

Design theory for vibration characterisation experiments on real turbine blades with underplatform damper

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Abstract. One of the main causes of turbine rotor blade failures is high-frequency fatigue caused by blade resonance, and the vibration of turbine blades can be effectively suppressed through the reasonable design of dry friction damping structure. In order to understand the vibration characteristics of the blade-disc system and to check whether the damping effect meets the technical specifications, it is necessary to design and carry out dry friction damping blade vibration characteristics experiment. This paper takes a certain type of underplatform damped turbine blade in production as an example, and briefly describes the design idea and design process of such blade vibration characteristic experiments under the premise of the experiment blade structure, material and other physical parameters.

Keywords: Aero-engine, blade vibration, vibration reduction, dry friction damping, underplatform damper, structural design, parameter optimization, vibration reduction experiment.

1. Introduction

With the high-speed development of the modern aviation industry, aero-engines are constantly advancing in the pursuit of high performance, and the structural design requirements for impeller machinery such as fans, compressors and turbines have become more critical. Turbine rotor blades are one of the key parts in the structural components of an aero-engine, and the vibration generated by the blades in the high temperature and high pressure gas flow is prone to lead to structural fatigue and fracture, so the suppression of vibration of the turbine blades is particularly important.

The vibration of the turbine blade can be suppressed by dry friction damping structure, and the common forms of dry friction damping devices are convex shoulder, shrouded blade, Underplatform damping and other forms. High-pressure turbine blade has a high level of aerodynamic load, and the underplatform damper compared with other forms of damping structure has no adverse effect on the aerodynamic efficiency, and has a simple structure, Damping efficiency is obvious and other advantages, so it is commonly used in high-pressure turbine blade vibration damping. The underplatform damper is installed under the blade edge plate, and achieves the purpose of energy dissipation by touching and grinding with the leaf root and platform portion. Current research applications at home and abroad have confirmed that the optimised underplatform damping structure has a good suppression effect on the vibration amplitude of the rotor blade in the low-order modes.

Up to now, the design optimisation of underplatform damping structure and corresponding platform structures of the blade is still not possible without experience and practice. To study the damping mechanism of dry friction damping structure and to design and optimise the dry friction damping device, it is necessary to design and carry out the vibration characteristics experiment of the blade with dry friction damping structure, so as to study the vibration characteristics of the blade and the integrated structure of the disc in a more in-depth manner. Experts and scholars have carried out a lot of research work on rotating [1-2] and non-rotating [3-6] blade vibration experiment. Among them, the non-rotating experiment bench simulates the centrifugal force in the form of preload force, uses force hammer, exciter, shaker, sound field and so on to stimulate the blade damping structure, picks up the response by using all kinds of sensors represented by displacement sensors, acceleration sensors, vibration meters, strain gauges and so on, and obtains the response data through the

corresponding data acquisition system, and then obtains general vibration characteristic parameters after processing the data.

According to the different research purposes, the blade vibration characteristic experiment can be roughly divided into two categories: one type of experiment is used to study the vibration damping mechanism of dry friction damping structure, to verify the correctness of the theory of dry friction damping, this type of experiments are designed by the researchers of the experiment blade, general structure is simple and representative, known as the Simulated Blade Vibration Experiment (as SBVE); The other type of experiment blade is the finalised production of the blade in use (hereinafter referred to as the real blade). The blade structure of the Real Blade Vibration Experiment (as RBVE) are more complex, and have excellent material mechanical properties, given the very reason to carry out the real blade vibration characteristics experiment in the aim of experimenting whether the vibration damping device on the installed blade be capable of meeting the technical specifications, or the existing damping device re-optimisation. There is a big difference between the experiment design ideas of the two types of experiments. The experiment blade design of simulated blade vibration experiment changes flexibly with the research objectives, the experiment boundary conditions are idealised, and the blade shape is not required to meet the aerodynamic performance requirements, so the structure can be designed very simply, and even in order to avoid the additional friction introduced in the assembly position of the blade root, the blade-fixture system can be integrated, which is convenient for the experiment to be carried out. The real blade vibration experiment requires the design of a special clamping device according to the experiment blade, which will introduce unavoidable experimental errors due to the friction between the slot of the fixture and the root of the experiment blade, and due to the shaping of the blade, it will result in a smaller design margin of damping structure that matches the platform portion. In addition, there are also difficulties such as in applying loads and in measuring signals due to complex geometries, which present more challenges in the design process than in simulated blade vibration experiment.

At present, the research on the frictional vibration mechanism of aero-engine blades is still in the exploratory stage. Therefore, it is of great theoretical and practical significance to study the vibration characteristics of the blade-disc structure, and to study the law of dry friction damping structure in reducing the amplitude of blade co-oscillation and changing the resonance frequency of the blade. This paper takes a certain type of underplatform damping turbine blade as an example, and briefly describes the design idea, design process, experimental content and problems to be solved in the real blade vibration characteristic experiment.

2. Design methodology and design process of Real Blade Vibration Characteristics Experiment

As before, compared with the simulated blade experiment, the design idea of the Real Blade Vibration Experiment is different. The purpose of designing the real blade vibration characteristic experiment is generally used to check whether the damping effect of the blade damping device meets the technical specifications, or to optimise the geometry, material and processing technology of the existing damping device, so as to obtain a better damping effect than the original damping device. Take a certain type of blade with underplatform damper as an example, assuming the purpose of the experiment is to compare the effect of damper's material and shape on the damping efficiency, then the experiment is generally carried out to design a damping device experiment system for multiple different kinds of dampers, in order to meet the technical requirements of the experiment under the premise of multiple changes in the shape of the damper, material, excitation force, loading force (simulation of centrifugal force) and other kinetic parameters of the experiment, with the versatility and repeatability. The experiment design process is as follows:

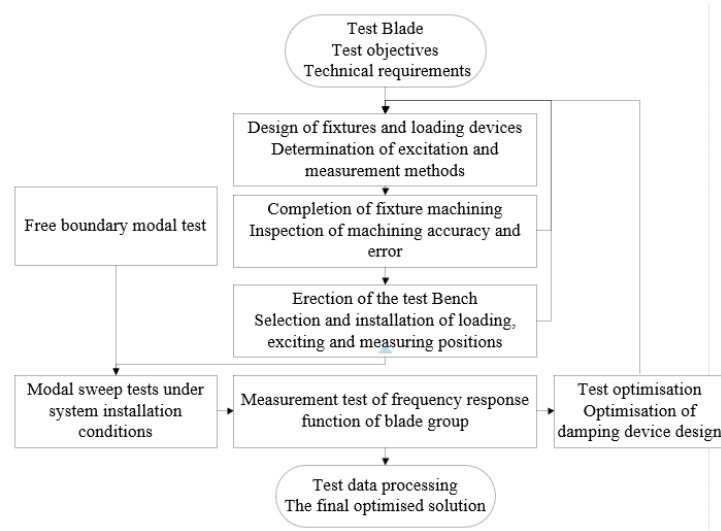


Figure 1. Design flow of RBVE.

3. Experiment system design

3.1 Design of fixture

The real blade experiment requires a special holding device designed for the experiment blade. The relationship between the blade root and the fixture slot is determined by the experiment requirements, besides special process like hot assembly, pre-twisted assembly and other special assembly processes, the relationship between the blade and the slot is generally a gap assembly relationship, in order to protect the experiment blade, easy to dismantle and repeat the experiment. Take a certain type of underplatform damping experiment blade as an example, experiment using a group of three experiment blades with two underplatform dampers, so in the design of the fixture. Considering that the assembly clearance of the blade set needs to be in strict compliance with the standard, the slots are arrayed in a $360/67^\circ$ circle, resulting in a three-groove fixture with a centreline of 5.373° between the mortise and tenon grooves and blade tenon as shown in Figure 2:

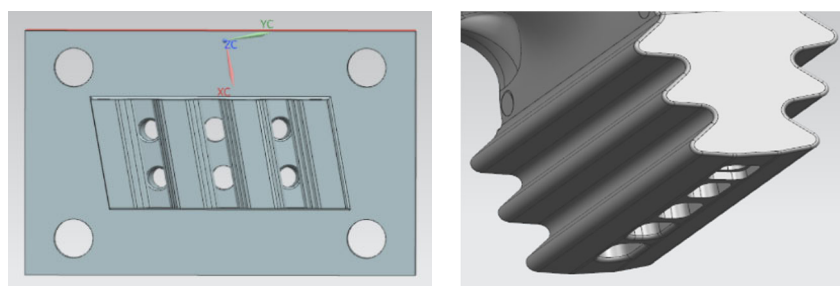


Figure 2. Fixture and blade tenon.

Threaded holes on the side of the fixture for mounting non-contact baffles. The function of the baffle is to act as a blade limiter during installation and experimenting. Since the blade retaining constraints are not provided by the baffle, it is assumed that the baffle is not load-bearing and can be removed if necessary. In addition, the baffle plate plays the role of groove alignment in the installation process, when installing the blade set, first install a baffle plate, the blade will be fixed before the installation of another baffle plate. Two threaded through holes under the mortise for fastening screws. Tightening screws provide a solid support for the blade, and the converted tightening torque of the required force at the bottom of the blade must not exceed the permissible torque limit of the screws. Use a torque spanner to control the tightening torque of the fastening screws during installation, and

keep the experiment boundary conditions consistent during repeated experiments. In addition, a spacer is placed at the bottom of the slot to prevent the fastening screw from scratching the blade.

After the modification of the design of the clamping device, the finite element analysis software should be used to carry out the modal analysis of the experiment blade, the fixture and the whole experiment system under the solid-support boundary conditions to make sure that the fixture's fixed mode frequencies are not in the vicinity of the lower order modal frequencies of the experiment piece and that there are no lower order modes with large frequency variations due to coupling of the experiment vane and the fixture.

3.2 Design of motivation system

The most common excitation method for non-rotating blade vibration experimenting is the use of electromagnetic shakers. There are two types of shaker installations, one where the specimen is fixed to the base, which is considered to be root-supported, and the shaker excites the leaf body through the flex bar, and the other where the shaker is placed vertically and used as a base excitation source, which is also known as a shaking table, and where the specimen is fixed to the shaking table through a fixture to perform the base excitation.

According to the technical requirements of the experiment, after repeated research and demonstration, it was decided to use a single shaker for excitation. The excitation system consists of a signal generator, a power amplifier and a shaker-top-rod system. The telescopic flex bar is fixed with an adjusting nut, one end is connected to the impedance head and the remaining length is in the shaker. Due to the complexity of the blade shape and the thermal barrier coating on the surface of the tooling blade, there is no proper space for the impedance head, so the other end of the impedance head is connected to the blade with a short M6 screw, and in order to bring stable excitation effect, a nut is installed on the head of the screw to increase the contact area with the blade as shown:



Figure 3. Motivation system.

Ideally, the theoretical best excitation method for this experiment would be to use two shakers to excite a set of three blades. Two shakers are placed opposite to each other to provide excitation force on both sides of the blade, and the phase difference of the excitation signal is set to 180° . The boundary condition of the middle blade of the blade group under this experiment condition is the most consistent with the actual blade-disk working condition, thus the measurement and analysis of the frequency response function of the middle blade can be used as an important index to measure the damping efficiency of the damping device.

In order to avoid the proximity of the excitation source to the experiment piece resulting in the transfer of some of the vibration energy through the experiment foundation, a suspended shaker can also be used. However, this method requires a separate design of the shaker mounting structure, and due to the large mass of the shaker, the lifting method often brings difficulties in adjusting the excitation position and certain safety hazards.

3.3 Design of loading system

Non-rotating blade vibration experimenting requires the application of an external load to the damping device to simulate the centrifugal force on a rotating impeller damper under actual operating conditions. Different damping structures apply external loads in different ways, in which the underplatform damping blade is generally compressed by external force to simulate the effect of centrifugal force between the damping sheet and the edge plate of the blade, and this load is known as the positive pressure on the contact surface. For simulated blade vibration experiment, the loading of the damping device is often very simple because the experiment system can be designed in-house; in contrast, real blade vibration experiment have a relatively complex experiment blade and damping device structure, and therefore the loading method and the loading device need to be specially designed.

The common loading methods of non-rotating experiment benches are broadly classified into two ways according to the source of loading force: loading by gravity using weights and loading by tension force. After repeated discussions and modifications, it was finally decided to use a tensioning device for the loading of underplatform damper. Mounting of the base and the loading system on the base, loading of the damper by means of a tensioning device. Compared with the weight loading method, the tensioning device is easy to operate when adjusting different positive pressure levels, and the tensioning device has a smaller size and lighter mass, which improves the safety during the experiment.

The loading device is mainly composed of clamping plate, pulley, wire rope, force gauge, flange bolt, eyebolt, pressure plate. The purpose of the loading device is to load the friction dampers mounted underneath the two platforms. The mounting pattern is shown in figure 5. It should be noted that the readings shown by the dynamometer in the loading device of this experiment system is not the actual size of the loading force borne by the damping device, but should be based on the use of the pulley device due to the use of the angle between the wire and the horizontal plane for the equivalent concentration of the force of the conversion.

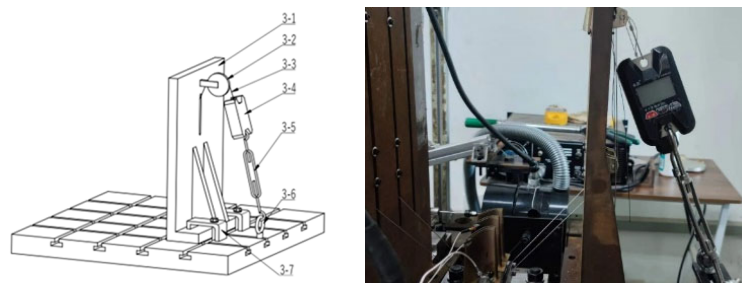


Figure 4. Loading system.

After determining the tension loading, it is necessary to design the loading device for the damping device. The two shapes of underplatform damper matched with experiment blade are shown in Figure 6, both of which are irregular prismatic structures. Considering that the experiment should minimise the introduction of additional frictional contact, the contact area between the loading device and the damper should be as small as possible. In addition, due to the concave side of the experiment blade edge plate, it is necessary to design the shape of the loading device to avoid contact with the blade edgeplate and prevent interference with blade vibration during the experiment. It is necessary to pay special attention to the use of additional loading device to apply external loads, the loading device of the converted concentration of force should be in the centre of gravity of the device and the centre of gravity of the damping piece of the line, that is to ensure that the loading device in the process of the experiment does not occur in the centre of gravity of the impact of the experiment results.

Designed to avoid the interference between the wire rope and the blade by adding the force arm at both ends of the loading piece, by adjusting the length of the force arm, so that the wire rope and the horizontal plane angle of 60° , the equivalent concentration of force and the tensile strength of the meter is equal. Design the contact surface between the loading sheet and the damper as four 0.5×0.5

mm square surfaces, and cut slots between the contact surfaces to reduce the contact area with the damping sheet, thus avoiding the introduction of additional friction as much as possible. In order to prevent the loading device from being eccentric when external load is applied, the foot support is designed on both sides of the loading plate, and the bottom of the loading plate is equipped with a fan-shaped groove with a radius of 1.6mm, which is used to match the different diameters of steel wires, and the foot support also prevents the steel wires from getting out of position.

3.4 Desing of measuring system

According to the technical requirements of the experiment, through the laser displacement sensors and acceleration sensors to achieve real-time monitoring and measurement of the amplitude of the blade to be measured, the sensor access to the signal collector can be output to the real-time transmission of digital signals to the computer. Sensor installation as shown:



Figure 5. Sensors.

Laser displacement sensors are non-contact measurements with high measurement accuracy, no additional mass or rigidity, and easy installation. Experiments recommend the use of laser displacement sensors with longer recognition distances and tripod mounting with better stability.

The acceleration sensor is a contact measurement, which changes the pressure-sensitive signal into an electrical signal by piezoelectric conversion and inputs it into the signal collector, which is more accurate, but sticking it on the surface of the blade will increase the additional mass. Other forms of measurement sensors are eddy current sensors, strain gauges, etc., which, eddy current sensors short range, short measurement distance, although the same belongs to the non-contact measurement method, but the installation is inconvenient, you need to be close to the experiment piece, the specific operation of the installation of the interference may occur; strain gauges measurement method is also inconvenient to install, the strain gauges of the pasting process is complex, paste the good and bad on the experiment results will have a greater impact.

The experiment is carried out by means of an impedance head that monitors and measures the amplitude of the force emitted by the electromagnetic shaker in real time. One end of the impedance head is connected to the flex bar, and the other end is connected to a short screw with a nut, which is bonded to the excitation point of the blade with a strong adhesive.

4. Vibration characterisation experiments on real turbine blades with underplatform damper

After completing the installation of each experiment piece according to the specified steps, the real turbine blade group vibration reduction characteristic experiment can be initiated. The experiment is divided into 18 groups, measuring the frequency-acceleration amplitude response functions of stimulated blade tip vibration points and intermediate blade tip vibration points under excitation forces of 5N, 10N, and 20N, and pressure conditions of 0N, 20N, 50N, 100N, 200N, and 300N. During each individual experiment, the excitation force amplitude is maintained at a constant value

through feedback control by an industrial computer, with adjustment errors not exceeding ± 0.2 N. The experimenting time for a single group is approximately 15 to 20 minutes during the experiment.

Taking 10N excitation force as an example, the figure below provides a summary of the amplitude-frequency curves for stimulated blade tips and intermediate blade tips under different positive pressure conditions. The table presents a compilation of the resonance amplitudes, relative resonance amplitudes, and vibration reduction efficiency for stimulated blades under the excitation force of 10N as they vary with positive pressure.

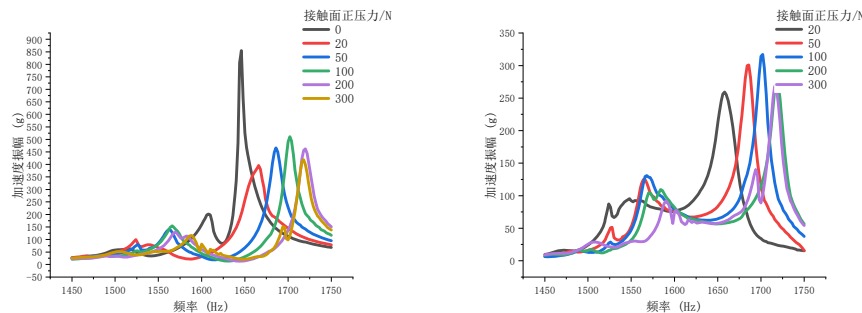


Figure 6. FRF for Stimulated Blades and Intermediate Blades under 10N Excitation Force.

Table 1. Critical assessment parameters of stimulated blade under 10N excitation force as they vary with positive pressure.

Pressure N/N	20	50	100	200	300
resonance amplitude A/g	233.2	282.7	274.8	257.4	257.4
relative resonance amplitude $\bar{A}$	54.6%	66.1%	64.3%	60.2%	60.2%
vibration reduction efficiency η	45.4%	33.9%	35.7%	39.8%	39.8%

The summary results of the analysis of frequency response functions and vibration reduction efficiency indicate that, under a 10N excitation force, the resonance amplitude decreases initially, then increases with the increment of positive pressure. There exists an optimal positive pressure value leading to the minimum resonance amplitude of the blade. The vibration reduction efficiency of the damper remains within the range of 30% to 50%. The optimum positive pressure value is found at 20N, resulting in a reduction of approximately 45% in resonance amplitude. This analysis result proves that the underplatform damping device exhibits good vibration reduction performance within the experiment frequency range.

5. Conclusion

In this paper, taking a certain kind of real blade with underplatform damping as an example, the design idea and design flow of real blade vibration characteristic experiment are discussed from the aspects of experiment base, excitation system, loading system and measurement system.

Conducting vibration reduction experiments on actual turbine blades equipped with underplatform damping, we obtained experimental data under different excitation forces and positive pressure conditions. The results confirm that the damping device's vibration reduction performance meets the technical requirements.

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