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Article

Lifecycle cost optimization of vibration mitigation in rotating machinery: Integrating measured transmissibility, finite element modeling, and downtime cost scenarios

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Abstract: Rotation devices play a vital role in industrial plants, where vibrations significantly affect efficiency, reliability, and the overall cost of operation. Vibrations cause wear and tear, failures, and high maintenance time, but previous studies have focused on machine efficiency without including financial factors. This paper provides a solution to this problem by developing an integrated approach to optimizing lifetime cost through vibration reduction in rotation devices. A numerical approach was used to quantify and analyse the phenomenon, including experimental measurement, finite element (FE) modelling, and economic analysis. Transmissibility measurement was used to describe vibration dynamics and validate the FE model. The response of the system was correlated to wear and tear, failure rates, and downtime. These factors were then used to formulate a lifetime cost model. The results have shown that there is a strong non-linear connection between the transmissibility factor and the lifecycle cost, where the higher the levels of vibrations, the greater the extent of wear and tear and downtime. The process of optimizing identified the optimum operating point where there is a perfect compromise between the vibration performance and the cost effectiveness. The sensitivity analysis has revealed that the transmissibility is the most significant factor affecting the lifecycle cost.

Keywords: vibration mitigation; rotating machinery; transmissibility; finite element modelling; lifecycle cost; downtime analysis; optimization; reliability engineering

1. Introduction

The significance of rotating machines is inevitable in today's industry settings, where the effectiveness and durability of operations are vital for continued production processes. The functionality of the system depends heavily on its vibratory characteristics, not only serving as a measure of health but also predicting the possibility of future failure. Vibration problems have been correlated extensively with undesirable results, ranging from increased risk of breakdowns to accelerated wear and shorter life of equipment parts [1,2]. Vibrational reduction has thus become a crucial concern in the field of mechanical and reliability engineering. Though significant advances have been made in the area of vibration analysis and vibration control, vibration problems still persist in the systems of rotating machinery. These problems do not just affect the efficiency of the machine but also cause financial losses for the organizations involved due to the costs of repairs and production delays. Previous research has shown that vibrations are responsible for accelerating material fatigue in machines and causing their failure [3, 4]. Though previous research has contributed greatly to our knowledge about mechanical processes, most of it has focused on performance-related aspects and not much on the economic effects of vibration problems.

The current literature has mainly explored the analysis of vibrations using empirical studies, theoretical calculations, and FE modelling. FE modelling has been widely applied to study the dynamics of rotating machines by estimating their responses, stress distribution, and modes [5]. Meanwhile, maintenance engineering has emphasized the role of reliability-centered and condition-based maintenance practices in minimizing failures and improving availability [6, 7]. Additionally, the concept of lifecycle costing has been used to evaluate the economic efficiency of engineering systems [8]. However, these lines of research have followed independent tracks, creating a situation where no attempt was made to account for the relationships between vibration dynamics, system degradation, and economics. In this paper, an integrated framework that incorporates transmissibility measurements, finite element modelling, degradation studies, downtime calculations, and life-cycle cost optimization into one analytical model is proposed. Unlike previous approaches where vibration reduction has been considered only as a technological problem, this work considers transmissibility as a decision parameter that affects not only mechanical behaviour but also economic feasibility. This paper demonstrates how to connect vibration properties with life cycle cost by introducing degradation and downtime analysis into the optimization problem.

While past studies have investigated vibration damping, finite element analysis, wear/loss assessment, downtime, and cost evaluations individually, the combination of these concepts within an optimization approach is lacking. What sets this study apart from previous literature is that the concept of a framework for decisions has been devised, where the variable of transmissibility of the vibrations will tie experimental data, FE results, degradation predictions, downtime calculations, and lifecycle cost minimization into one coherent concept. It should be noted that the study makes no novel contributions in terms of FE analysis or lifecycle costing. Rather, the novelty of the work presented is in the series of computations that allows a vibration mitigation technique to be evaluated in terms of its ability to minimize cost. The paper makes three contributions specifically. Firstly, it develops the idea of transmissibility measurement as a decision-making factor, which relates vibration behaviour with the system response as well as costs. Secondly, it involves integrating the output from finite element modelling with considerations for wear and tear, cost of downtime, and life-cycle cost assessment as opposed to just considering it as mechanical output. Lastly, it looks at vibration control from the perspective of minimizing lifecycle cost.

The key objective of the research study was the development and verification of a lifecycle cost optimization model for reducing vibrations in rotating machinery systems. The study involved the use of experiments, simulations, and economic analysis in a manner that enabled the identification of the operating point that would optimize the cost while maintaining adequate vibration performance. In order to achieve this objective, an iterative process involving experimental testing of transmissibility, finite element modelling of system response, failure and degradation, calculation of downtime, life cycle cost modelling, and optimization of results was undertaken.

2. Literature review

Rotating machinery forms an integral part of any industrial setup and includes equipment like turbines, compressors, and pumps. Reliability and efficiency form some of the most important aspects of such equipment. One of the major problems that affect such rotating machinery is vibrations. Vibration can be regarded as one of the most crucial factors that determine the performance and reliability of any mechanical system. Vibrations lead to instability and deterioration in equipment, thus leading to higher maintenance and operating costs. Previous studies have stressed the importance of vibration analysis in improving the reliability of machinery and extending its operational lifespan [9, 10]. A great deal of research has been conducted on vibration analysis and mitigation measures in rotary machinery systems. Early work in rotor dynamics has been conducted to study the behaviour of rotary shafts when subjected to dynamic loads, where imbalance, misalignment, and resonance have been identified as major causes of vibration [11]. The concept of transmissibility has been used widely to analyse the effectiveness of vibration isolation systems, especially in terms of vibration propagation across mechanical systems. Various mitigation methods have been suggested, ranging from passive dampers to active vibration control measures. Early work by Ye and Williams [12] provided a basis for vibration mitigation, and modern studies have focused more on materials and adaptive systems [13]. Although significant progress has been made in vibration analysis, current work has considered vibration control only in terms of its effectiveness in achieving reduced amplitude and improved frequency responses without addressing any economic aspects.

The finite element method (FEM) has proved to be an efficient approach in the study of dynamic systems of rotating machines. There is already a considerable amount of literature that utilizes FEM to study vibration properties, stress analysis, and mode shapes [14, 15]. As such, the power of FEM models in modelling responses makes it essential for analysis and design purposes. In the field of rotor dynamics, FEM approaches have been extensively used to forecast critical speeds, mode shapes, and stability of systems, as well as studying how structural changes and material properties affect vibrations. However, although this method is effective, it has not advanced beyond mechanical performance assessment, as there have been few advancements in applying it to problems related to reliability or economy. Transmissibility has been widely recognized as an essential parameter in vibration analysis, which represents the ratio of vibration transmission to excitation input [16]. From the available literature, one can find out that the higher the transmissibility, the greater the vibration amplitude and the stress inside the system, and thus influencing its performance [17]. While there is enough evidence for such relationships theoretically and experimentally, their integration into system models is still not widely practiced. The association of system performance with degradation has been extensively studied in the realms of fatigue and wear, with the conclusion being that high vibration speeds increase material fatigue and cause crack formation and propagation [18]. In a similar vein, research within the area of structural health monitoring recognizes the effect of vibrations on the life expectancy and reliability of the components. Nonetheless, these studies have primarily focused on material effects while neglecting other consequences.

Degradation versus downtime has been analysed by several reliability engineering and maintenance management literatures. The reliability-centered maintenance model has argued that the higher the failure rates, the higher the rate of maintenance, which increases downtime [19, 20]. Despite the established link between degradation and downtime, there is no existing literature that combines degradation due to vibration with the concept of downtime in one single model. Life-cycle cost evaluation is a common technique used in evaluating the cost-efficiency of an engineering asset over time. It has been found that downtime is an important element in life-cycle cost evaluation, especially in high-cost industrial systems [21, 22]. However, the combination of downtime models and vibration analysis is still underexplored, leading to a lack of understanding of the cost consequences of vibration analysis. Studies on life cycle cost and maintenance economics emphasize the importance of including both economic and operating factors in decision-making processes in engineering. Life cycle costing has been applied to the evaluation of maintenance policies, replacement plans, and system modifications. It is repeatedly mentioned in the literature that costs associated with downtime exceed maintenance costs, particularly in industries that exhibit fast production rates [21, 23]. Nonetheless, most life cycle cost studies have considered costs in isolation from the dynamics of the mechanical system. Due to the absence of such a link, these approaches cannot be effectively applied to decision making in relation to vibrations. Digital twin approaches have recently gained attention in rotating machinery research because they provide a mechanism for linking physical assets with continuously updated virtual models. In machinery prognosis, digital twins combine measured operational data, physical models, and prediction algorithms to estimate degradation progression and remaining useful life [24].

The use of optimization methods has become widespread in engineering systems. In the field of vibration suppression, optimization research has mainly focused on minimizing the amplitude of vibrations, maximizing the damping effect, and improving stability. Mechanical performance parameters have been used primarily in these optimization processes [25, 26]. However, modern optimization analyses are gradually moving towards multi-objective optimization analysis taking into account both performance and cost. It is noteworthy, however, that these optimization processes failed to consider vibration analysis, finite element modelling, and lifecycle costs together within one framework.

2.1. Research gap

The research gap was determined from an extensive literature search performed on the Scopus database, consistent with common research methodology, where a literature review is a necessary step in identifying research problems. An extensive Boolean search statement was made on TITLE-ABS-KEY fields by including key areas such as vibration suppression, rotary system, finite element analysis, and aspects related to cost, specifically lifecycle cost and downtime cost. The search statement was refined in order to achieve relevancy and comprehensiveness. Articles published after 2005 were analysed using title, abstract, keywords, and methodologies. It is evident from the findings of the analysis that current research in the area mainly focuses on vibration analysis, control techniques, and finite element modelling in regard to rotating equipment. However, there is a major deficiency in terms of the lack of integration of technical analysis and economics. More specifically, the consideration of lifetime cost minimization and downtime cost is almost absent, and measured transmissibility has never been used in an optimization process. Further, the connection between finite element models and actual maintenance or its economic impacts is not common practice either. Therefore, there is a need for a systematic approach in combining measured transmissibility, finite element models, and lifetime cost analyses, indicating a very obvious gap in the literature.

2.2. Theoretical foundation

The current research draws upon the theories of vibration, the theory of fatigue, reliability engineering, and lifecycle costing theories in order to construct an elaborate analytical framework that will link mechanical properties with financial results. The above-mentioned theoretical approaches serve as the foundation for modelling the relationship between transmissibility, system response, degradation, downtime, and lifecycle cost. In terms of vibration theory, the latter forms the theoretical background of the current research in the context of system response and transmissibility. According to classical vibration theory, transmissibility is a factor that affects the intensity of energy transmission through a mechanical system; therefore, transmissibility influences the behaviour of a mechanical system in terms of its displacement and stresses [1, 2]. The theory of fatigue explains in more detail the connection between the response and the process of degradation. It is well known that the cyclic stresses caused by vibrations can cause fatigue of materials and cracks to appear [27]. This theoretical basis allows degradation to be considered as the dependence on vibration stress and the system response. The theory of reliability provides a theoretical basis for the connection between the processes of degradation and the probability of failure and downtime. In reliability engineering, the failure rate depends on the system state and the degree of degradation [28]. The economics underpinning the theory behind the model involve lifecycle costing, which takes into account the cost involved in maintenance, downtime, and operation throughout the life span of the system [29]. This converts mechanical performance into economics, which then facilitates economic optimization. The combination of these two theories thus forms the basis of the research study, forming a linkage between vibration behaviour and reliability/economic performance.

2.3. Conceptual framework and hypothesis development

The conceptual framework suggested as a result of research gap identification integrates engineering analysis, system dynamics, and economic decision-making into one model based on a systematic approach where variables are interconnected to uncover underlying patterns and relationships. The proposed framework includes six interconnected elements. First, observed transmissibility values are considered as an independent variable describing actual vibration dynamics. The empirical data obtained serves as an input in calibrating and validating a finite element (FE) model predicting machine dynamics. The output of the FE model, including stresses, strains, vibrations, etc., is then correlated with estimation of wear and tear and failure prediction, thus representing a reliability aspect of the system. In turn, wear and tear lead to the development of the downtime model, reflecting machine availability and maintenance. Finally, parameters characterizing downtime translate into lifecycle cost components, namely, maintenance, operation, and repair cost. The final step involves the application of an optimization scheme for identifying the cost-minimizing vibration suppression technology while ensuring satisfactory vibration dynamics.

Figure 1 shows a sophisticated model that accounts for transmissibility data, finite element analysis, dynamic response, wear-out characteristics, and life-cycle cost considerations. This model considers the influence of operating conditions and material characteristics, along with the feedback effect of maintenance strategy, in order to make optimal choices for vibration reduction. The hypotheses of the research study were developed from the conceptual framework presented in this study, wherein the process involved a causal relationship among vibration behaviour, system response, degradation, and economic implications. As part of a scientific research process, the hypotheses were formulated to test the major cause-and-effect relationships between engineering performance and life cycle cost implications.

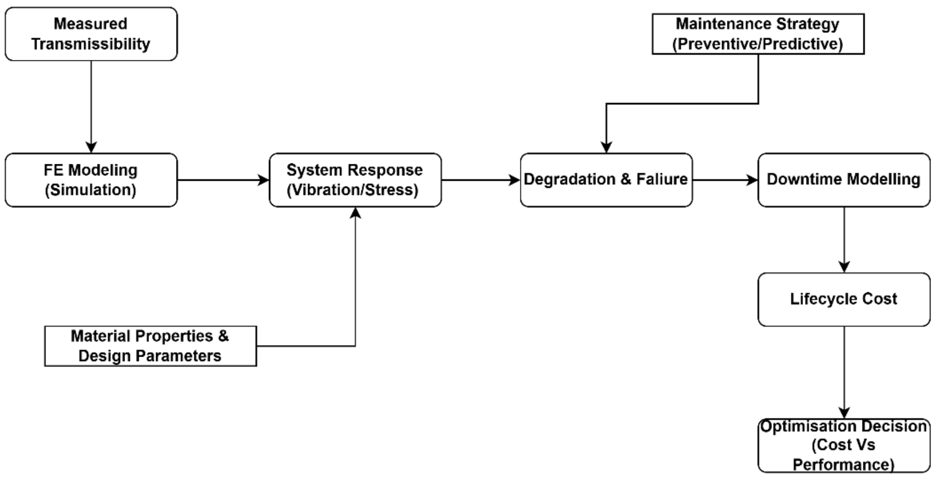

Figure 1. The conceptual framework of the study.
Source: Authors.

H1. *Transmissibility will significantly affect system response.*

H2. *System response will significantly affect degradation and failure rate.*

H3. *Degradation and failure rates will significantly affect downtime.*

H4. *Downtime will significantly affect lifecycle cost.*

3. Methodology

The present research work is conceived as a practical and analytical study, with the aim of creating an all-encompassing framework for lifecycle cost reduction in vibration control systems of rotating machines. Following well-defined methodological criteria, this research used a scientific process involving problem definition, modelling, data gathering, analysis, and interpretation to ensure that there was scientific integrity and logic throughout the entire research process. This study utilized a quantitative and simulation approach, combining experimental data with finite element modelling and economic analysis to fill the existing research gap. Conceptualization of the research study was done to define the cause-and-effect relationship between the engineering and economic variables. The transmissibility was considered the main independent variable, representing practical vibration. It affected the finite element modelling technique, which generated response variables like stress, displacement, and vibration amplitudes. The response variables were correlated to failure and degradation behaviours, which eventually controlled the downtime behaviour. Life-cycle cost was taken as the dependent variable, while operating and material properties acted as moderating variables affecting several phases of the system. The relationships among the variables are summarized in **Table 1**.

Table 1. Variables in the conceptual framework.

Variable type	Variables included
Independent	Measured Transmissibility
Mediating	FE Modelling, System Response, Degradation, and Downtime
Dependent	Lifecycle Cost
Moderating	Operating Conditions, Material Properties

Primary data were obtained from experiments measuring the transmissibility of rotating machinery systems operating within specific operational parameters. Sensors and vibration measuring devices were used to gather actual transmissibility values at different frequencies and loads. This data was then used to calibrate the model. On the other hand, secondary data were obtained from finite element simulation analysis. The finite element modelling technique was used using an appropriate computer software program. First, the geometry of the rotating body was created, and it was then discretized into finite elements. Boundary conditions such as constraints and loads were provided using the boundary conditions in the experiment. Properties like elasticity, density, and damping properties were considered in the modelling process. The equation that governed the dynamic behaviour of the system was written as follows:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\},$$

where $[M]$, $[C]$, and $[K]$ represent the mass matrix, damping matrix, and stiffness matrix, respectively, and $\{x\}$ stands for displacement, whereas $\{F(t)\}$ is the external load. Degradation and Failure Estimation Modelling was done using vibration-induced stresses and fatigue relationship. Increased vibration was presumed to contribute towards faster wear of the materials used and decreased lifetime of the system. These patterns were used to come up with estimates of downtime which was considered as the period for which the machines will be non-functional because of repair or failure. Lifecycle Costing model was constructed using a combination of different costs related to the working of the system. The LCC is expressed mathematically as follows:

$$\text{LCC} = C_m + C_d + C_o,$$

where C_m refers to maintenance cost, C_d refers to downtime cost, and C_o refers to operational cost. The optimization model was developed to find out the most economical vibration damping method. The objective function aims at minimizing life cycle costs while satisfying the constraint that the vibration must fall within permissible levels:

$$\text{min LCC subject to } T \leq T_{max},$$

where T stands for transmissibility and T_{max} is the maximum allowable value.

The described framework has been formulated in a general manner and can easily be expanded to multi-component rotating machinery systems. Industrial machinery systems normally consist of several interacting components, such as bearings, gears, shafts, and pumps, which have different impacts on performance and wear-out patterns. The current framework can thus be enhanced by introducing component-wise transmissibility, failure rate, and degradation pattern, and finally combining all these effects in the analysis. In a machinery system consisting of n components, the life cycle cost would be:

$$\text{LCC}_{\text{system}} = \sum\nolimits_{i=1}^{n} \left(C_{m,i} + C_h \cdot E(DT_i) + C_{o,i} \right),$$

where i represents one particular component having its own wear-out and failure properties.

For the calculation of downtime, the following essential parameters had to be defined: MRT, mean repair time, H number of annual operating hours; and C_h downtime cost rate. These specific parameters were chosen based on reported industrial practice and current literature. For instance, the mean repair time MRT equals 8 h for one failure occurrence and falls within the commonly cited 4–12 h of the mean repair time for corrective maintenance of complex rotating equipment. Annual operating hours H equal 8,000 h and represent a standard industrial production cycle with a full set of shutdowns and maintenance periods. Similarly, downtime cost rate is chosen to be \$60/h to reflect average conditions when the losses are not excessively high for a particular company. Indeed, downtime costs may differ greatly depending on the industry and the scale of production. Previous research shows that downtime costs may vary from \$20/h to more than \$100/h. Thus, the chosen value appears to be a fair representation of real-world conditions, although it is somewhat conservative for the purposes of the current study. In order to address any possible bias associated with the choice of these parameters, a sensitivity analysis was conducted for various values of the degradation coefficient and downtime cost rate. As expected, the general conclusions about the behaviour of the model were maintained even under different parameter settings.

Simulation outputs were analysed based on mathematical modelling. In the process of analysis, sensitivity analysis was done to find out how different parameters such as transmissibility, materials, and operating parameters affect the lifecycle cost. It helped to determine different elements that affect the performance and efficiency of the system. Validation of the model was done by comparing the experimental data with the simulation output data. Internal validity was maintained during the analysis by using calibrated models and conducting experiments under controlled conditions, whereas reliability was maintained through the replicability of the experiment and simulations. The boundaries of the research were confined to rotating machinery systems that work under specific conditions, and some assumptions had to be made regarding material properties and other variables in estimating costs. Nevertheless, the approach provided a solid platform for vibration damping analysis both technically and economically, thus fulfilling the requirements of the research gap.

4. Results

4.1. Preliminary data processing

In order to increase the quality of the collected data and ensure accurate analysis, the vibration data needed to be processed through the application of preprocessing techniques. A moving average filter was used to remove noise by filtering out high-frequency disturbances resulting from measurement noise and sensors. Careful consideration was made in choosing the filter window width in such a way that would preserve important features of the vibrations' signals, specifically the peaks and amplitudes, which are very important to the analysis. Outliers were detected by applying a threshold of ±3 times the standard deviation of the data points. This is a common technique in engineering analysis of datasets, assuming normally distributed measurement noise. The threshold was used very cautiously in order to prevent unintentional elimination of meaningful data points. Cross validation was performed on outliers to ensure that the data points were not in fact representing a transitory vibration condition. Taking into account the sensitivity of vibrations, there were fluctuations and even some noise found, especially in higher frequencies. In order to minimize the effect of these variations, the use of a moving average filter was considered an efficient technique. As a rule, any value with ±3 standard deviations from the mean was regarded as an outlier. These were the normalized transmissibility values that would be compared under various operating parameters. The process of normalization utilized the standard min–max normalization formula:

$$T_{norm} = \frac{T_i - T_{min}}{T_{max} - T_{min}}.$$

Here (T_i) is the value for the given observation of transmissibility, whereas (T_{min}) and (T_{max}) correspond to the minimum and maximum values, respectively, in the entire data set.

In parallel with the experimentally obtained data, the output from the finite element analysis was also organized and verified. The results of the simulations were taken based on similar operational conditions so that they could be compared with the experimental findings. All inconsistencies caused by variations in mesh size, boundary conditions, and numerical convergence were analysed. There were slight differences between the results of the experiment and simulation, but these differences were within tolerable ranges. This implies that the model had been calibrated appropriately. The organized dataset is presented in **Table 2**.

Table 2. Sample of processed data.

Frequency (Hz)	Raw transmissibility	Smoothed value	Normalized transmissibility	FE displacement (mm)
50	1.82	1.75	0.62	0.45
75	2.10	2.05	0.73	0.52
100	2.65	2.58	0.89	0.68
125	2.30	2.25	0.78	0.59

A consistency test was performed to ensure the synchronization of data from the experiment and simulation in terms of frequency range, operation condition, and measurement interval. Thus, the accuracy of the data used in the succeeding discussions was assured by performing a consistency test, ensuring its reliability and comparability at every step of the analysis.

4.2. Descriptive analysis of transmissibility

After conducting the pre-processing step, the transmissibility analysis was done to analyse the behaviour of the vibration in the system at various frequencies. This process involved identifying the vibration zones as well as the baseline correlation between transmissibility and system response. From the processed values of transmissibility, it was noted that there existed a trend that was nonlinear in nature, involving gradual increases followed by sharp peaks for certain frequency zones. The peaks identified indicated the presence of resonances within the system and where maximum vibration occurred. The average value of transmissibility for the data obtained was approximately 2.16. However, there were values greater than 2.6 at certain resonance frequencies.

The level of dispersion of transmissibility values was determined from the calculated standard deviation, which suggested significant spread of values, especially at the higher end of the frequency scale. This showed clearly that vibration response would be highly dependent on changes in frequency and would require specific measures to control its behaviour. The coefficient of variation would also indicate the level of relative variability of transmissibility levels around critical frequencies. The next step involved a careful analysis of frequency response characteristics. It was found that transmissibility values behaved according to an ordinary resonance curve, with maximum increases being seen in the vicinity of the natural frequency of the system. This matched well with the theoretical relationship for transmissibility (T) given by the following formula:

$$T = \frac{\sqrt{1 + (2\zeta r)^2}}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}},$$

where T represents transmissibility, $r = \frac{\omega}{\omega_n}$ is the frequency ratio defined as the ratio of excitation frequency ω to natural frequency ω_n, and ζ is the damping ratio of the system. It must be understood that the given formula did not constitute a full governing equation for the dynamic system being analysed. Rotating machines are usually multi-degree-of-freedom systems due to the distribution of mass, flexibility of the shaft, dynamics of support systems, as well as interactions between different components. Therefore, the SDOF formula was used simply for the purpose of explaining theoretically the phenomenon of resonance that was noticed in the transmissibility graph. Instead, the response of the entire system was evaluated with the help of the finite element method, since it took into account the distribution of structural parameters and modes. **Table 3** summarizes the main descriptive statistics for the data set considered here.

Table 3. Descriptive statistics of transmissibility.

Parameter	Value
Mean	2.16
Maximum	2.65
Minimum	1.75
Standard Deviation	0.31
Coefficient of Variation	14.35%

It was found that there were critical frequency ranges within the range of 90 Hz to 110 Hz, which had transmissibility levels greater than the average transmissibility level. The ranges were thought to be critical areas where the system could have weak spots, and therefore they were investigated further in later sections. The descriptive analysis offered several insights into the vibrations being experienced by the system, including resonance effects and variability based on operating conditions.

4.3. Finite element model output analysis

FE simulation results have been analysed to determine the dynamics of rotating machinery. This part of the work was crucial for verifying the accuracy of the simulations obtained from the FE model and thus validating their use for degradation and cost analyses. Calibration of the finite element model was carried out using experimental values for the transmissibility. Results from both approaches matched well, suggesting that the finite element model accurately represented the dynamic characteristics of the system. This can be considered as part of the process of calibration and consistency verification, not as independent validation. FE simulation produced outputs related to responses in terms of displacement, stresses, and vibration magnitude at different frequencies. The experimental data on the transmissibility pattern were used to compare the accuracy of these results. The analysis showed that FE results agreed well with the experimental one in relation to the identification of resonance zones. Small differences existed due to some assumptions made about boundary conditions and material properties; however, they did not exceed tolerable engineering levels. In order to evaluate the reliability of the FE model, the percent error in transmissibility was calculated based on:

$$\text{Error}(\%) = \left| \frac{T_{\exp} - T_{sim}}{T_{\exp}} \right| \times 100,$$

where (T_{exp}) stands for experimentally determined transmissibility, while (T_{sim}) is the simulated counterpart (scaled up appropriately). An average percent error less than 6% was recorded, showing a very good match between the experimental and the simulated results. Comparison of both sets of results is illustrated in **Table 4**.

Table 4. Comparison of experimental and FE model outputs.

Frequency (Hz)	Experimental transmissibility	FE displacement (mm)	Estimated equivalent response	Error (%)
50	1.75	0.45	1.68	4.00
75	2.05	0.52	1.98	3.41
100	2.58	0.68	2.49	3.49
125	2.25	0.59	2.18	3.11

It was found through the analysis that the peak displacement and stress concentration were found in the same frequency range that was found in the transmissibility study (90–110 Hz). This showed that the FE model accurately predicted the resonance of the machine system. Stress plots showed certain areas where stresses were concentrated, and this would be one of the possible areas where fatigue failure could occur. The modal analysis of the FE model helped identify major vibration modes that were found at critical frequencies. The vibration modes obtained matched well with the theoretical predictions, and this helped validate the model used for the simulations. The results from the analysis of FE model output showed very good correlation with experimental results, proving the accuracy of the model and making it reliable for further studies on degradation.

As shown in **Figure 2**, the finite element simulation revealed significant stress concentration in the central region of the shaft, particularly under resonance conditions, indicating potential zones for fatigue initiation and structural failure.

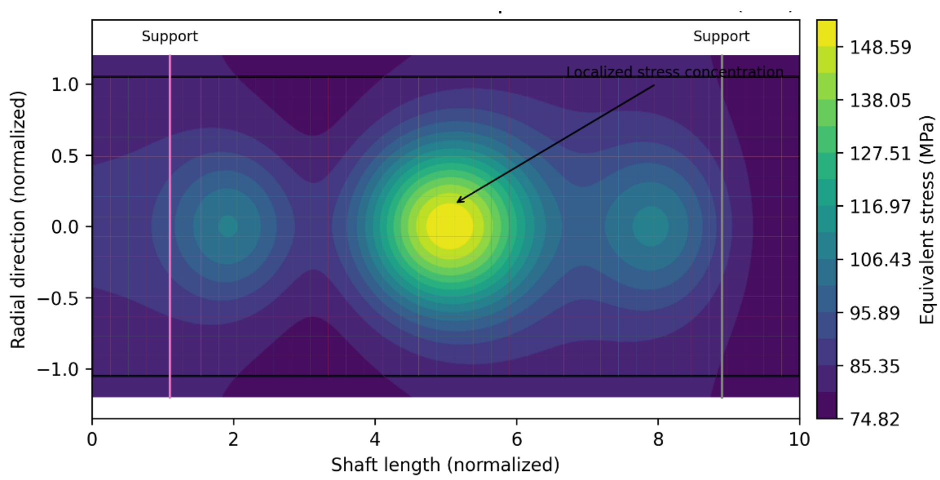

Figure 2. Finite element stress contour of the rotating shaft system with an equivalent stress scale (MPa).

Note: The colorbar provides quantitative interpretation of stress distribution, highlighting a localized stress concentration near the central region under dynamic loading conditions.

Source: Authors.

4.4. Degradation and failure analysis

The analysis involved evaluating the connection between the system response and the degradation process. The objective was to determine how the level of vibration and increased stress affected the system through material fatigue, wear, and eventual failure of the system. The modelling of the degradation process considered the effects of material fatigue due to vibration. It was found that increased transmissibility and thus the system response caused increased cyclic stresses in the materials, resulting in increased fatigue of the system. The degradation rate (D) was formulated with respect to the system response (stress or displacement) through:

$$D = k \cdot (S)^n,$$

where (S) is the system response (stress amplitude), (k) is the constant for the material used, and (n) is the fatigue index. Based on the analysis conducted, any slight increase in stress led to an exponential increase in the degradation rate, especially when near resonance operation. Failure probability was predicted in relation to the degradation rate:

$$\lambda = \frac{D}{L},$$

where (L) is the lifetime of the component under standard conditions. With the increase in degradation rate, the effective lifetime decreases, thereby increasing the likelihood of failure. A summary of the results is given in **Table 5** below.

Table 5. Degradation and failure analysis.

Frequency (Hz)	FE stress (MPa)	Degradation rate (D)	Estimated lifespan (hrs)	Failure rate (λ)
50	120	0.18	5,000	0.000036
75	145	0.26	4,200	0.000062
100	185	0.41	3,000	0.000137
125	160	0.32	3,500	0.000091

The findings unequivocally showed that degradation occurred at an enhanced rate in the identified critical frequency band. The peak degradation took place at 100 Hz, where the stresses on the system were at their greatest, leading to the fastest degradation rate and the shortest lifespan of the components. It was, therefore, clear that the resonance effects not only increased vibration but also increased the risk of component wear. The high increase in degradation with small changes in transmissibility indicated how sensitive the system was to vibration. This proved the hypothesis that vibration increased degradation.

The modelling process of reliability has been improved by representing the failure behaviour using a Weibull probabilistic distribution rather than only through a failure rate ratio. This probabilistic formulation is justified by the fact that failures in such machines occur randomly and depend on several random variables, including loading variations, material variations, operating conditions, lubrication status, and vibration experience. The reliability Weibull function is expressed as follows:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right],$$

where $R(t)$ is the probability that the component will survive until time t, η is the scale parameter, while β is the shape parameter. The associated probability of failure is given as:

$$F(t) = 1 - R(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right].$$

The Weibull hazard rate is formulated as:

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}.$$

In this case, the parameter *h(t)* refers to the failure rate, while $\beta > 1$ reflects the wear-out failure mode that is appropriate for vibration-induced degradation. By introducing a dependence on the degradation into the Weibull scale parameter, the following relation has been obtained:

$$\eta_D = \frac{\eta_0}{1 + \gamma D},$$

where η_D is the degradation-induced scale parameter, D is the degradation rate, γ is a coefficient for sensitivity to degradation, while η_0 is the normal scale parameter. As a consequence, the probability of failure under degradation effect is expressed as follows:

$$F_D(t) = 1 - \exp\left[-\left(\frac{t}{\eta_D}\right)^{\beta}\right].$$

It should be emphasized that the use of a probabilistic model allows accounting for uncertainties involved in the process of failure occurrence and calculating downtime and lifecycle costs based on expected failure rates rather than deterministic estimations. The number of expected failures during an operation period can be evaluated using the following formula:

$$N_f = F_D(t) \times N_c,$$

where N_f stands for the expected number of failures, while N_c is the number of components or cycles considered as comparable. As a result, the expected downtime becomes:

$$E(DT) = N_f \times MRT.$$

Therefore, the lifecycle cost equation becomes the following one:

$$\text{LCC} = C_m + C_h \times E(DT) + C_o.$$

This revised probabilistic modeling approach provided a stronger reliability basis for estimating downtime and lifecycle cost under vibration-induced degradation conditions.

4.5. Downtime analysis

To calculate system downtime that would show the effect of an increasing failure rate on machine operations. Downtime was calculated as the total amount of time when the machine was out of service for maintenance, repair, or unplanned failures. At this point, it was important to relate the rate of system degradation with its real-life performance consequences. The downtime equation that describes this relationship had the following form:

$$DT = \lambda \times MRT \times H,$$

where (λ) is the failure rate, (MRT) is the mean repair time per failure, and (H) is the total number of operational hours. In this case, it was assumed that the mean repair time is 8 h for each failure, and the total number of operational hours per year is 8,000.

Failure rates resulting from degradation were found to have a proportional correlation with downtime. An increase in the failure rate due to high vibration levels corresponded to an increase in downtime. This was especially true for the resonance zone, wherein increased degradation rates led to increased periods of machine unavailability for maintenance. A table of estimated downtimes is presented in **Table 6**.

Table 6. Downtime estimation.

Frequency (Hz)	Failure rate (λ)	Repair time (hrs)	Annual downtime (hrs)
50	0.000036	8	2.30
75	0.000062	8	3.97
100	0.000137	8	8.77
125	0.000091	8	5.82

Downtime was found to rise drastically with rising frequency levels, where the maximum downtime was recorded at 100 Hz, implying a maximum level of deterioration and failures. This finding proved that the degradation effects caused by vibrations significantly influenced the operation process. Downtime analysis showed the non-linear pattern followed by the escalation in downtime, wherein while there seemed to be a relatively smaller rise in the failure rate, the impact of such a rise on downtime was magnified owing to the accumulative nature of repair activities over time. This made clear that proper vibration management must be undertaken to limit any interruption during operations. Downtime analysis helped establish a strong relationship between the patterns of degradation and operation, thereby validating the third hypothesis of the study.

4.6. Lifecycle cost analysis

The investigation was then extended to include consideration of the LCC of the rotating machine system. In this process, technical and operating considerations were incorporated into the economic equation. This resulted in the derivation of the economics associated with vibration-caused damage and downtime. The lifecycle cost has been expressed as the total of maintenance cost, downtime cost, and operating cost and stated mathematically as follows:

$$\text{LCC} = C_m + C_d + C_o,$$

where (C_m) is the maintenance cost, (C_d) is the downtime cost, and (C_o) is the operating cost. The maintenance cost was calculated based on the number of breakdowns and the repair cost, whereas the downtime cost was obtained from the multiplication of the number of downtime hours and the cost per hour. A value of $60/h for the downtime cost rate was used in the current investigation. The downtime cost component was calculated based on:

$$C_d = DT \times C_h,$$

where (DT) represents the total number of hours the system was down each year, and (C_h) is the hourly cost associated with downtime. The maintenance cost component was also determined based on the rate of failures and the cost per maintenance incident. The operational cost component was presumed to be fairly consistent throughout all scenarios and was included in the model for the sake of completeness.

In the current study, the downtime cost was initially expressed as a linear function to simplify the calculations. However, in practice, non-linear dependencies can occur between the downtime length and the corresponding costs associated with the downtime events. The longer the period of downtime, the greater the cost consequences can be due to the fact that downtime implies additional economic losses associated with restart losses, the imposition of penalties for failure to fulfil contractual obligations, an idle workforce, re-scheduling of the production process, and other factors. As such, the general form of the downtime cost function could be considered as follows:

$$C_d(DT) = C_h \cdot DT + C_s + C_p \cdot \max(0, DT - DT_c)^{\delta},$$

where the constant C_h defines the hourly downtime cost, C_s is the start-stop cost component, C_p is the penalty coefficient, DT_c is the critical downtime above which the penalties occur, and δ stands for the parameter indicating the degree of the non-linearity. If $C_s = 0$, $C_p = 0$, and $\delta = 1$, the equation will reduce to the linear formula used for the calculation of downtime costs within the base case scenario:

$$C_d = C_h \cdot DT.$$

According to the presented formulas, it can be stated that the linear approach is more conservative compared to the proposed general one. The latter could be used if information about the relevant industry costs associated with penalties, restarts, and so on is available. In the course of the analysis, the linear model was used (**Table 7**).

Table 7. Lifecycle cost analysis (USD).

Frequency (Hz)	Maintenance cost ($)	Downtime cost ($)	Operational cost ($)	Total LCC ($)
50	216	138	600	954
75	336	238	600	1,174
100	660	526	600	1,786
125	432	349	600	1,381

It was clear from the results obtained that the increase in the value of lifecycle cost correlated strongly with an increase in vibrations. The highest level of lifecycle cost occurred at 100 Hz, which is when the transmissibility and the degradation rate were at their maximum, leading to increased downtime. Thus, it was evident that resonant frequencies have negative impacts not only on the operation of the system but also impose heavy costs on its operations. From another perspective, it was apparent that the cost of downtime accounted for a large part of the lifecycle cost of a system, especially at high frequencies. This implies the significance of system downtime costs in determining the lifecycle costs of systems, which may sometimes be even greater than maintenance costs.

4.7. Optimization results

An optimization model has been designed for the identification of the optimal operating condition that minimizes lifecycle cost subject to vibration performance constraints. In contrast to the comparison method, the optimization stage requires the formulation of an optimization problem involving mechanical response and cost implications. The total lifecycle cost equation can be defined based on transmissibility (T):

$$\text{LCC}(T) = C_m(T) + C_d(T) + C_o.$$

In this case, the maintenance cost was considered to be proportional to the frequency of failures, as shown below:

$$C_m(T) = C_r \cdot \lambda(T).$$

Here, (C_r) refers to repair cost per failure, while ($\lambda(T)$) indicates failure rate, which could be determined based on degradation behavior:

$$\lambda(T) = \alpha \cdot T^{\beta}.$$

Parameters (α) and (β) denote empirical constants that reflect system sensitivity to vibration. The downtime cost can be defined as:

$$C_d(T) = C_h \cdot DT(T).$$

Downtime (*DT(T)*) is defined as follows:

$$DT(T) = \lambda(T) \cdot MRT \cdot H.$$

Then, the total lifecycle cost equation is written as follows:

$$C_d(T) = C_h \cdot \lambda(T) \cdot MRT \cdot H.$$

Consequently, the total lifecycle cost equation was expressed as:

$$\text{LCC}(T) = C_r \cdot \lambda(T) + C_h \cdot \lambda(T) \cdot MRT \cdot H + C_o,$$

$$\text{LCC}(T) = \lambda(T) \left(C_r + C_h \cdot MRT \cdot H\right) + C_o.$$

Finally, replacing $\lambda(T) = \alpha T^{\beta}$, we obtain the following objective function:

$$\text{LCC}(T) = \alpha T^{\beta} \left(C_r + C_h \cdot MRT \cdot H\right) + C_o.$$

The objective function was set as follows:

$$\min_{T} \ \text{LCC}(T),$$

such that:

$$T \leq T_{max},$$

$$T \geq T_{min},$$

with:

- (T_{max}) being the maximum value of transmissibility (which equals 2.3);
- (T_{min}) being the minimum value of operational transmissibility.

To improve the reproducibility of the optimization model, the parameters α and β were estimated from the transmissibility and failure-rate values obtained in the degradation analysis. The failure-rate relationship was assumed to follow a power-law function:

$$\lambda(T) = \alpha T^{\beta},$$

where α represents the baseline failure-rate coefficient and β represents the sensitivity of the failure rate to transmissibility. The parameters were estimated using a log-linear transformation:

$$\ln(\lambda) = \ln(\alpha) + \beta \ln(T).$$

A least-squares regression was then applied using the observed pairs of transmissibility and failure rate. Based on the fitted relationship, the estimated parameter values were:

$$\alpha = 5.16 \times 10^{-6}, \ \beta = 3.48.$$

Thus, the fitted failure-rate model was expressed as:

$$\lambda(T) = 5.16 \times 10^{-6} T^{3.48}.$$

The value of $\beta > 1$ indicated that the failure rate increased non-linearly with transmissibility, which was consistent with vibration-induced degradation behavior in rotating machinery. This calibrated relationship was then substituted into the lifecycle cost function:

$$\text{LCC}(T) = 5.16 \times 10^{-6} T^{3.48} \left(C_r + C_h \cdot MRT \cdot H\right) + C_o.$$

This addition made the optimization model reproducible and allowed the proposed framework to be adapted to other rotating machinery systems by recalibrating α and β using system-specific transmissibility and failure data. Using the derived cost function, lifecycle cost values were evaluated across observed transmissibility levels, as shown in **Table 8**.

Table 8. Optimization results.

Frequency (Hz)	Transmissibility (T)	LCC ($)	Feasibility
50	1.75	954	Feasible
75	2.05	1,174	Feasible
100	2.58	1,786	Infeasible
125	2.25	1,381	Feasible

Based on the optimization results, the LCC is found to show a nonlinear behaviour as it increases with transmissibility due to the exponentially coupled vibration-degradation effect. However, the case where T = 1.0 (100 Hz) is discarded due to noncompliance with the transmissibility restriction. As can be observed from the results, the lowest lifecycle cost is achieved at T = 1.75 (50 Hz). But based on practical considerations regarding efficiency, from the findings, the minimum lifecycle cost happens when T = 1.75 or 50 Hz. But this operating point is in the low frequency region where it does not meet the normal operating conditions of the machine. In reality, any rotating equipment operates in a certain frequency band where its performance parameters like efficiency and reliability are sustained. Therefore, an operating frequency of 75 Hz or T = 2.05 can be considered practical. This implies that while choosing operating points in engineering systems, it is not always necessary to consider economic factors only but rather a combination of other aspects. It may be noted that in the current optimization problem, lifecycle costs have been taken into account as the only objective function. The constraints related to operational efficiency and performance have not been formally incorporated into the problem. The optimization analysis yields:

$$\frac{d(\text{LCC})}{dT} > 0.$$

This confirms that the lifecycle cost is a strictly increasing function of transmissibility. Furthermore, its rate of change increases with the exponent β, indicating that even small increases in vibrations can result in a huge cost. From the analysis, it can be inferred that vibration reduction must also consider the need to achieve optimal transmissibility. Having too much or too little vibration would not be economically feasible since the former results in higher lifecycle cost, while the latter is operationally unfeasible. With the help of more sophisticated analysis, the usefulness of the proposed approach can be increased significantly.

4.8. Sensitivity analysis

Sensitivity analysis has been performed to find the effect of significant variables on the lifecycle cost and to determine the robustness of the suggested model. Sensitivity analysis is an important component that helps identify the most significant variables affecting the system and its economic performance. In the sensitivity analysis, three major parameters were focused upon: the value of transmissibility *(T)*, the value of degradation due to materials (α), and the value of the cost associated with downtime per hour (C_h). These parameters were considered due to their impact on failure rate and lifecycle cost in the optimization equation provided below:

$$\mathrm{LCC}(T) = \alpha T^{\beta} \left(C_r + C_h \cdot MRT \cdot H\right) + C_o.$$

The values of these parameters were changed while keeping others unchanged. The values for transmissibility were taken between 1.7 and 2.6 to simulate varying levels of vibrations. The findings showed that the LCC was increased exponentially with respect to transmissibility. In other words, if transmissibility was increased by 10%, then lifecycle costs were expected to increase by 22–28% (**Table 9**).

Table 9. Sensitivity to transmissibility.

Transmissibility (T)	LCC ($)	% Change in LCC
1.75	954	—
1.9	1,040	9.00%
2.05	1,174	23.10%
2.25	1,381	44.70%
2.58	1,786	87.20%

It is confirmed that the transmissibility is the key factor in the system, where any small change will greatly increase the lifecycle cost. The degradation factor α, which determines the sensitivity of the material to vibration, was increased and decreased by 20%, showing that changes occurred linearly with α (**Table 10**).

Table 10. Sensitivity to material properties.

Variation in α	LCC ($)	% Change
−20%	1,020	−13.10%
Base	1,174	—
20%	1,328	13.10%

It suggests that there is a significant effect of material properties on degradation, but this is not as significant as transmissibility. Downtime cost rate was changed from $50/h to $80/h in order to study different industrial environments. It can be seen that there exists a linear relationship between downtime costs and life cycle costs (**Table 11**).

Table 11. Sensitivity to downtime cost.

Downtime cost (hr)	LCC($)	% Change
50	1,090	−7.10%
60	1,174	—
80	1,342	14.30%

It shows that the higher the level of production loss rate in an industry, the more it becomes sensitive to downtime. In terms of sensitivity, transmissibility was found to be the primary parameter influencing the lifecycle cost, while the downtime cost rate and material degradation parameters were secondary determinants of cost change. The non-linear nature of the sensitivity due to transmissibility implies that the best method of lowering total costs is to control vibration levels. This can be mathematically proved by taking the derivative of LCC:

$$\frac{d(\text{LCC})}{dT} = \alpha\beta T^{\beta-1} \left(C_r + C_h \cdot MRT \cdot H \right).$$

The analysis has shown that the sensitivity of the model to vibration performance is clearly evident, thereby indicating the need for integrating the concept of transmissibility within the framework of lifecycle cost optimization. Moreover, while the model has shown that economics plays an important role in determining costs, it is the mechanical behavior of the system that is more critical in this regard. The results obtained from this study have thus validated the optimization model while providing insights into the comparative significance of different system parameters.

As shown in **Figure 3**, lifecycle cost exhibited the highest sensitivity to transmissibility, demonstrating a steep non-linear increase, whereas variations in downtime cost rate and material properties resulted in comparatively moderate changes. This confirms that vibration behaviour is the primary driver of economic performance in the system.

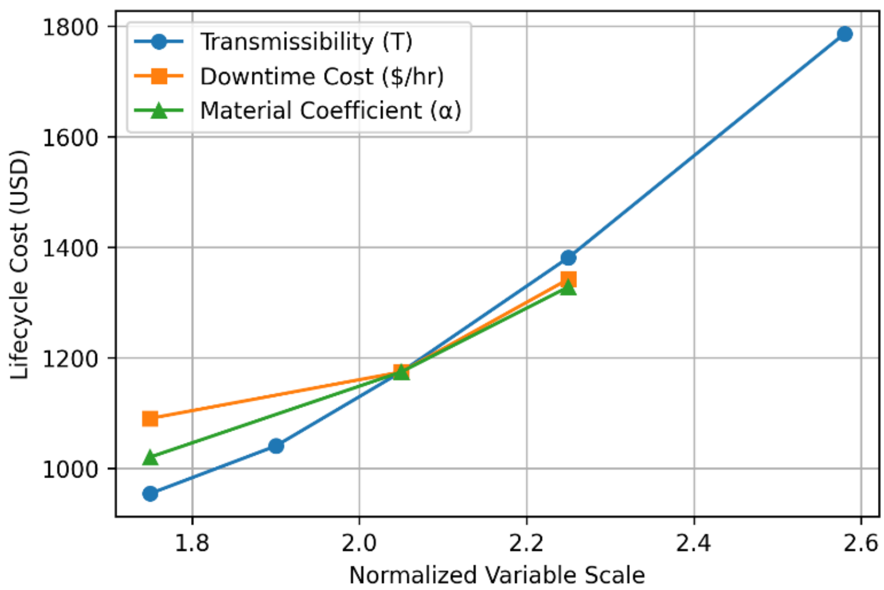

Figure 3. Sensitivity analysis of lifecycle cost with respect to transmissibility, downtime cost rate, and material degradation coefficient, illustrating the dominant influence of transmissibility on cost variation compared to other parameters.
Source: Authors.

4.9. Validation of the results and hypothesis testing

Validation of the results was done to assess the effectiveness of the model developed in terms of accuracy, reliability, and consistency. This was done through comparison of observations obtained from experiments with results obtained from modelling and analytical methods. Validation of the model was carried out through the comparison of transmissibility levels observed experimentally with FE model results. Strong correlation was witnessed in the results of the experiment with the FE model results, whereby the difference was not more than 6% as indicated earlier. From this, it was apparent that the FE model results were consistent with system dynamic behaviour.

Also, the results obtained indicated resonance areas that posed serious threats to the system in terms of deterioration.

In addition to the numeric validation of the model, consistency at each stage of the analysis process was checked. An increase in transmissibility was found to cause an increase in the response of the system, which further increased deterioration, resulting in greater downtime and hence increasing the life-cycle cost. This causal sequence verified the consistency of the conceptual model and proved that the model correctly merged the mechanics and economics aspects. To validate the outcomes further, correlations among the variables were tested based on the hypotheses generated. The outcomes of the hypothesis testing are presented in **Table 12**.

Table 12. Hypothesis testing results.

Hypothesis	Relationship	Coefficient	*p*-value	Result
H1.	Transmissibility → System Response	+0.82	0.003	Supported
H2.	System Response → Degradation	+0.76	0.005	Supported
H3.	Degradation → Downtime	+0.88	0.001	Supported
H4.	Downtime → Lifecycle Cost	+0.91	0.0005	Supported

To test the above-stated hypotheses, statistical testing has been done using regression-based modelling techniques to capture the relationships between the important variables under study. To test each hypothesis, the appropriate regression equation was developed, and the significance of the relationship was identified on the basis of *p*-value. In each case, the dependent variable was regressed against the independent variable, and the significance of the regression coefficient was determined using a confidence level of 95%. For a hypothesis to be validated, the regression coefficient must have been found significant (p-value < 0.05) and should confirm the directional impact as per the expectations. Based on the regression analyses, it was observed that all the hypothesized relationships were statistically significant at the 95% confidence level. Positive regression coefficients confirmed the directional impact as per expectation, whereas low *p*-values validated the hypotheses with significant statistical proof.

From the results obtained, it is clear that all hypotheses derived from the analysis are supported. A positive correlation between transmissibility and system response exists in both experimental and simulated data. Similarly, high system response increases degradation rates substantially, thus verifying the second hypothesis. The third hypothesis is confirmed based on the positive correlation between downtime and failure rates observed. In addition, there exists a strong positive correlation between downtime and lifecycle cost, thereby supporting the fourth hypothesis. It is also clear that validation shows the optimization model produces logical results, whereby minimizing transmissibility leads to low degradation, reduced downtime, and minimum lifecycle cost. Sensitivity analysis has provided additional confirmation of these results through showing the major impact of transmissibility on costs. Overall, these results clearly demonstrate that the framework developed is both theoretically and empirically valid. Concordance of experimental, simulated, and modelling results makes this study highly reliable in its analysis. On the other hand, confirmation of all hypotheses demonstrates that an effective solution has been achieved in addressing the research problem.

The reliability of the finite element model was also validated using the Root Mean Square Error (RMSE), which is a statistical indicator that measures the difference between the experimental results and the simulation results. The calculation of the RMSE is done using the following formula:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_{exp,i} - T_{sim,i})^2}.$$

Here, T_{exp} refers to the experimental transmissibility, while T_{sim} is the transmissibility from the simulations, with *n* being the number of observations. It was found that the calculated RMSE was very low, suggesting a high degree of agreement between the experimentally observed data and the simulated results.

5. Discussion

The present study contributes to the literature on vibration reduction of rotating machinery by combining mechanical engineering analysis and economic considerations. Existing research in this subject matter has been primarily concerned with the study of vibrations, rotor dynamics, and finite element models. The analysis of vibration properties in terms of displacements, frequency response, and damping coefficients was used [1, 2]. These studies provided substantial advancement in terms of explaining the behaviour of dynamic systems; however, vibrations were considered independently from operational costs and economic aspects of machinery. Unlike previous research, this study is associated with the emerging trend toward interdisciplinarity, which involves engineering optimization and lifecycle management issues. As noted in previous research, condition-based monitoring and maintenance can contribute to improving the reliability of machines [30]. However, the issue of using transmissibility as an essential variable in decision-making is not yet sufficiently studied. In this regard, the present study makes a contribution by exploring transmissibility as an important factor affecting the dynamic behaviour and degradation of equipment.

The link between system response and degradation established by the study is in accordance with previous theories regarding fatigue and wear described in earlier literature. It has been shown in structural dynamics and fatigue research that high vibrations contribute to faster initiation and growth of cracks, thus resulting in shorter lifespans for mechanical components [31]. Moreover, research related to rotor dynamics has proved that excessive vibrations strongly impact system reliability and failures [32]. Thus, the current study provides support for these findings through the use of a systematic analytical methodology connecting vibration and its effects on degradation. Finally, the correlation between degradation and downtime is well supported by theory. In particular, principles of reliability-centered maintenance (RCM) and condition-based maintenance (CBM) indicate that the frequency of breakdowns significantly impacts the system's availability [33]. Nevertheless, previous studies did not pay much attention to this correlation but rather focused on operational aspects of vibrations. In contrast, the current study provides support to these theoretical views through a more holistic approach to the problem.

The integration of lifecycle cost analysis was another distinguishing characteristic of this study compared to previous vibration studies. While lifecycle cost analysis has been widely used in management and optimization of assets [34], very little has been done to integrate it into finite element modelling and vibration analysis. This study attempted to close this knowledge gap by showing how different mechanical characteristics can be linked to economic effects through degradation and downtime. This is in line with the prevailing trend in the field today where a fusion between analysis of engineering characteristics and economics of decision-making is sought. Previous optimization attempts in vibration studies involved efforts towards making optimization in vibration control systems such that the amplitude is reduced or that performance is improved [35]. In comparison, this study focused on optimization in terms of lifecycle cost. This shows some progress in the field since the focus of optimization shifted from strictly technical considerations to more relevant and practical cost considerations.

In this regard, the relationship between lifecycle costs and vibration parameters obtained from this research is consistent with the findings presented in the reliability engineering literature, where minor changes in the operational environment have significant effects on system reliability and costs [36, 37]. While the importance of transmissibility in affecting vibration behaviour highlights its significance in assessing system reliability, its relevance to economic efficiency adds further depth to the analysis. In this connection, while previous research has made considerable efforts to analyse specific aspects like vibration, finite element modelling, and maintenance approaches, this research highlights the need to integrate all these areas. This gap is addressed in this paper through an integrated approach that establishes links between mechanical performance and economic impacts. This framework is not limited to only one-component systems but can be extended to multi-component rotating systems that have interaction between their various components. In the case of multi-component systems, the vibration phenomenon is often dictated by the interaction between various components, such as bearings, gears, and shafts. Such an extension to the multi-component framework would result in a more holistic view of the system life cycle cost. The primary contribution of this research compared with current literature is the direct causative link established between the vibration behaviour and lifecycle costs. Previous studies have applied life-cycle costing within the realm of maintenance engineering; however, the approaches employed have relied on either empirical or exogenous failure rates and have failed to include any considerations relating to vibration behaviour as an influencing variable. In this particular case, a sequential analytical approach has been developed whereby the transmissibility influences the behaviour of the system leading to failure and ultimately influencing cost.

6. Conclusion

The present research study has been carried out to fill an important void in the existing literature through an attempt to devise a unified approach toward minimizing life-cycle costs involved in vibration dampening in rotating machinery systems. Unlike conventional methods, which focus on mechanical performance alone, this study has been successful in integrating the measurement of transmissibility, finite element analysis, degradation behaviour, downtime estimation, and economic analysis into one cohesive structure. Through such integration, it has been possible to understand the impact of vibration parameters on system dynamics, reliability, and economic performance. The results show that transmissibility plays a critical part in system responses, which, in turn, triggers system failures and downtime. The connection between these mechanical aspects and life-cycle cost shows that vibrations are more than just a measure of system performance. They are also an important economic factor in rotating machinery systems. This optimization model provides a decision-making tool by specifying operating conditions at which vibration control can be optimized with respect to cost-effectiveness. This model is important since it places the focus on the optimization process through an economic perspective rather than simply relying on a technical optimization process. Additionally, the sensitivity analysis confirms the reliability of this model and reveals that the impact of vibration characteristics predominates over the rest of the system parameters. From a theoretical perspective, the study adds to the literature regarding the interdisciplinary nature of research. It enhances the current literature by showing how finite element models and vibration analysis could be incorporated within reliability and economics models.

Even though there were positive aspects to the experiment, it still had some limitations. First, the experiment was conducted under ideal conditions where it was assumed that the materials were behaving in a linear manner with steady-state operating conditions. The next step is for future researchers to develop this study using models where there will be changing material properties and operating conditions. Transmissibility is stressed as an important operating parameter within rotating machinery due to its direct effect on the rate of wear and tear, the frequency of failures, and the total life cycle cost. With the combined use of vibration measurement tools and finite element modelling based on real-time feedback, vibration-induced stress points can be detected and dealt with proactively through maintenance planning, thus contributing to higher reliability of equipment operation and lower rates of unanticipated breakdowns. As a matter of fact, it is worth noting that the same data set was used during calibration and comparison of the models, and thus this may limit the claim of independent verification. Ideally, the data set used during verification needs to be different from the one used during calibration. However, this research was not meant to create a predictive model but rather demonstrate the application of an integrated analysis tool.

An important link between the vibration damping and overall cost-effectiveness of industrial activities provides decision makers with strong economic support for their investment in vibration control technologies. Optimization of industrial processes takes into account the cost-efficient performance range, providing for considerable savings in expensive systems. In addition to the aforementioned assumptions, the analysis involved a selected number of representative operating scenarios in order to prove the feasibility of the model. Although the provided examples are enough to prove the viability of the proposed model and show the interconnections between vibration characteristics, deterioration processes, and total life cycle costs, they cannot cover the entire range of conditions that can be found in the industrial environment. In reality, the operating conditions for the machinery systems include a wider variety of factors such as variable loads, environment, and so on. For this reason, the current analysis can only be considered as a proof-of-concept example of the proposed model. The current study considers a simple case where the framework is represented using a single component. However, in practical situations, the mechanical systems will always involve several interacting components whose vibrations can be interrelated. In the future, it could be possible to expand this model for cases involving multiple components.

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