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Research Article

Fatigue Life and Modal Analysis of Centrifugal Fan's Impeller in Portable Pneumatic Extinguisher for Forest Fires

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Abstract:
The centrifugal fan used in a Portable Pneumatic Extinguisher (PPE) designed for forest fires is a high-speed rotating machine that is vulnerable to vibrations, which can ultimately lead to system failure. Therefore, fatigue and modal analysis of the fan are crucial in the design and development process to prevent premature failure. Previous work optimized the PPE impeller design with the inner blade angle set to 64°, the outlet blade angle to 120°, and the number of blades to 24. However, fatigue analysis and modal analysis were not considered. Thus, this study examined the fatigue life and modal behavior of the impeller in a centrifugal fan used in a PPE, utilizing the Finite Element Analysis (FEA) method. The results showed that the impeller experienced a maximum von Mises stress of 26.4 MPa, with a maximum deformation of 3.07 $\times 10^{-4}$ mm in the section with the highest stress. The minimum deformation was 1.52 $\times 10^{-6}$ mm, and the maximum displacement recorded was 0.056 mm. Fatigue life analysis indicated minimal or no visible damage to the impeller. Modal analysis revealed that the lowest frequency was 150.8 Hz, approximately 22.6% lower than the natural frequency, suggesting that resonance is unlikely under normal operating conditions. Overall, the impeller design demonstrated sufficient structural integrity and fatigue life for the PPE's intended use in forest fire applications.

Keywords: *Fatigue life, Modal analysis, Centrifugal fan, Portable pneumatic extinguisher*

1. Introduction

Determining the fatigue life of the equipment is a critical task that involves evaluating the time span between its installation and the point of failure [1-3]. Over the years, extensive research has been conducted to analyze the fatigue properties of impellers in centrifugal fans, shedding light on their structural integrity and lifespan [4-7]. These studies have yielded valuable insights into the factors affecting the fatigue life of impellers and have paved the way for advancements in impeller design and maintenance strategies. Understanding the fatigue behavior of impellers is crucial for ensuring the efficient and reliable operation of centrifugal fans in various industries.

Kashyzadeh et al. [8] conducted a study to analyze the fatigue of a centrifugal compressor impeller using Finite Element Analysis (FEA). The investigation involved performing stress analysis and identifying the region where failure is most likely to occur. The stress tensor was extracted for the critical region at various time points during operation. Additionally, the study compared the results obtained from finite element models made of different

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materials to assess their performance. Liu et al. [9] conducted a study that encompassed both centrifugal and aerodynamic loads in the analysis of impeller life FEA. Their research led to the conclusion that the failure mechanism of the impeller can be expressed analytically, and furthermore, its reliability can be assessed in real-time online. Xie et al. [10] conducted research specifically on the centrifugal fan blades used in high-speed train cooling systems. They established an experimental system and research methodology for fatigue analysis and fault diagnosis. The results of their study demonstrated the accurate classification of faults in centrifugal fan blades. They also developed a comprehensive research flow and methodology, which serves as a valuable reference for future studies on fatigue and fault pattern recognition in fan blades. Jinlong et al. [11] utilized the backpropagation neural network (BP neural network) to evaluate centrifugal impellers' very high cycle fatigue life. Their objective was to investigate the impact of internal inclusions and the granular bright facet (GBF) region on fatigue life. The results of their study demonstrated that by employing the BP neural network comprehensively, it was possible to predict the fatigue life with various input parameters. Notably, the predictions varied when different input parameters were used, and the evaluation of very-high cycle fatigue life, considering both internal inclusions and the GBF region, yielded highly satisfactory results. Many studies related to fatigue life assessment of impellers with different methods have also been published [12-17].

In addition to fatigue analysis, modal analysis has gained prominence in evaluating the dynamic characteristics of impellers in various applications [18-21]. Modal analysis helps identify the impeller's natural frequencies and mode shapes, enabling engineers to optimize its design and mitigate potential resonance issues. Oza and Shah [22] employed FEA to perform modal analysis on a radial flow impeller utilized in a centrifugal pump. Additionally, experimental modal analysis was conducted using an impact hammer, enabling the identification of the first twenty natural frequencies. A comparison was made between the natural frequencies obtained from both methods, revealing a high degree of agreement between the results. Wang et al. [23] conducted a study to examine the impact of added mass, centrifugal force, and hydraulic load on the natural frequencies of a Reactor Coolant Pump (RCP). They performed modal analysis on a full-scale RCP using simulation techniques, allowing them to evaluate the system's dynamic behavior. As a result of their analysis, they proposed an improved impeller design aimed at preventing hydraulic resonance, which can help enhance the overall performance and reliability of the RCP. In the study conducted by More et al. [24], both experimental and numerical analyses were carried out to investigate the impact of impeller blade thickness and rotating speed on impeller performance. The numerical study included modal analysis using the ANSYS Workbench commercial software. The results indicated that the impeller blade with a thickness of 1.5 mm exhibited reduced noise and vibrations when operated at the maximum rotating speed.

Forest fires pose significant threats to human life and the environment, necessitating the development of efficient firefighting equipment. Portable pneumatic extinguishers (PPE), equipped with centrifugal fans have emerged as a valuable tool for combating forest fires due to their compact design and high-performance capabilities [25, 26]. The centrifugal fan's impeller, a critical component of these devices, is subjected to dynamic loading conditions during operation, making its fatigue behavior and modal characteristics of utmost importance to ensure the reliability and performance of the portable pneumatic extinguisher.

A previous study was conducted to optimize the effects of impeller parameters on the velocity and pressure at the outlet of a PPE using CFD. This study determined the optimized values for the inner blade angle, blade angle output, and the number of blades to be 64°, 120°, and 24, respectively. The corresponding velocity and pressure at the outlet were found to be 75.15 m/s and 2065.76 Pa. The results of this study were further validated through physical model tests, which showed a deviation of less than 5%. However, it should be noted that fatigue analysis and modal analysis were not conducted as part of this research [27].

This study focuses on the fatigue and modal analysis of the impeller in a specialized PPE designed for forest fire fighting. The analysis was conducted using SolidWorks software, which allowed for the creation of a finite element model to evaluate the impeller's fatigue life and modal characteristics. The fatigue analysis considered various factors, including material properties, operating conditions, and impeller geometries, to assess the impeller's structural integrity under cyclic loading. On the other hand, the modal analysis aimed to identify the impeller's natural frequencies and mode shapes, providing essential insights for optimizing the design and implementing vibration control strategies. These results are crucial for ensuring the impeller's reliable performance, minimizing potential issues such as excessive noise, and preventing impeller fatigue.

2. Materials and Methods

2.1 Portable Pneumatic Extinguisher

The Portable Pneumatic Extinguisher (PPE) is a specialized firefighting device engineered to combat low-intensity forest fires (Fig. 1). It offers portability and versatility, allowing for efficient deployment in various firefighting scenarios. Its effectiveness in suppressing fires has led to widespread adoption by forest firefighting forces and other relevant departments. The PPE operates using a two-stroke gasoline engine, which serves as the primary power source. This engine drives a blower, creating a high-speed vapor flow that is directed toward the flames to extinguish them. The design of the PPE enables it to effectively combat newly ignited or low-intensity forest fires, including canopy fires at specific altitudes, forest surface fires, and grassland fires. However, the PPE faces certain challenges that affect its overall performance. One such challenge is related to low energy utilization. Due to the nature of the two-stroke gasoline engine, there may be inefficiencies in converting fuel energy into useful power. This can result in suboptimal performance and reduced effectiveness in firefighting operations. Another challenge is the suboptimal fan efficiency. The lightweight centrifugal fan used in the PPE may not be fully optimized for maximum airflow and pressure generation. This can limit the device's ability to deliver an adequate amount of extinguishing agent to the flames, potentially affecting its firefighting capabilities [27].

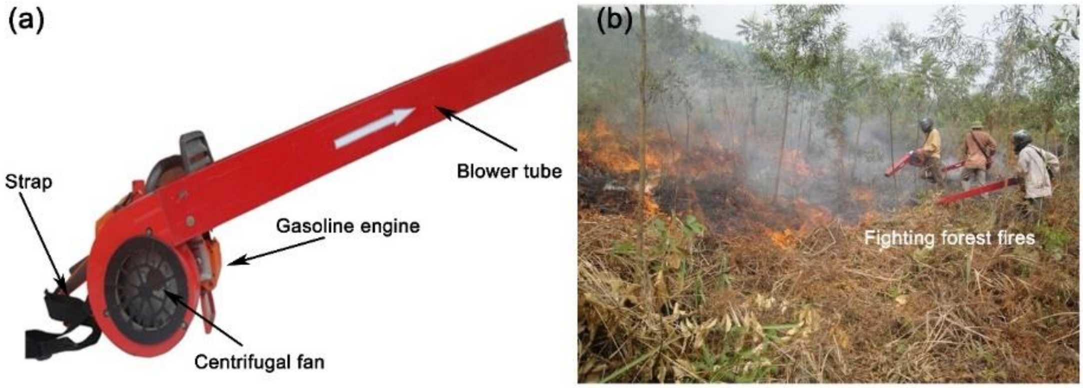

Fig. 1. General structure of PPE (a) and reality used in firefighting (b)

Additionally, the PPE may experience issues such as excessive vibration and noise. These issues can arise due to the composition and design of the device, which incorporates a small gasoline engine and a lightweight centrifugal fan. The vibrations and noise generated during operation can not only impact the comfort and safety of the firefighting personnel but also potentially affect the device's reliability and lifespan. To address these challenges, optimizing the design of the centrifugal fan structure becomes crucial. By carefully analyzing and improving the fan's design, including its blade geometry, inlet and outlet configurations, and overall structural integrity, the performance of the PPE can be enhanced. Improving the PPE's overall performance through design optimization can enhance energy utilization, increase fan efficiency, and reduce vibration and noise levels. These improvements can contribute to the device's effectiveness in combating low-intensity forest fires, providing firefighters with a more reliable and efficient tool for firefighting operations in challenging environments.

2.2 FEA Method

The FEA process for the impeller of the PPF can be outlined in four distinct steps: 3D modeling, meshing, setup of operational conditions, and conducting the analysis. To begin, a 3D impeller model was created using SolidWorks software. Subsequently, the SolidWorks Simulation option was utilized for meshing, incorporating the fluid field, and performing the analysis. This comprehensive approach allowed for a detailed examination of the impeller's structural integrity and performance. In particular, attention was given to identifying stress concentration areas, which are typically prone to fatigue crack formation in engineering applications. The mean stress at these critical points of stress concentration was also determined, providing valuable insights into potential failure mechanisms and the impeller's overall durability. This study constructed a full-sized model of the centrifugal impeller based on the entity depicted in Fig. 2. The impeller under investigation belongs to the fan impeller of a wind fire extinguisher and features forward-curved single blades. The inner blade angle, blade angle output, and the number of blades were set to 64°, 120°, and 24, respectively.

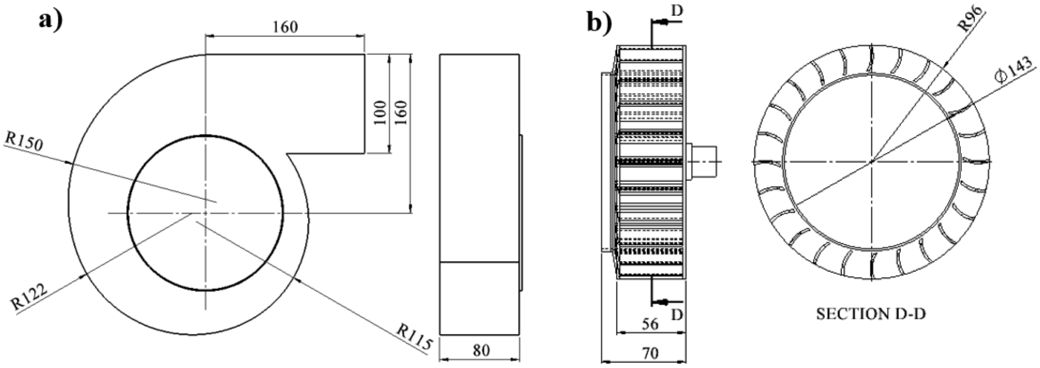

Fig. 2. The main dimensions of centrifugal impeller casing and blade [27]

The impeller was selected for analysis from 6061-T6 aluminum alloy based on actual samples that have been fabricated. Some of the main mechanical properties of 6061-T6 are as follows: an ultimate tensile strength exceeding 310 MPa, a Poisson's ratio of 0.33, and an elastic modulus of 68.9 GPa, all established during simulation analysis. These parameters are important for accurately representing the mechanical behavior of the impeller and ensuring the validity of the analysis conducted in this study.

In setting up the operational conditions, various stress factors such as machining residual stress, assembly stress, thermal stress, centrifugal stress, and stress from the fluid medium can influence the impeller in a combined manner. However, in this study, the impeller is directly attached to the working shaft of the gasoline engine. Therefore, only centrifugal and aerodynamic loads are considered relevant stress factors for analysis. The impeller's direct connection to the engine shaft simplifies the stress modeling such that thermal, assembly, and other stresses involved in a more complex setup are not applicable in this case. The analysis focuses on the primary operational loads of centrifugal and aerodynamic forces acting on the impeller during engine running conditions.

In the analysis step, it is crucial to account for the intricate dynamics of fluid motion, encompassing phenomena such as three-dimensional turbulent flow, separated flow, and reflux. To model and understand the fluid flow, computational fluid mechanics techniques are employed to numerically solve the governing differential equations. This allows for obtaining an approximation of the fluid behavior. By examining the fluid flow patterns around the impeller surface, it becomes possible to determine the aerodynamic load. Previous research findings suggest that the aerodynamic load can be simplified by assuming a uniform pressure distribution of 3.34×10^{-3} N/mm^2 on both the suction and pressure surfaces of the impeller. Simultaneously, a centrifugal load is applied to the impeller spindle, assuming a constant rotation velocity of 7000 RPM. This accounts for the centrifugal forces acting on the impeller. By considering the combined effects of the centrifugal load and the simplified aerodynamic load, a comprehensive analysis can be conducted to assess the system's behavior under these conditions.

2.3 Fatigue Life and Modal Analysis

Determining model fatigue life is crucial in engineering and design, as it helps predict the durability and lifespan of a PPE's impeller or structure subjected to cyclic loading, which can lead to fatigue failure over time. In addition, the impeller experiences vibration due to various factors, including centrifugal force, air-induced vibration, and the instability of the sealing rotor. When the excitation frequency aligns closely with the impeller's natural vibration frequency or integer multiples thereof, it leads to pronounced resonance and generates significant dynamic stress. Consequently, this high stress can cause the impeller to fail in terms of strength. In reality, two main methods commonly employed to determine fatigue life are fatigue life testing and fatigue life analysis. Fatigue life testing involves subjecting a representative specimen or component to repeated loading cycles until failure occurs. This method provides direct empirical data on the fatigue life of the material or structure under specific loading conditions. However, fatigue life testing can be expensive and time-consuming, especially when dealing with complex or largescale systems. It often requires the construction of multiple prototypes and extensive testing, which can significantly delay the development process.

In this study, the SolidWorks Simulation module is used to investigate the fatigue life and Modal analysis of the PPE's impeller model after it has been optimized for size. Once the operating conditions and geometry are defined, Solidworks Simulation can simulate the cyclic loading on the impeller and calculate the corresponding stress distribution. The analysis considers factors such as centrifugal forces, fluid forces, and any additional external loads. By simulating the cyclic loading conditions and analyzing the stress distribution, the software can determine the areas of maximum stress and the stress ranges experienced by the impeller. Based on the stress distribution, Solidworks Simulation applies established fatigue models, such as the stress-life (S-N) curve or strain-life (ε-N) curve, to estimate the impeller's fatigue life. These fatigue models consider the relationship between stress or strain levels and the number of cycles to failure. Solidworks Simulation can predict the impeller's expected fatigue life by comparing the calculated stress or strain levels with the fatigue curve.

Solidworks Simulation also provides a modal analysis tool that calculates the impeller's natural frequencies, mode shapes, and mode participation factors. Modal analysis in Solidworks involves creating a finite element model of the impeller and defining the material properties and boundary conditions. The software then solves the eigenvalue problem to determine the impeller's natural frequencies and mode shapes. The mode shapes represent the deformation patterns of the impeller at different frequencies or vibration modes. By analyzing the mode shapes and natural frequencies can gain insights into the impeller's dynamic behavior and potential resonance issues. Resonance can lead to excessive vibrations, adversely affecting the impeller's performance and longevity.

3. Resuts and Disscusion

3.1 FEA Results

The mesh of the PPE impeller was constructed using triangular elements of solid mesh type, with each side of the triangle measuring 5 mm and a tolerance of 0.25 mm. Other mesh parameters are shown in Table 1, and the mesh model of the impeller is presented in Fig. 3.

Table 1: Parameters of the PPE impeller mesh

No.	Parameters	Value
1	Mesher Used	Standard mesh
2	Automatic Transition	Off
3	Include Mesh Auto Loops	Off
4	Jacobian points for High quality mesh	16 points
5	Element size	5 mm
6	Tolerance	0.25 mm
7	Mesh quality	High
8	Total nodes	39666
9	Total elements	19188
10	Maximum Aspect Ratio	24.358
11	Percentage of elements with Aspect Ratio < 3	71.7
12	Percentage of elements with Aspect Ratio > 10	0.12
13	Percentage of distorted elements	0
14	Number of distorted elements	0

The deformations and von Mises stress distribution of the solid parts of the PPE's impeller can be observed in Fig. 4. Von Mises stress is a measure used in engineering to predict the yielding of materials under complex loading. It provides a single value that represents the combined effect of different types of stress (tensile, compressive, and shear) acting on a material. In this simulation, the maximum von Mises stress experienced by the impeller is 26.4 MPa, while the minimum recorded stress is 0.1 MPa. The highest stress is localized at the feet of the impeller blade inlet, indicating that this area is subjected to significant mechanical loading. Deformation refers to the change in shape or size of an object due to applied forces. In this analysis, the maximum equivalent strain (ESTRN) observed in the region of highest stress is 3.07×10^{-4}, while the minimum deformation is 1.52×10^{-6}. This suggests that certain areas of the impeller experience negligible deformation, while others are more affected by the applied loads. The maximum displacement recorded during the analysis was 0.056 mm, reflecting the extent of movement the impeller undergoes under loading conditions. The safety factor is a measure of the reliability of a design, defined as the ratio of the material's strength to the maximum stress experienced in service. A higher safety factor indicates a greater margin of safety. In this case, the smallest calculated safety factor is 1.04, suggesting that the impeller design has a limited margin for error. This raises concerns about potential failures or fatigue issues, highlighting the need for careful evaluation of the design.

These findings are essential for assessing the structural integrity and performance of the PPE's impeller. They provide valuable insights for further optimization and refinement of the design to ensure compliance with performance and safety standards. A more detailed explanation of the figures and their implications would enhance understanding and facilitate informed decision-making in the design process.

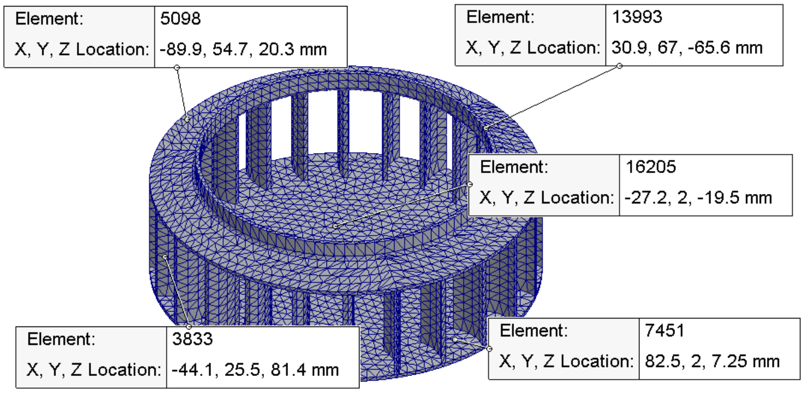

Fig. 3. The mesh model of the impeller

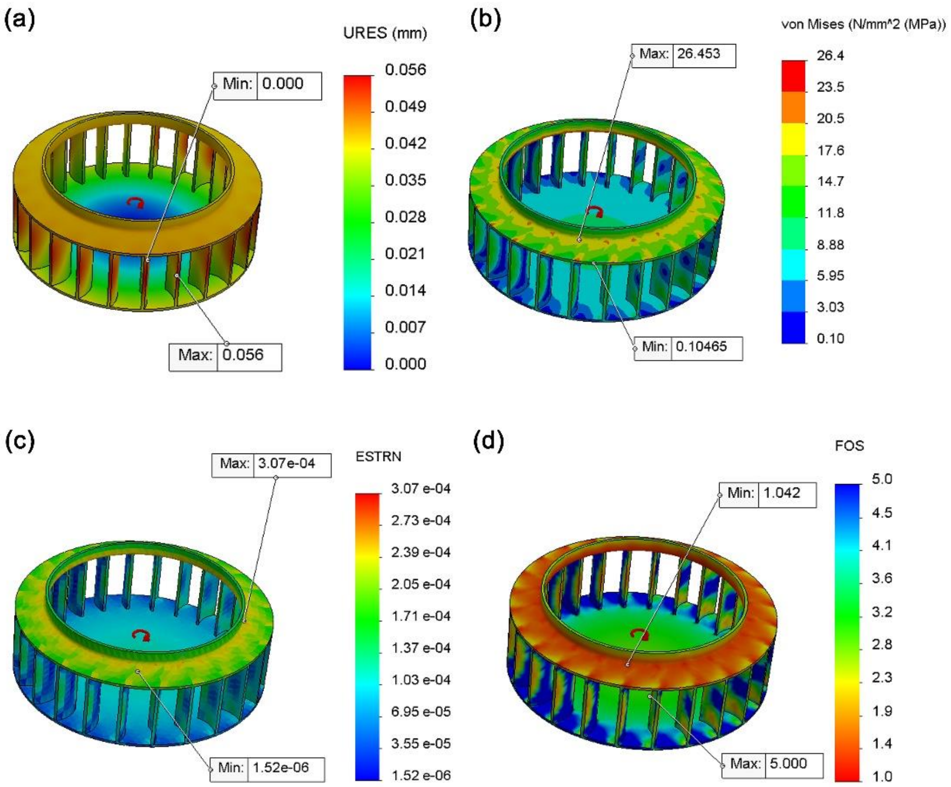

Fig. 4. FEA results of the PPE model: displacement (a), von Mises stress (b), deformation (c), and safety factor (d)

3.2 Fatigue Life

A damage plot is a valuable tool in the product design and development process, as it allows engineers and designers to understand how a structure reacts to a given load and identify areas needing improvement or design changes to optimize product performance and strength [28]. In this study, the damage plot of the PPE impeller was generated using a fatigue analysis tool. The equivalent von Mises maximum stress, based on static simulation, serves as the boundary condition for the impeller's analysis. The fatigue analysis results are shown in Fig. 5.

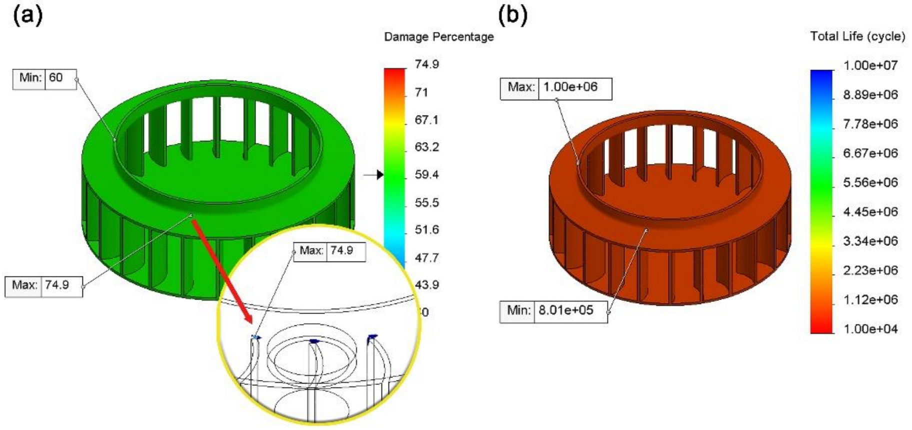

Fig. 5. The fatigue life results of the PPE's impeller: a) Damage plots, b) Tolal life cycle

The results indicate that the highest damage rate is 74.9%, concentrated at the connection between the blade and plates of the impeller (Fig. 5a). However, no damaged points were identified, so no design changes are necessary. Fig. 5b presents the results of the life analysis, representing the number of lives cycles the PPE impeller can withstand before failing due to fatigue. The plot shows that the outer rim area of the impeller has the shortest lifespan of 8.01×10^5 cycles, as it is subjected to greater force and pressure, making it susceptible to deformation. Other areas have longer lifespans, reaching values of up to 10^6 cycles.

3.3 Modal Analysis

The purpose of this analysis is to verify that the PPE impeller's operating speed frequency does not coincide with its natural frequency. This precaution is necessary to prevent resonance, which can result in vibration failure of the impeller and impact its performance during operation. At 7000 RPM, the corresponding generated frequency is:

$$f = \frac{n}{60} = \frac{7000}{60} = 116.7\text{Hz} \tag{1}$$

where f is the operating speed frequency (Hz) and n is the impeller's rotating speed (RPM).

The modal analysis solution provides the twenty lowest-order vibration modes, with the fifteen natural frequencies of the impeller presented in Table 2. Among these frequencies, the PPE impeller's natural frequency of 150.8 Hz is the lowest. Therefore, in theory, resonance will not occur during normal operation because the operating frequency is lower than all the natural frequencies. However, despite the relatively small difference of 22.6%, there remains a possibility of resonance, which could lead to vibration failure or excessive noise. Thus, it is crucial to ensure that the operating speed frequency does not coincide with the natural frequency to minimize the risk of resonance-related issues and maintain optimal PPE impeller performance.

The modal analysis results of the six PPE impeller's lowest-order vibration modes are illustrated in Fig. 6. The resultant amplitude plot for the mode shapes (AMPRES) provides insight into how the fans deform when vibrating in a particular mode. It shows the magnitude of displacement across the fans, highlighting areas that may experience the most significant movement. The results indicate that mode shape 1 at 150.8 Hz exhibits the maximum relative displacement of 2.76 mm at the impeller plates during vibration. A similar result for mode shape 2 at 150.9 Hz is 2.75 mm. Mode shape 3 at 245.5 Hz has a smaller relative displacement of 1.70 mm, but this displacement is concentrated at the outer edge of the blades. However, in these three modes, the overall shape of the fans does not bend or twist significantly. Mode shape 4 shows a maximum relative displacement of 2.79 mm at the blade plates. However, at 682.8 Hz, the overall shape of the fan bends and twists significantly. This behavior is also observed in modes 5 and 6 at 809.9 Hz and 810.6 Hz, respectively. This indicates that the blades undergo significant bending and twisting motions, highlighting their involvement in the primary vibrational behavior of the fan.

Table 2: The first fifteen natural frequencies and their deviation from the operating speed frequency

Frequency Number	Natural frequency (Hz)	Deviation (%)
1	150.8	22.6
2	150.9	22.6
3	245.5	52.5
4	682.8	82.9
5	809.9	85.6
6	810.6	85.6
7	1062.3	89.0
8	1067.4	89.1
9	1510.3	92.3
10	1514.6	92.3
11	1766.4	93.4
12	1768.0	93.4
13	1791.5	93.5
14	2636.4	95.6
15	2637.2	95.6

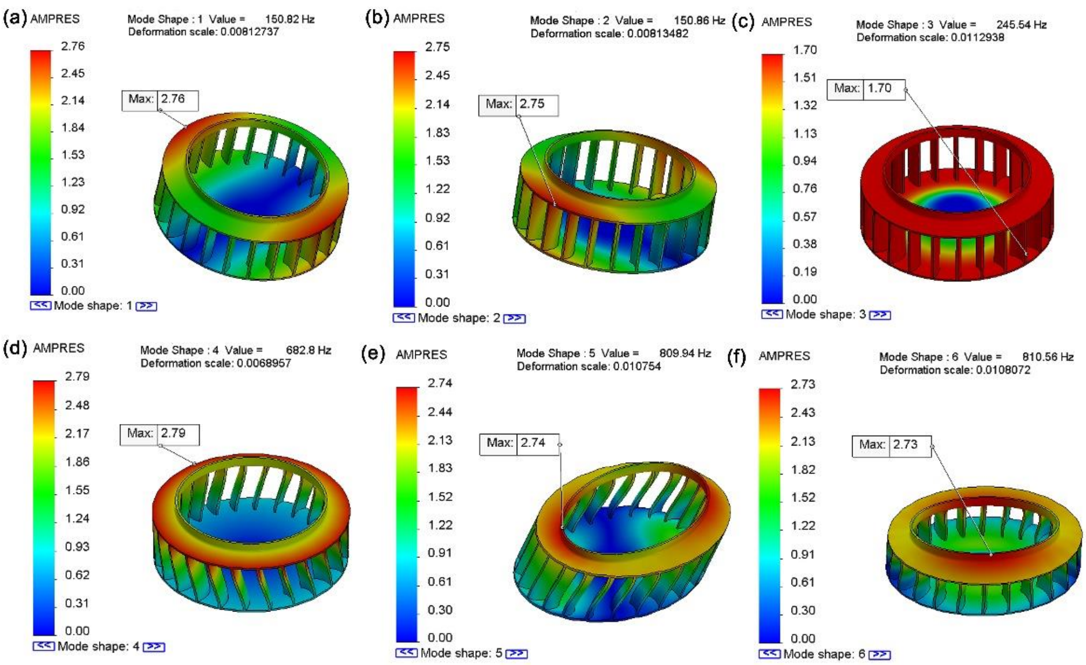

Fig. 6. The six lowest-order vibration modes of the PPE's impeller

These results are crucial for understanding potential resonance issues. If the operating frequency of the PPE impeller approaches its natural frequency, there is a risk of resonance, which can lead to excessive vibrations, noise, or even structural failure. Consequently, engineers and designers can identify specific areas of the PPE impeller that require attention concerning structural integrity, material selection, or damping mechanisms. Understanding the distribution of relative displacements aids in optimizing the PPE's performance, ensuring reliable operation, and minimizing associated issues such as excessive noise or component fatigue.

4. Conclusion

This study focuses on the fatigue and modal analysis of the impeller in a specialized PPE designed for forest fire fighting. The FEA results have provided valuable insights into the structural integrity and performance of the PPE's impeller. The fatigue analysis indicated no visible damage points, suggesting that design changes may not be necessary under the simulated conditions. Additionally, the modal analysis revealed that the fan's operating speed frequency does not coincide with its natural frequency; however, the relatively small difference raises concerns about potential resonance, which could lead to fan failure and excessive noise. These findings underscore the importance of understanding stress distribution, deformation patterns, and vibrational behavior. Nevertheless, further validation through experimental testing is essential to confirm these results in real-world conditions. Simulation-based conclusions must be approached with caution, as they may not fully capture the complexities of actual operational environments. Future work should focus on experimental verification and the exploration of various operating conditions to enhance the reliability and performance of the impeller design. By integrating these insights, engineers and designers can make more informed decisions regarding material selection, structural enhancements, and damping mechanisms, ultimately ensuring the reliable operation of this critical PPE component.

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