An Experimental Platform with Rotating Airflow Excitation and Stationary Blisk Vibration Measurement

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Abstract. With the question that the vibration of the realistic blisk in the engine is hard to be predicted, researchers need an experimental test platform to study the realistic dynamic properties and monitor the vibration of the designed blisk. For keeping the relative motion between airflow and blisk in a real engine, and facilitating the measurement of the blisk vibration, a new experimental platform with rotating air excitation and stationary blisk vibration measurement is developed in this paper. Firstly, the schematic diagram of the test platform is shown and all the components are illustrated clearly, including the stationary airflow excitation system, the test rig, and the vibration measurement system. Then two typical experiments are conducted with the designed academic blisk. A stationary excitation and a transient acceleration excitation are employed to the stationary blisk. Through the time-frequency analysis of the vibration signal measured by the Laser Doppler Vibrometer, the source of each component of the vibration signal is obtained. The experiment results show that the stationary and transient vibration of the blisk can be measured and identified correctly.

1. Introduction

The safe operation of the blisk is an important prerequisite for the normal working of the engine. While the vibration of the realistic blisk in the engine is hard to be predicted due to the actual intricate working conditions. Even some researchers have proposed some predictions of the maximum amplitude of blisk in the stationary [1,2] and transient [3,4] excitations, experimental investigations of the blisk vibration are still needed for validating the predictions. Moreover, for studying the dynamic properties of the designed blisk, an experimental platform with excitation and measurement is demanded.

Experimental studies published in the field of platforms with blisk excitation and vibration measurement can be divided into two categories, depending on whether the blisk is rotating or stationary. (i) The blisk is rotating by the airflow. The vibration of the blisk can be measured by strain gauges with a slip ring or telemetry system [5], Laser Doppler Vibrometer (LDV) with a self-tracking mirror [6,7], and tip timing [8-11]. These techniques can obtain blisk vibration in real operation status. However, they contain additional centrifugal effect that is usually not considered in the analysis and prediction of the vibration. And the measurement techniques are too expensive. (ii) The blisk is stationary. The blades are excited by the electromagnets [12,13], piezoelectric actuators [14,15], or acoustic excitations [16,17] to obtain any deterministic excitation. The vibration of the stationary blisk can be conveniently measured by a variety of techniques, such as strain gauge[18,19], accelerometer [20], proximity probe [21], LDV
[22], or holographic equipment [23]. Even these tests can obtain an accurate response under the deterministic excitation, they cannot form a real airflow excitation in engine operation.

To conveniently measure the blisk vibration in the real airflow excitation, a new experimental test platform is needed to be designed. The blisk is set to be stationary for avoiding the centrifugal effect and employing convenient measurement techniques. The contact measurement techniques, such as strain gauge and accelerometer, may bring additional mass effect [24]. As for the non-contact measurement, the holographic equipment is too expensive to afford. Then LDV is employed to measure the vibration of blisk for its non-intrusive nature and mature commercial use. The nozzle is driven to be rotating for keeping the relative motion between airflow and blisk, also this setting can ensure that the airflow excitation is similar to the real operation condition.

In this paper, a new experimental test platform with rotating nozzle and stationary blisk is developed. The vibrations of the blisk in stationary and transient excitation are measured and analyzed. In Section 2, the experiment test platform is introduced in detail. The schematic diagram of the test platform is shown and explain all the components clearly. The detailed structure of the test rig and the actual test arrangement for the experiment are demonstrated. Then a simplified academic blisk is designed and the mode characteristic is analyzed. In Section 3, Two experiments are conducted. A stationary excitation and a transient excitation are employed to the blisk and the vibrations are measured and analyzed. Moreover, an analysis of the truncated excitation is given. The last is the conclusion.

2. Experiment test platform

2.1. Test platform design

For measuring the vibration of the stationary blisk under the rotating airflow excitation in a non-contact way, the experimental test platform is designed with three parts: the airflow excitation system, the test rig, and the vibration measurement system. The schematic diagram of the platform is shown in Figure 1.

![Schematic diagram of the experimental test platform](image)

**Figure 1.** Schematic diagram of the experimental test platform.

The airflow excitation system provides the rotating excitation which is similar to the real air jet in the engine to the blisk. The air is compressed in the air compressor (LiuTECH LU22G-8) and transferred to the air tank (Haikong C1/8). The air tank can provide stable air pressure. Then the air is imported to the test rig. The nozzle number in the nozzle plate indicates the engine order and can be replaced according to the requested engine order.
The test rig combines the high-speed rotating mechanical structure and high-pressure airflow, which contains the high-speed motor, rotating nozzle system, and stationary blisk. The detailed design of the test rig is shown in Figure 2. The high-speed motor (Hualian TYG-7.5kW) drives the nozzle system to rotate, and the airflow spurted from the rotating nozzle plate to form a travelling wave excitation. The tested blisk is mounted to be stationary for avoiding the centrifugal effect.

![Figure 2. The detailed structure of the test rig.](image)

Under the excitation of the travelling airflow excitation, the blade will vibrate. To measure the vibration of the blade tip in a non-contact technology, LDV (Polytec CLV-2534) is employed based on the Doppler principle. The vibration data is collected by the data acquisition (SIEMENS LMS-SCADAS-mobile-202) and is analyzed by the vibration analysis software (SIEMENS Test.Lab) on the computer.

Figure 3 shows the test arrangement for the experiment. Figure 3(a) demonstrates the airflow excitation setups and test rig. Moreover, an air dryer is added in the air excitation setups for drying the airflow in a humid environment. The air pressure to excite and the speed of the motor are controlled in the software compiled by NI LabVIEW. The side view of the test rig in Figure 3(b) shows clearly the rotating nozzle and stationary blisk. The nozzle and blisk can be replaced quickly and easily for any experiment needs. Figure 3(c) shows the vibration measurement and controllers. Besides, a pressure sensor is equipped in the inlet of the test rig and a PID closed-loop control is employed for ensuring that the input pressure is stable.

### 2.2. Blisk design

The blisk is the test piece of the experiment and can be designed for any shapes and sizes. For simplicity and convenience of simulation, the blisk in the experiment is designed to be flat, and the sector number is 6. The three-dimensional model of the blisk is shown in Figure 4(a). The key geometric parameters of the blisk are listed as follows. The disk is an annulus with 80 mm outer diameter, 20 mm inner diameter, and 10 mm thickness. The blade tip is on the 160 mm diameter circle. The width and thickness of the blade are 34 mm and 5 mm respectively.

For prior knowledge of the dynamic characteristic of the blisk, a simulative modal analysis of the blisk is given based on the ANSYS software. The cyclic symmetry modelling method is employed that only one sector of the blisk model is needed. The mesh grid is controlled in the software with the 1 mm element size by adaptive size control function. The number of elements in the meshed model is 11417. The material of the blisk is aluminum alloy with Young’s modulus = 80 GPa and density = 2600 kg/m³.

With these setting parameters, the first three family natural frequencies in different nodal diameters can be obtained and plotted in Figure 4(b). It can be inferred that the first family natural frequencies are the blade dominated frequencies, and are chosen as the excited frequencies in the latter experiments. Figure 4(b) also shows parts of the mode shapes in zero and one nodal diameters. In the first mode with zero nodal diameter, every blade arrives to the maximum deformation at the same time and can be conveniently measured. While in the second mode with zero nodal diameter which the disk mode dominates, the blade mode follows the disk mode. Then blade vibrates in the circumferential direction.
Figure 3. Test arrangement for the experiment: (a) air excitation system and test rig (b) side view of the test rig (c) vibration measurement and controllers.

Figure 4. Basic characteristic of the blisk model: (a) geometry of the model (b) the first three family natural frequencies in different nodal diameters with part of the mode shapes.
Because LDV measures the vibration in the normal direction of the blisk, then in this mode, the blade vibration cannot be measured. And in the third mode with zero nodal diameter, the torsional vibration of the blade is obvious and is the same as the blade mode in the second mode with one nodal diameter except for the different nodal diameter.

3. Experiments on the stationary and transient excitation

3.1. Response measurement and analysis

To testify the experiment ability of the test platform developed in Section 2, a stationary excitation and a transient excitation are employed in the experiments. The air pressure of the experiments is set to be 0.1 MPa that the blade will be excited at an observable level. The number of exhaust ports of the rotating nozzle is 12 so that the engine order of the excitation is 12. Because there are small differences in natural frequency between the real blisk and the designed model, the natural frequency of the experimental blisk is pre-tested and is 2332 Hz. As for the setting for measurement, the sampling frequency is 51200 Hz. Then even in the resonance, the sampling number in a vibration period is 22. The measurement would not lose the peak information of the vibration. Moreover, because of the LDV equipment, the velocity of the vibration is measured and is regarded as a description of the vibration. And the measured blades in the experiments are all the same. After these settings are completed, two experiments are conducted.

Firstly, a stationary excitation is employed to the blisk. The rotating speed of the rotating nozzle is constant with 11660 rpm (revolutions per minute). Combined with this rotating speed and engine order, the blisk will be excited exactly in the resonance. The stationary response is measured and shown in Figure 5(a). From the partial enlarged drawing, the vibration signal is fully sampled. After the time-frequency analysis, the autopower spectrum of the stationary vibration is shown in Figure 5(b). It can be indicated that the natural frequency of the blisk is truly excited and dominates among all frequency bandwidth. Moreover, because of the interval of the exhaust ports are not ideally evenly spaced, the lower eleven orders of the excitations will be shown in the figure. And the high order harmonic is shown because of the truncated excitation and will be discussed latter.

Secondly, a transient excitation is employed to the blisk. The transient excitation is constant acceleration with the acceleration rate is 600 rpm/s, so that in a time duration of 30 seconds, the rotating speed will linearly increase to 18000 rpm, and will pass through the resonance of the blisk with the 12-engine order. The transient response in the time domain is measured and shown in Figure 6(a).
Combined with the time-frequency analysis of the transient response in Figure 6(b), the multiple resonances in the time domain can be explained.

![Figure 6](image-url)

**Figure 6.** Transient response and analysis in 10 Hz/s acceleration: (a) transient response in the time domain (b) time-frequency analysis of the transient response.

The resonance in the red frame is the desired response because of the time and frequency matches. The blisk is passing through its first natural frequency. The first and second natural frequency of the real blade is nearly the same with the simulated model in Figure 4(b). Because of the truncated excitation, there exist multiple high harmonic excitations. The second and third harmonic excitations are passing through the second natural frequency of the blisk, therefore, two resonance are shown in cyan frames and yellow frames respectively. Moreover, other high order harmonic excitations will excite the first two natural frequencies in the beginning of time period in green frame. In addition, the responses due to lower eleven orders of the excitations can be shown because the exhaust ports are not ideally evenly spaced. Besides, when the second and third harmonic excitations are passing through the second natural frequency of the blisk, the drastic vibration of the blisk may excite other test setups and bring white noise in the whole spectrum at that moment.

3.2. Effect of excitation truncation

Theoretically, the acceleration excitations in the industrial jet are sinusoidal waves with frequency linearly increased, which is shown in the blue dashed curve in Figure 7 (a). However, because of the structural design of the blisk and the air passage, the rotating nozzle only can provide positive pressure to the blisk, and cannot provide the negative pressure to the blisk. Therefore, the excitation signal is truncated in the negative parts. Besides, when the airflow sweeps across the blade surface, the pressure will keep in constant in a short time, and it can be regarded as the truncated in the top parts of the excitation signal. Figure 7 (b) shows the time-frequency spectrum of the truncated excitation. It can be inferred that except for the first harmonic excitation, which is corresponding to the theoretical excitation, there exist higher multiple harmonic excitations. Therefore, the truncated excitation is the reason for multiple harmonic responses in transient vibration shown in Figure 6 (a).

4. Conclusions

In this work, a new experimental platform with rotating airflow excitation and stationary blisk vibration measurement is developed. The experimental platform contains the rotating airflow excitation system, test rig, and non-contact vibration measurement system. The test rig unites the air passage and rotor to generate a rotating airflow excitation. Compare to the realistic engine with stationary nozzle and rotating blisk, the new experimental test platform can keep the relative motion between airflow and blisk, and
Figure 7. Analysis of the truncated excitation in the experiment: (a) comparison the theoretical and truncated excitation in the time domain (b) time-frequency analysis of the truncated excitation.

can avoid the centrifugal effect of the rotating blisk. Also, the vibration of blisk is conveniently to be measured by LDV in a non-contact way because the blisk is stationary. Besides, the blisk and the nozzle is replaceable, which satisfies any shaped blisk in any engine order.

The vibrations of the blisk in stationary and transient excitations in the experiment platform are measured and analyzed. For stationary excitation, the frequency of the vibration is matched with the product of the excitation frequency and engine order. For transient acceleration excitation, the blisk is passing through its first natural frequency band. Besides, the lower engine order is excited for the non-strictly distributed intervals of the exhaust ports, and higher harmonic excitation is brought in the blisk for the design induced excitation truncation. Also, the white noise caused by high harmonic induced resonance is introduced in the vibration measurement. Even so, the first harmonic resonance which is the desired one is recognized and dominates among all other vibrations.

For further research, combined with the vibration amplitude prediction proposed by the authors before, several validations will be conducted. And the mistuning will be intentionally added in the tested blisk in the later investigation.

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