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Article

Collaborative study on vibration modes and stability of key components of hydropower units based on multi-physical field joint test

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Abstract: In recent years, the gradual molding of new power systems has required hydroelectric units to assume more grid regulation tasks. Consequently, these units frequently traverse vibration zones, leading to severe blade cracking that compromises safe power production. Based on actual blade cracking faults in a power plant, this study conducts joint field experimental research focusing on the stability of hydropower units and the vibration modes of runners and blades. Vibration modal parameters and unit stability data under various working conditions were acquired through hammering and stability tests. The results demonstrate that mass imbalance is a primary factor affecting unit stability, with minor differences observed in the intrinsic frequency distribution among different blades. Under small load conditions, the vibration frequency at multiple measurement points approaches half of the blades' multi-order intrinsic frequency, potentially triggering sub-harmonic resonance. Furthermore, the fourth to sixth-order intrinsic frequencies of the runner are similar to the intrinsic frequency, increasing the risk of high-order resonance. To mitigate these issues, recommendations including dynamic balancing tests, optimized operation strategies, and periodic inspections of component connections are proposed. Ultimately, this research provides crucial data and a theoretical foundation for the safe operation, optimal design, and future investigation of hydropower units, significantly promoting the sustainable development of the hydropower industry.

Keywords: hydropower units; stability; vibration modes; resonance analysis; dynamic balancing

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1. Introduction

In the context of accelerating the construction of a new power system, hydropower, as an important clean energy source, plays a crucial role in ensuring a stable electricity supply and promoting the transformation of the energy structure. Hydropower unit operating conditions are inherently complex and variable, influenced by a dynamic interplay of factors. The runner, as a key core component of a hydropower unit, directly impacts the operational stability of the unit. Therefore, conducting in-depth research on the stability of hydropower units and the vibration modes of runners is essential to ensure the safe and stable operation of these units. Such research can significantly enhance power generation efficiency, effectively extend the service life of equipment, and promote the development of a greener, more efficient, and reliable power system.

Many researchers have explored the vibration characteristics of hydropower units, particularly focusing on the vibration modes of runners. Advanced simulation techniques, such as finite element analysis, have been employed to model and analyze the vibration modes of runners under various operating conditions. These studies have provided valuable insights into the optimization of runner structures, revealing the intrinsic connections between structural parameters and vibration characteristics. Additionally, experimental approaches, including the use of advanced measurement technologies like laser-based systems, have enabled precise assessments of blade vibration responses under different conditions. Such methodologies have introduced innovative ways to study the vibration characteristics of blades, offering new perspectives for improving the design and performance of hydropower units.

Further investigations have highlighted the impact of mechanical and hydraulic factors on unit stability. For instance, imbalances in unit mass can lead to increased mechanical vibrations, while hydraulic phenomena such as pressure pulsations can significantly affect stability. Optimizing the design of turbine runners has been shown to reduce the amplitude of pressure pulsations, thereby improving overall stability. Similarly, the influence of electromagnetic factors on unit vibration has been analyzed, with strategies proposed to mitigate these effects through optimized excitation control. These findings underscore the multifaceted nature of hydropower unit stability and the importance of addressing various contributing factors to enhance performance and reliability.

Despite these advancements, there remains a notable gap in the comprehensive and systematic study of the joint stability and vibration modes of hydropower units. Current research often lacks the depth and breadth required to fully address the growing demand for the safe and stable operation of hydropower units. Field test data, while valuable, are often underutilized, limiting their potential to inform optimization and transformation efforts. This gap in research has practical implications, as evidenced by operational challenges faced by hydropower plants. Issues such as increased vibration, frequent cracks, and even the detachment of components during unit operation pose significant risks to stability and economic performance. These challenges highlight the urgent need for joint testing initiatives that can provide a comprehensive understanding of unit characteristics. By leveraging such insights, it becomes possible to develop targeted strategies for optimization and transformation, ensuring the long-term stability and efficiency of hydropower units.

However, at present, there are relatively few studies that integrate the joint testing of stability and runner vibration modes in hydropower units. This lack of comprehensive research has resulted in a limited understanding of the complex interactions that govern unit performance. Moreover, the depth of analysis and application of test data remains insufficient, making it challenging to meet the increasing demands for the safe and stable operation of hydropower units.

In practical scenarios, hydropower plants often encounter significant operational challenges. During the operation of units, issues such as increased vibration, frequent cracking, and even the detachment of components are not uncommon. These problems not only compromise the stability of the units but also have adverse economic implications, as they can lead to costly repairs and downtime. Such challenges underscore the critical need for a more detailed and systematic approach to understanding unit behavior under various conditions.

To address these issues, joint testing initiatives are being undertaken to provide a more comprehensive understanding of unit characteristics. These tests aim to capture a wide range of data, encompassing both stability and vibration mode parameters, to offer a holistic view of unit performance [1]. By analyzing this data, researchers can identify key factors influencing unit behavior and develop targeted strategies for optimization. For instance, understanding the relationship between structural parameters and vibration characteristics can inform the design of more robust and efficient runners. Similarly, insights into the effects of hydraulic and mechanical factors can guide the development of measures to mitigate adverse impacts, such as pressure pulsations and mass imbalances.

The ultimate goal of these efforts is to ensure the safe and stable operation of hydropower units while maximizing their efficiency and lifespan. By addressing the root causes of operational challenges and leveraging advanced testing and analysis techniques, it is possible to achieve significant improvements in unit performance. This, in turn, contributes to the broader objective of advancing the development of a new power system that is greener, more efficient, and more reliable. The findings from such research not only have practical implications for the operation of existing hydropower plants but also provide valuable insights for the design and development of future systems. Through continued innovation and collaboration, the hydropower industry can play a pivotal role in shaping a sustainable energy future.

2. Theoretical Foundation

2.1. Theoretical Basis of Vibration Modes

As the core component of energy conversion, the rotor of a hydropower unit exhibits significant vibration modal characteristics due to fluid-structure coupling. When subjected to high-speed and complex water flow excitation, the vibration modes of the runner and blades demonstrate multi-order and non-linear behaviors [2]. These characteristics are governed by the vibration differential equation, where M represents the mass matrix, C denotes the damping matrix, K is the stiffness matrix, and $F(t)$ accounts for the coupled excitation arising from water flow pulsation and mechanical load. The dynamic interaction between these factors plays a critical role in determining the operational stability of the system.

$$M\ddot{x} + C\dot{x} + Kx = F(t)$$

For the Francis turbine, the runner blades are subjected to periodic pressure pulsations within a non-constant flow field. The vibration modes of these blades are influenced by several factors, including material properties such as modulus of elasticity and density, as well as geometrical parameters like blade thickness and twisting angle. Additionally, the boundary conditions, such as the stiffness of the connection between the blades and the hub, significantly affect the modal behavior. Modal tests reveal that the low-order modes of the runner primarily exhibit overall bending and torsion coupling, which are indicative of global structural deformations. In contrast, the higher-order modes display localized modal characteristics, often confined to specific regions of the blades. These localized modes can amplify stress concentrations and pose a potential threat to the operational stability and longevity of the unit [3, 4]. Understanding these modal characteristics is essential for optimizing the design and ensuring the reliability of hydropower systems under varying operational conditions.

2.2. Mechanisms of Unit Stability under the Action of Multi-Field Coupling

The stability of hydropower units is influenced by the complex interplay of mechanical, hydraulic, and electromagnetic factors, which collectively form a multi-field coupling effect. This phenomenon arises from the intricate interactions between these fields, each contributing to the overall operational behavior of the unit. Mechanical factors include the structural integrity and dynamic response of components under varying loads, while hydraulic factors involve fluid dynamics, pressure fluctuations, and flow-induced vibrations. Electromagnetic influences stem from the performance of generators and associated electrical systems, which can affect the stability of the entire unit. Understanding these interactions is critical for optimizing performance and ensuring reliability, particularly under varying operational conditions and external environmental influences [5]. Advanced modeling and simulation techniques are often employed to analyze these factors comprehensively.

2.2.1. Mechanical Factor

The centrifugal force induced by mass eccentricity plays a critical role in the dynamic behavior of rotating machinery. This force arises due to the uneven distribution of mass around the rotational axis, which generates oscillatory forces as the machinery operates. The magnitude of the centrifugal force is directly proportional to the eccentricity of the mass and the square of the rotational speed. This phenomenon can lead to significant mechanical vibrations, which may compromise the stability and operational efficiency of the equipment. Understanding and mitigating these forces is essential for maintaining the reliability and safety of mechanical systems, particularly in high-speed applications. Engineers often employ advanced balancing techniques and precision manufacturing processes to minimize mass eccentricity and its associated effects. Additionally, monitoring systems are implemented to detect and address any deviations from the design specifications, ensuring optimal performance and reducing the risk of mechanical failure.

$$F = mr\omega^2$$

When the eccentricity of a rotating component exceeds the design threshold, such as 0.05 mm as specified in GB/T 8564 - 2023, the resulting vibration amplitude increases significantly with the square of the rotational speed. This relationship underscores the importance of maintaining strict adherence to design tolerances to prevent excessive vibrations. Empirical data indicate that at 50% load in a power station unit, the upper guide oscillation caused by mass imbalance constitutes approximately 67% of the total vibration component. Such findings highlight the critical need for precise balancing and alignment during the manufacturing and operational phases of mechanical systems [6]. Engineers must carefully analyze these dynamics to optimize the performance and longevity of equipment, particularly in high-load scenarios. Advanced diagnostic tools and real-time monitoring systems are often employed to identify and mitigate vibration-related issues, ensuring compliance with stringent operational standards.

2.2.2. Hydraulic Factor

At partial load conditions, typically ranging between 30% and 60% of the rated load, the separation of inlet and outlet flows around the runner blades generates a phenomenon known as the Carmen vortex. This vortex is characterized by a specific ratio to the rotational frequency, referred to as the Strauhl number, which generally falls within the range of 0.2 to 0.4. When the frequency of this vortex aligns closely with the intrinsic frequency of the blades, a resonance effect is triggered. Such resonance can have significant implications for the operational stability and efficiency of hydraulic systems. For instance, in a power plant operating at a load of 25 MW, the primary frequency of pressure pulsations within the tailpipe is observed to be approximately 0.13 times the rotational frequency [7]. This frequency coincides with a 1/3 crossover resonance involving the third-order intrinsic frequency of the blade, which is measured at 415 Hz. This interaction underscores the critical importance of understanding and managing hydraulic dynamics to mitigate potential resonance-induced stresses and ensure the longevity and reliability of turbine components.

2.2.3. Electromagnetic Factor

Electromagnetic force is a coupling force that arises from the interaction between the magnetic fields of the generator's stator and rotor. Its magnitude is significantly influenced by the excitation current and the distribution of the air gap magnetic field [8]. In hydro generators, any asymmetry in the stator windings or eccentricity in the rotor can result in an uneven distribution of air gap magnetic density. This imbalance subsequently generates unbalanced electromagnetic forces. Based on Maxwell's stress tensor theory, the electromagnetic force density can be mathematically expressed as: $\mathrm{f} = \frac{1}{2\mu_0}(\mathrm{B}^2\nabla\mu_r - \mu_r\mathrm{B}\cdot\nabla\mathrm{B})$. Such forces play a critical role in the operational stability of hydro generators, as they directly impact the mechanical and vibrational behavior of the system. Understanding these forces is essential for optimizing generator design and ensuring long-term reliability.

$$\mathrm{f} = \frac{1}{2\mu_0}(\mathrm{B}^2\nabla\mu_r - \mu_r\mathrm{B}\cdot\nabla\mathrm{B})$$

The vacuum permeability, relative permeability, and magnetic induction strength are key parameters influencing the electromagnetic force [3, 9]. When fluctuations in the excitation current or air gap eccentricity occur, the electromagnetic force exhibits components at the rotational frequency and its higher-order harmonics, such as two-fold and three-fold frequencies. These high-frequency components are particularly significant because they can induce coupling resonance with the natural frequencies of the generator's structural components. For instance, measured data from a power station indicate that a 10% fluctuation in the excitation current can lead to a 35% increase in the amplitude of stator vibration. Furthermore, the primary frequency of this vibration aligns closely with twice the rotational frequency. This phenomenon underscores the importance of maintaining stable excitation currents and minimizing air gap eccentricity to prevent excessive vibrations and potential structural damage. By addressing these factors, engineers can enhance the operational efficiency and longevity of hydro generators.

2.3. Multi-Field Coupled Vibration Characterization

In the practical operation of hydropower units, the intricate interplay of mechanical, hydraulic, and electromagnetic excitations significantly amplifies the complexity of vibration analysis. While fluid-solid coupling simulation techniques offer valuable insights into the mechanisms of multi-field coupling, these models often face limitations in accurately representing the nonlinear characteristics observed under real-world operating conditions. This discrepancy arises due to the simplifications inherent in boundary conditions and the uncertainties associated with parameter estimation. Consequently, field stability testing has emerged as the predominant approach for investigating the vibration characteristics of hydropower units. By employing a distributed sensor array, researchers can collect comprehensive dynamic response data from the unit under a variety of complex operating scenarios. This data serves as a critical foundation for diagnosing potential faults within the system. Furthermore, the integration of advanced data processing techniques, such as signal decomposition and pattern recognition, enhances the ability to identify subtle anomalies and predict potential failures. These advancements not only improve the reliability of hydropower units but also contribute to the optimization of their operational efficiency. The combination of empirical testing and analytical methodologies ensures a robust framework for understanding and mitigating the challenges posed by multi-field coupled vibrations in hydropower systems.

3. Test Principle and Results

3.1. Hammering Test

The hammering test is conducted to evaluate the mechanical structure's response under impact by applying a hammering force. This process helps construct the frequency response function matrix, which characterizes the mechanical structure's properties [10]. Through this matrix, the modal frequency, damping, and vibration modes of the structure can be identified. For a mechanical structure, the frequency response at a specific point, induced by a unit force applied at that same point, is represented by the frequency response function. By applying the principle of linear superposition, the frequency response relationship for a multi-degree-of-freedom system can be derived. This relationship provides a comprehensive understanding of the dynamic behavior of the structure, enabling engineers to assess its performance and identify potential weaknesses or areas for improvement. Such tests are critical in ensuring the reliability and safety of mechanical systems, particularly in applications where structural integrity is paramount.

$$X = \begin{Bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{Bmatrix} = \begin{Bmatrix} H_{11} & H_{12} & \cdots & H_{1N} \\ H_{21} & H_{22} & \cdots & H_{11} \\ \vdots & \vdots & \vdots & \vdots \\ H_{N1} & H_{N2} & \cdots & H_{NN} \end{Bmatrix} \begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ F_N \end{Bmatrix} = [H]\{F\}$$

Each row or column within the frequency response function matrix encapsulates all the modal information of the structure. According to the JB/T 8990-1999 protocol, it is possible to derive a column of the frequency response function through a one-point excitation combined with multi-point measurements. This approach ensures a systematic and efficient method for capturing the dynamic characteristics of the structure. By adhering to this protocol, engineers can obtain precise and reliable data, which is essential for accurate modal analysis [11]. The protocol's standardized methodology facilitates consistency across different testing scenarios, enabling comparative analysis and benchmarking of structural performance. This systematic approach is particularly valuable in industrial applications, where precision and repeatability are critical for ensuring the quality and safety of mechanical components (As shown in Figure 1).

Figure 1. Map of measurement points in the field.

Based on the actual conditions at the testing site, specific locations such as the drain cone and the lower ring were selected for arranging the measurement points. These points were distributed around the runner circumference, with consideration given to both horizontal and vertical orientations. Additionally, six blades were chosen for the hammering test to ensure comprehensive coverage of the structure's dynamic behavior. The arrangement of measurement points was carefully planned to capture the most relevant data, reflecting the structural response under various conditions. The results of these tests are presented in Table 1 and Table 2, which provide detailed insights into the rotor and blade characteristics. This meticulous approach to measurement point selection and data collection underscores the importance of precision in experimental design, ensuring that the findings are both accurate and representative of the structure's overall performance (As shown in Figure 2).

Table 1. Rotor Hammering Test Results

ordinal number	Frequency (Hz)	ordinal number	Frequency (Hz)
1	29	2	99
3	174	4	230
5	266	6	299
7	351	-	-

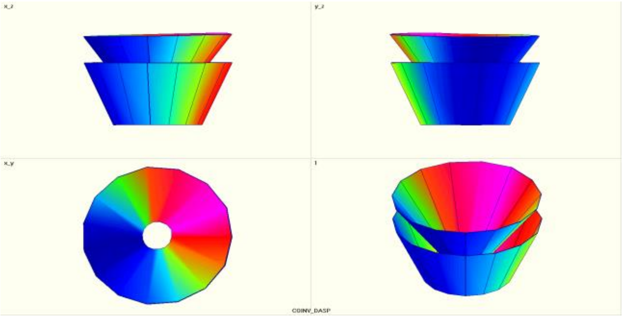
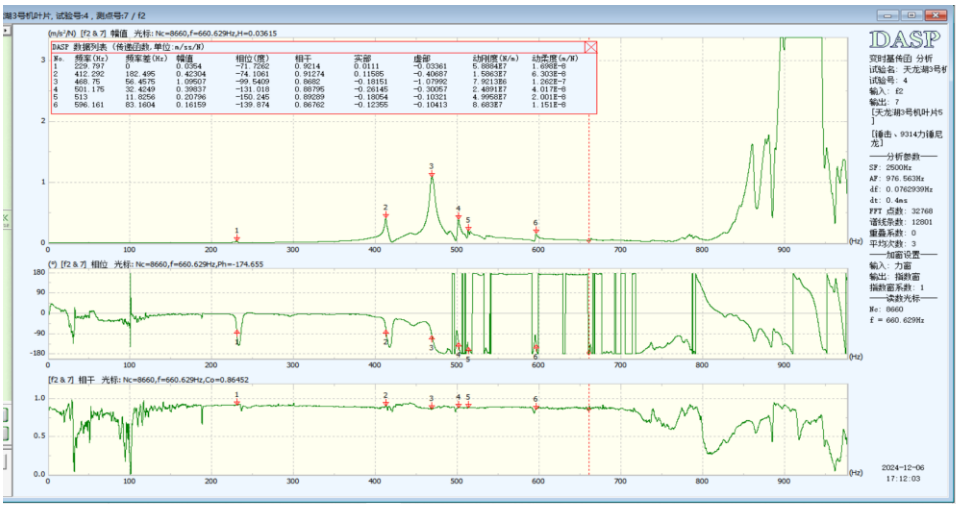


Figure 2. 1st order modes of rotor.

Table 2. Results of the first 6 orders of intrinsic frequency test of the blade

Object Leaf	Frequency 1	Frequency 2	Frequency 3	Frequency 4	Frequency 5	Frequency 6	note
No. 3	413	485	511	539	600	757	restored
No. 4	415	487	500	514	534	601	in good condition
No. 5	229	412	468	501	513	596	restored
No. 10	412	485	490	507	512	519	in good condition
No. 14	416	490	500	511	516	536	restored
No. 1	229	415	488	500	507	515	in good condition

The test results indicate that the primary intrinsic frequency of the blade is concentrated within the range of 410 to 500 Hz. Notably, there is no significant difference observed between the intact blade and the blade that was cracked and subsequently repaired. This finding suggests that the repair process effectively restores the blade's dynamic properties to a level comparable to that of an undamaged blade. Such results are critical for validating the effectiveness of repair techniques and ensuring the continued reliability of mechanical components. The data, as illustrated in Figure 3, provide a clear frequency response profile for the blades, offering valuable insights into their structural behavior. This information is essential for optimizing maintenance strategies and enhancing the overall performance and longevity of mechanical systems.



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DASP 数据列表 (传递函数,单位:m/ss/N)
No.  频率(Hz)   频率差(Hz)  幅值      相位(度)   相干      实部       虚部       动刚度(N/m)  动柔度(m/N)
1    229.797    0           0.0354    -71.7262   0.9214    0.0111     -0.03361   5.8884E7     1.698E-8
2    412.292    182.495     0.42304   -74.1061   0.91274   0.11585    -0.40687   1.5863E7     6.303E-8
3    468.75     56.4575     1.09507   -99.5409   0.8682    -0.18151   -1.07992   7.9213E6     1.262E-7
4    501.175    32.4249     0.39837   -131.018   0.88795   -0.26145   -0.30057   2.4891E7     4.017E-8
5    513        11.8256     0.20796   -150.245   0.89289   -0.18054   -0.10321   4.9958E7     2.001E-8
6    596.161    83.1604     0.16159   -139.874   0.86762   -0.12355   -0.10413   8.683E7      1.151E-8
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实时基传函 分析
试验名: 天龙湖3号机
试验号: 4
输入: f2
输出: 7
[天龙湖3号机叶片5
]
[锤击、9314力锤尼
龙]
——分析参数——
SF: 2500Hz
AF: 976.563Hz
df: 0.0762939Hz
dt: 0.4ms
FFT 点数: 32768
谱线条数: 12801
重叠系数: 0
平均次数: 3
——加窗设置——
输入: 力窗
输出: 指数窗
指数窗系数: 1
——读数光标——
Nc: 8660
f = 660.629Hz
2024-12-06
17:12:03
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Figure 3. Frequency response diagram of a certain number of blades.

3.2. Stability Tests

The stability test is categorized into three distinct types: variable speed, variable excitation, and variable load tests. Each of these tests is designed to evaluate the stability of the unit under specific influencing factors, namely mechanical, electromagnetic, and hydraulic conditions. The variable speed test assesses how the unit performs when subjected to changes in rotational speed, ensuring that the system remains stable and functional under dynamic conditions. The variable excitation test examines the unit's response to fluctuations in electromagnetic excitation, which is critical for maintaining consistent performance in electrical systems. Lastly, the variable load test evaluates the unit's ability to handle varying load conditions, which is essential for ensuring operational reliability under different demand scenarios. The results of these tests are presented in Table 3 and Table 4, providing a comprehensive overview of the unit's stability across these critical parameters.

Table 3. Variable speed, variable excitation test results

working condition	33Hz	39Hz	45Hz	50Hz	25%U	50% U	75% U	100% U
Diaphragm opening	2.48%	3.48%	5.82%	6.46%	6.59%			
Downward guidance +X-direction pendulum	151	199	250	309	325	347	374	395
Downward guide +Y-direction pendulum	178	229	271	324	331	351	372	392
Water guide +X-direction pendulum	106	118	135	149	159	163	172	172
Water guide +Y-direction pendulum	110	129	142	155	163	161	171	171
Upper rack +X horizontal vibration	11	33	60	73	64	87	114	102
Upper frame +Y horizontal vibration	15	21	31	42	42	47	48	53
Upper frame +Y vertical vibration	8	9	17	19	34	27	33	27
Lower rack +X horizontal vibration	25	34	44	57	61	65	71	76
Lower frame +Y horizontal vibration	18	28	38	51	54	58	63	69
Top cover +Y horizontal vibration	6	8	31	52	51	80	67	31
Top cover +Y vertical vibration	15	17	18	32	21	20	18	29
Tailgate horizontal vibration	23	20	35	42	55	46	66	28
Vertical vibration of tailgate	18	9	26	31	42	32	42	23
Stator base + Y horizontal vibration	14	23	37	49	59	55	62	63

Table 4. Variable load test results

working condition	5MW	10MW	15MW	20MW	25MW	30MW	35MW	40MW	45MW	50MW	55MW	60MW
Diaphragm opening	14.94	20.35	26.49	32.09	37.64	43.16	48.96	54.12	60.04	65.61	72.43	80.02
Downward guidance +X-direction pendulum	422	423	436	444	487	480	457	446	441	443	448	444
Downward guide +Y-direction pendulum	406	405	411	422	473	440	431	428	427	424	423	422
Water guide +X-direction pendulum	182	184	188	189	198	189	188	191	191	198	204	209
Water guide +Y-direction pendulum	176	170	172	178	185	177	176	178	183	187	196	197
Upper rack +X	101	113	85	87	92	91	89	89	85	85	86	88

horizontal vibration												
Upper frame +Y horizontal vibration	57	60	62	63	64	65	65	63	61	63	62	61
Upper frame +Y vertical vibration	21	17	14	11	19	10	11	12	7	7	9	7
Lower rack +X horizontal vibration	79	80	82	81	87	83	83	81	80	78	76	76
Lower frame +Y horizontal vibration	72	72	72	73	78	75	74	72	71	70	69	67
Top cover +Y horizontal vibration	24	13	10	16	12	10	9	9	14	8	12	17
Top cover +Y vertical vibration	17	14	22	26	17	15	14	16	15	16	15	16
Tailgate horizontal vibration	40	60	70	62	100	75	44	11	4	4	5	7
Vertical vibration of tailgate	30	35	42	33	50	46	41	15	8	8	8	9

3.3. Analysis of Test Data

The stability test results indicate that the maximum value of the upper guide oscillation of the unit reaches 487μm, with the rotational frequency component accounting for 67%. This significantly exceeds the limit value of zone B as defined by the national standard. Furthermore, as the rotational speed increases, the growth trend at each measurement point becomes more pronounced. The horizontal vibration of the upper frame is primarily influenced by the rotational frequency, suggesting that the unit is affected by a substantial mass imbalance. Additionally, the main frequency of the pressure pulsation in the tail water pipe is observed to be 0.13 times the rotational frequency, which results in a 1/3 crossover resonance with the third-order intrinsic frequency of the blade. At a load range of 25-40 MW, the main frequency of the vibration acceleration in the tail water pipe is measured at 281 Hz, which is close to half the intrinsic frequency of the blade. This condition is prone to triggering sub-harmonic resonance. Moreover, there is a frequency difference of 0.87% between this frequency and the fourth to sixth-order intrinsic frequencies of the runner, indicating a potential risk of multi-field coupling resonance. Modal testing reveals no significant difference in the intrinsic frequency between repaired and intact blades. However, a frequency proximity of 0.39% is noted between the third-order frequency of blade 3 and the main frequency of the pressure pulsation in the tailpipe. Comprehensive analysis identifies the 25 MW load as a critical condition that can trigger blade modal resonance and higher-order coupling of the rotor (Figure 4).

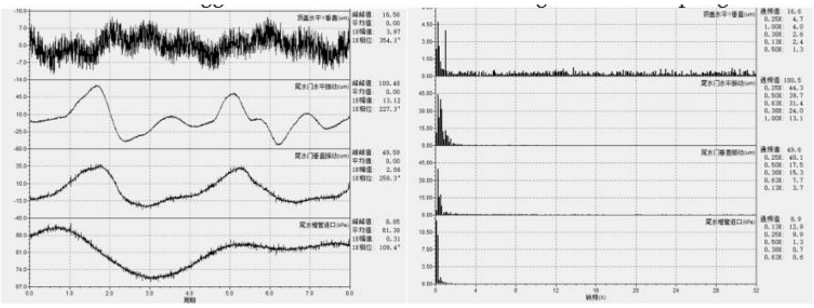

Figure 4. Time-frequency diagram of 25MW tailwater.

Based on the findings, several optimization proposals are recommended to mitigate the identified risks and improve operational stability [12]. These proposals aim to address the critical issues observed during the analysis and ensure the safe and efficient functioning of the unit.

1. Close monitoring of the vibration trends of the unit is essential. The horizontal vibration of the upper and lower racks exceeds the standard across the full-load section and is primarily influenced by the rotational frequency. To address this, dynamic balancing tests should be conducted promptly to identify and rectify any imbalances.
2. It is advisable to avoid operating the unit within the 25 MW to 40 MW range. This load range has been identified as a critical condition that can trigger resonance phenomena, posing significant risks to the structural integrity and operational stability of the unit.
3. A thorough inspection of the upper frame X-direction frame locking bolts should be conducted to identify any abnormalities. Ensuring the integrity of these components is crucial for maintaining the stability and safety of the unit during operation.

4. Reach a Verdict

With the advancement of the "double carbon" goal, the strategic importance of hydropower as a sustainable and clean energy source has been increasingly recognized. This growing emphasis necessitates enhanced stability and operational reliability of hydropower units to meet the evolving demands of the energy sector. In this study, the root cause of abnormal vibration in a specific power plant unit was identified through comprehensive modal and stability tests. The findings revealed that low-load hydraulic excitation, coupled with the 1/3 crossover frequency resonance of the blade's third-order intrinsic frequency, played a pivotal role in the observed anomalies. Additionally, the coupling effects of the runner's higher-order modes were found to exacerbate the vibration issues. These insights are critical as they provide robust experimental data to support the multi-field coupling vibration analysis of mixed-flow units. Furthermore, the results contribute valuable empirical evidence for advancing simulation studies in fluid-solid-electromagnetic multi-field coupling phenomena. Such advancements are essential for optimizing the design and operational parameters of hydropower units, ensuring their long-term stability and efficiency. The outcomes of this research not only address immediate technical challenges but also offer a solid foundation for future innovations aimed at achieving high-quality development in the hydropower industry. This work underscores the importance of integrating experimental and simulation-based approaches to tackle complex engineering problems in renewable energy systems.

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