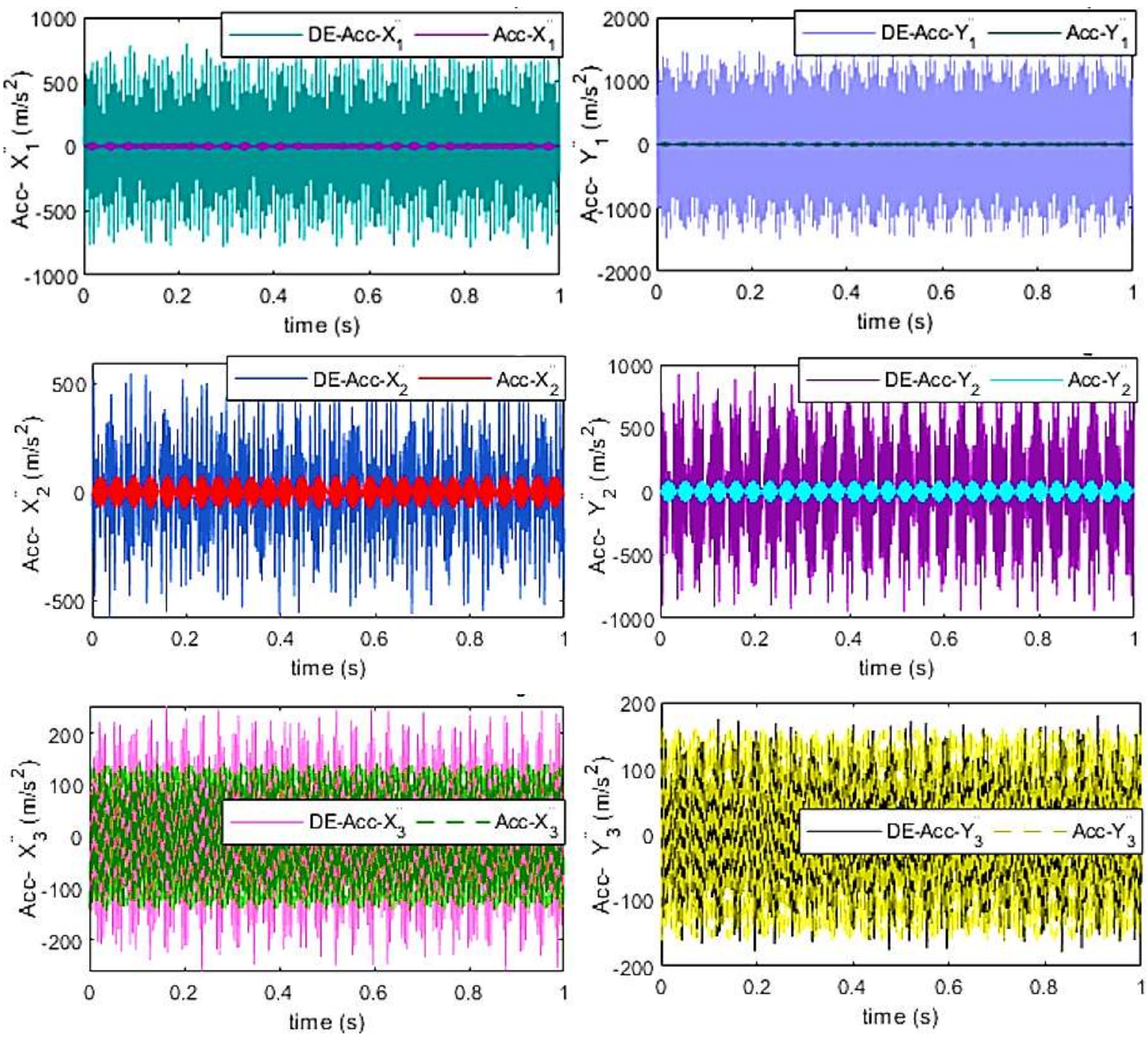

Fig. 7. Linear accelerations with and without misalignment defect

Fig. 7 shows the dynamic response of the linear accelerations of the three bearings, both with and without the presence of a fault. In the fault-free case, it can be observed that the vibration level of the first two bearings is higher than at the bearing near the pump. This result suggests that the two elastic couplings act as vibration absorbers. Another notable observation is that the amplitude along the y-axis is higher and particularly significant at the first two bearings. In the presence of a defect, a comparison of the linear acceleration displacements along the three axes was conducted. The difference in behaviour due to misalignment is very significant compared to the fault free condition, particularly noticeable at the first and second bearings. The percentage of amplitude increase depends on the position of the bearing and the direction of vibration. On the other hand, the comparison of angular displacement behaviour showed no difference between the two simulations (Fig. 8).

The influence of the misalignment fault is very negligible. It can also be observed that the amplitude of angular vibration is greater at the shaft connected to the pump.

Fig. 9 shows the displacement spectra of the second bearing in the x and y directions for two cases: without and with misalignment. A vibration in the radial direction of the component indicates a peak corresponding to twice the rotation frequency f_r (50 Hz), with amplitudes greater than the peak corresponding to the shaft rotation frequency (Lee, 2021 and Reddy, 2015). The other peaks in the spectra (in both cases) correspond to the system's eigenfrequencies. The same phenomenon occurs in the axial direction, but it is less pronounced than in the radial direction. this result of the identification of the misalignment of the shaft conforms with the interpretations of the work refs. (Lal, 2021, Kumar, 2023, Wu, 2020 and Wng, 2019). They show that with the presence of this type of defect, there will be an amplification of vibrations and the exceptional appearance of a harmonic component at twice the rotational frequency in the signal spectrum.

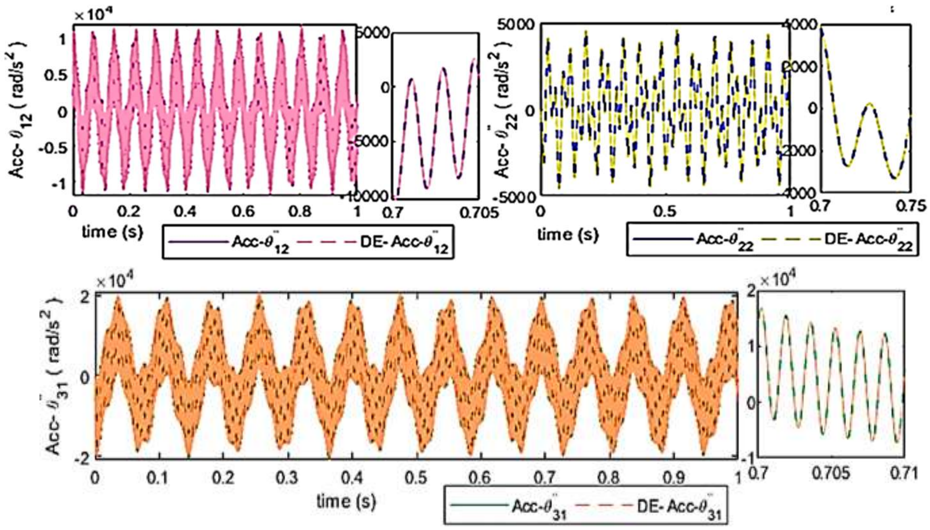

Fig. 8. Angular accelerations with and without misalignment defect

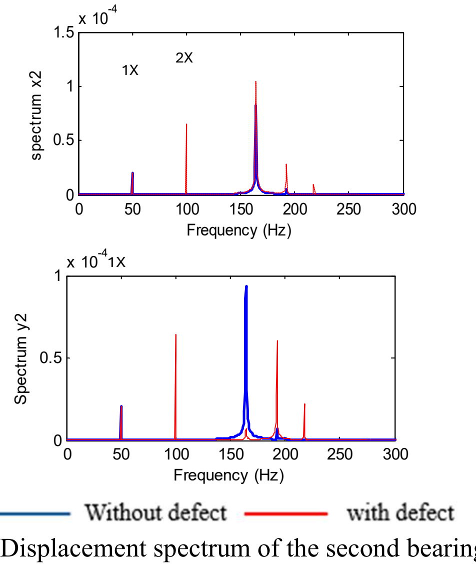

Fig 9. Displacement spectrum of the second bearing along (a) *x* direction, (b) *y* direction

Dynamic behavior in the presence of uncertainty parameters

To assess the robustness and reliability of the proposed system, an uncertainty analysis is carried out by considering variations in two critical parameters: the misalignment fault and the torsional stiffness of the coupling. This investigation aims to evaluate the dynamic performance of flexible couplings in rotary motion transmission systems under realistic, non-ideal conditions. These two parameters are particularly influential, as misalignment can induce significant linear vibration amplitudes, while torsional stiffness directly affects angular displacement behaviour, both of which are crucial to the system's overall stability and operational safety. The uncertainty propagation is analysed using two complementary approaches: the deterministic (MC) method, based on 1000 simulations, and the second-order (GPC) method, which offers a more computationally efficient alternative.

Misalignment defect value

Developing or installing a pumping station requires human intervention, particularly in tasks such as floor preparation and securing various components of the station (motor, bearings, pump), as illustrated in Fig. 1. This process can introduce uncertainties related to misalignment. In this section, we will focus on the uncertainty of misalignment, characterized by a mean value 5.10^{-3}m and a standard deviation of the defect (*DE*) of 20%. Figure 10 shows the curves of the mean linear acceleration values at the first and third levels. Several scenarios for the default value were studied. Comparing the results of the two methods addressing uncertainty, we observe a strong correspondence between the two curves. Additionally, these curves are almost consistent with the deterministic case using the Newmark resolution method without the presence of uncertain parameters. The most noticeable curve is that of the maximum value obtained from the Monte Carlo (MC) method. Therefore, it is crucial to be particularly cautious with high values of non-eccentricity.

Torsional stiffness of the coupling

After establishing the uncertainty of misalignment, we proceeded to evaluate the torsional stiffness of the coupling under misalignment conditions. This stiffness primarily depends on the intermediate element of the coupling (the yellow spring in Fig. 2). Figure 11 displays the angular accelerations of the three shafts: the shaft linked to the motor, the shaft between the two couplings, and the shaft linked to the pump. This aims to comprehensively understand the system's behaviour and how it is influenced by uncertainties in the coupling's stiffness.

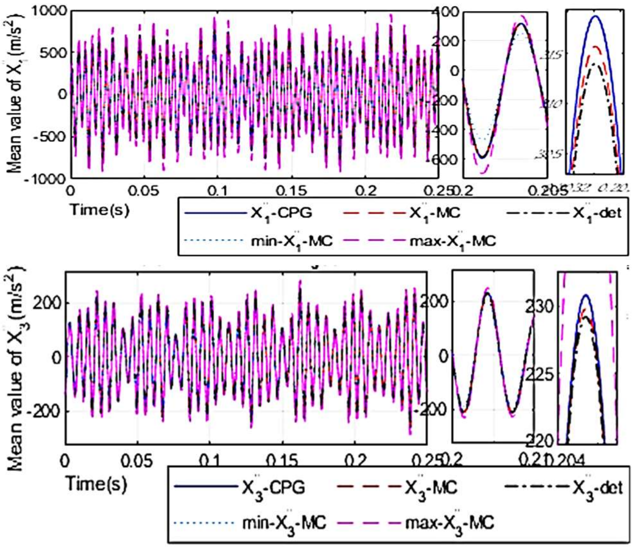

Fig. 10. Mean value for σ_{DE}=20%

The MC and GPC methods show the best agreement in the curves representing the average and standard deviation of angular displacement acceleration across the three axes, assuming a 10% standard deviation in the torsional stiffness of the coupling. From the figure, we observe a satisfactory correspondence between these methods and the deterministic curve.

rotational frequency of the shafts, especially in the presence of misalignment faults. Therefore, uncertainty in torsional stiffness has implications for the dynamic behaviour of water distribution systems. Moreover, it is clear that the uncertainty in misalignment directly impacts the linear dynamic response, while uncertainty in the torsional stiffness of the coupling affects torsional fluctuations.

Results discussion

The analysis of results shows that a misalignment of 0.5 mm leads to a significant increase in lateral vibration amplitudes, particularly at the bearing located nearest to the coupling. Furthermore, the spectral analysis in both the *x* and *y* directions; under aligned and misaligned conditions, reveals the emergence of a frequency peak at twice the rotational speed ($2 \cdot f_r$ = 100 Hz), indicating the characteristic signature of parallel misalignment. In the case that the uncertain parameter is the misalignment value, the developed GPC-based model demonstrates an accuracy of R^2= 92% compared to Monte Carlo simulations while reducing computational costs by 80%, thus providing a practical tool for industrial uncertainty quantification. When the torsional stiffness of the coupling is considered as the uncertain parameter, the developed GPC-based model achieves a 96% accuracy relative to Monte Carlo simulations, while reducing computational costs by 82%. This highlights its effectiveness as a practical tool for industrial uncertainty quantification.

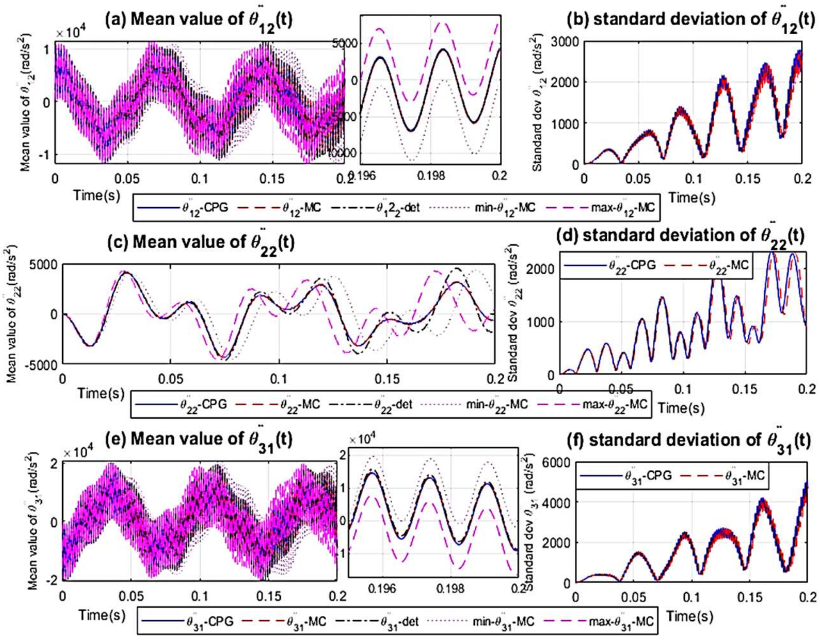

Fig .11. Mean value for σ_{kc}=10%

However, at the second shaft, there is a noticeable phase shift between the uncertainty simulation curves and the curves of maximum and minimum values. This suggests that coupling stiffness can influence the

The accuracy of the Generalized Polynomial Chaos (GPC) model was quantified using the coefficient of determination (R^2) against Monte Carlo (MC) reference simulations. The R^2 metric compares predicted vibration amplitudes (x_{GPC}) with MC results (x_{MC}) across all frequencies:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(x_{MC}^{i} - x_{GPC}^{i})^2}{\sum_{i=1}^{N}(x_{MC}^{i} - \bar{x}_{MC})^2} \quad (7)$$

where x_{MC} and x_{GPC} represent the MC and GPC-predicted amplitudes respectively, and $\bar{x}_{MC}$ is the mean of MC results.

The results of this study provide valuable insights for improving fault detection accuracy in predictive maintenance, optimizing the operation of rotating machinery, and enhancing the reliability of machine design.

- Predictive Maintenance Planning

Uncertainty analysis helps identify the most critical parameters affecting system performance. Maintenance teams can use this information to prioritize inspections and schedule preventive maintenance before failures occur or disrupt machine operation.

- Enhanced Condition Monitoring

This study highlights the impact of misalignment on vibration characteristics. By integrating our findings into real-time monitoring systems, vibration thresholds can be defined more precisely, reducing false alarms, and increasing the reliability of fault detection. For instance, an increase in vibration levels may not always indicate a fault but it could result from variations in uncertain parameters. Understanding these variations helps in distinguishing actual failures from normal operational fluctuations.

- Design Optimization for Reliability

The analysis provides a deeper understanding of the influence of uncertain parameters, such as coupling stiffness, on system behaviour. Engineers can leverage these insights to optimize system design by selecting more robust components that minimize sensitivity to parameter variations. Additionally, regular assessment of component properties is essential to ensure they remain within safe operational limits, further enhancing system reliability and performance.

CONCLUSION

The reliability of rotating systems with flexible couplings is a crucial consideration in the development of pumping stations. These systems play a vital role in ensuring the robustness, safety, and performance of water distribution in dam systems, while also managing maintenance without interruptions or unexpected issues. To this end, a new dynamic model of a pumping station, primarily consisting of a motor, two flexible couplings, and a centrifugal pump, was developed. The vibration behavior of the system was then analyzed both in the fault-free case and with misalignment at the coupling. The results indicate that a 0.5 mm misalignment causes a notable increase in lateral vibration amplitudes, especially near the coupling. Spectral analysis in both x and y directions reveals a distinct peak at twice the rotational frequency, serving as a clear indicator of parallel misalignment.

This paper also examines the dynamic behaviour of the pumping station system by considering the uncertainty of two significant parameters: the misalignment defect value and the coupling torsional stiffness. This process is carried out using two approaches: the Monte Carlo method (MC), which provides the fundamental results, and the probabilistic Generalized Polynomial Chaos method (GPC), which employs a regression approach. The MC simulation method is used to validate the results obtained from the GPC method, which describes the propagation of parameter uncertainties. The results obtained from the two methods addressing uncertainty show a strong correspondence between them. The developed GPC-based model demonstrates an accuracy ranging from 92% to 96% compared to Monte Carlo simulations, while reducing computational costs by nearly 80%, making it a practical and efficient tool for industrial uncertainty quantification. Another finding is that misalignment has a significant effect on linear displacements, while torsional stiffness affects angular displacements. Additionally, a strong correspondence between these methods and the deterministic curve (without uncertainty) is observed. However, at the second shaft, there is a noticeable phase shift between the uncertainty simulation curves and the curves representing the maximum and minimum values. This study demonstrates the significant impact of the uncertainty of alignment fault and coupling torsional stiffness on the system's dynamic response. This study suggests three key directions for future research: extending the uncertainty analysis to additional parameters; developing an instrumented test bench to experimentally validate misalignment responses under controlled conditions; and implementing hybrid intelligent diagnostics that combine physical models with artificial intelligence for real-time monitoring. Together, these advancements would significantly enhance the predictive maintenance capabilities of rotating systems.

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