Research on blade modal testing method based on 3D scanning laser Doppler vibration measurement technology

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Abstract: The 1D modal test and 3D modal test of an aero engine turbine blade were studied based on the theory of 3D scanning laser Doppler vibration test. Through the identification of modal parameters, the first six natural frequencies of the blade and their corresponding modal modes are obtained. The 1D, 3D modal test results and finite element analysis results of the blades are compared and verified. The results show that the 3D scanning laser Doppler modal test method can obtain the 3D full field mode of the accurate test of light-weight and small-scale structural modal parameters without the influence of additional mass and additional rigidity.

1. Introduction

The aero engine turbine blade is a typical thin-walled curved structure with small mass, complicated structure and high natural frequency range. In recent years, aero engine turbine blades and other components have gradually exposed many problems in terms of strength, life and reliability. In order to prevent the occurrence of operational failures caused by mechanical vibrations, engineers often need to carry out vibration characteristics tests of aero engine turbine blades to obtain the dynamic characteristics of the structure, so as to predict and realize the control of the blade vibration level. Modal analysis is one of the important means to have a good command of the dynamic characteristics of the structure. The "General Specification of Aviation Turbojet and Turbofan Engines"[1] pointed out that: Before the engine test, the engine and its components must be modal analyzed.

At present, the modal tests of turbine blades mostly use hammers to excite the blades, and the acceleration sensor or displacement sensor reads the response. The test method can only obtain the unidirectional bending mode of the blade, and there is often a modal loss phenomenon for tangential vibration.

Laser Doppler vibration (LDV) is a technique that uses Doppler Effect and heterodyne interference principle to measure the surface vibration of an object. As a non-contact measurement method, LDV has the unmatched testing advantages compared with traditional contact sensors: it is not limited by the size, temperature and position of the measured object. It has the advantages of long-distance measurement, high spatial resolution, short measurement time, and no additional mass which has been widely used in structural flaw detection, agricultural product quality testing, medical, aerospace structural modal analysis and other fields. [2, 4].

The early LDV was just a single-point speed sensor. In practical applications, it is difficult to apply it to the modal test of multi-point output. In order to achieve multi-point testing, the researchers applied a scanning system (a pair of orthogonal scanning mirrors) to the single-point LDV to constitute a commonly used scanning laser Doppler vibration measurement system (SLDV) [5]。SLDV uses the point-by-point scanning method to test different measuring points separately. It can quickly measure the response, and the spatial resolution is limited only by the laser beam diameter (usually a few tenths of a millimeter) and the time it takes to capture each measurement point. [6].

The vibration response of the structure is mostly three-dimensional, however, the modal data obtained from the vibration response signals collected by traditional sensors are unidirectional, which leads to the fact that the test results cannot correctly describe the actual modal vibration mode. 3D Scanning Laser Doppler Vibrometer (3D-SLDV) is a new vibration measurement technology. Focus three independent LDVs simultaneously to one point to collect the response. Through coordinate decomposition, the vibration speed of this point in any XYZ direction of space can be obtained [7].

This paper will study the 3D-SLDV modal testing technology of an aero engine turbine blade. The first six natural frequencies and three-dimensional mode shapes are obtained through experiments, which can realize the fast and accurate measurement of the three-dimensional vibration modes of the blades, and provide more complete data for the optimal design of the dynamic structure of the turbine blades.

2. Principle of Laser Doppler vibration

When the single-point LDV is measured perpendicular to the surface of the object, a high-precision surface normal velocity can be obtained. However, when there is a certain angle between the laser beam and the surface of the measured object, the measurement accuracy will decrease with the increase of the angle [8].

Assuming that the vibration velocity at a point on the surface of the structure T is **u**, when there is an angle θ between the laser measurement direction and the object surface normal, the actual vibration velocity measured by the laser is the cosine component of the object's true velocity, as shown in Figure 1.

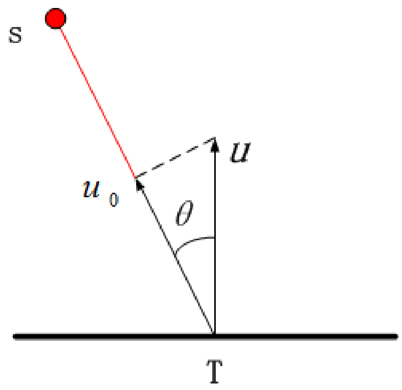


Figure 1. Laser test with angel

$$u_0 = u \cos\theta \tag{1}$$

Which: u_0——Vibration speed measured by laser;

U——the actual vibration speed of the surface of the measured object.

Therefore, when using a single-point LDV for accurate testing, the laser head must be installed perpendicular to the measured point. However, most engineering tests cannot meet this condition, Moreover, most object vibrations are three-dimensional vibrations. LDV measurement at an angle to the surface of the object is easily disturbed by other velocity components.

In order to overcome these shortcomings, 3D Scanning Laser Doppler Vibrometer came into being. 3D-SLDV can effectively remove the test error caused by the in-plane vibration of the object. The vibration measurement data can be matched with the finite element model, which provides more complete test data for the modification of the finite element model [8].

The measurement principle of 3D-SLDV is shown in Figure 2. The response acquisition is carried out by focusing three independent LDVs to a point at the same time, and performing coordinate transformation on the obtained data to obtain the vibration speed of the point in any XYZ direction in space.

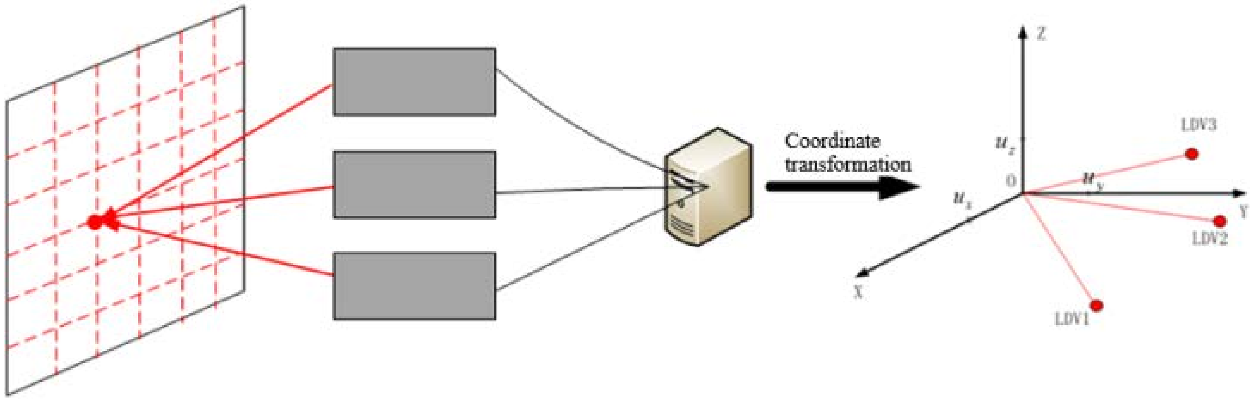


Figure 2. Schematic diagram of 3D-SLDV test

As shown in Fig. 3, the actual vibration velocity at point O on the structure surface is ***u***, According to equation (1), when there is an angle θ between the laser test direction and ***u***, the actual measured velocity of LDV is $u_0 = u\cos\theta$ 。 Let the measuring point on the surface of the structure be the coordinate origin O, and the relationship between the three laser test directions and the coordinate axis is shown in Table 1:

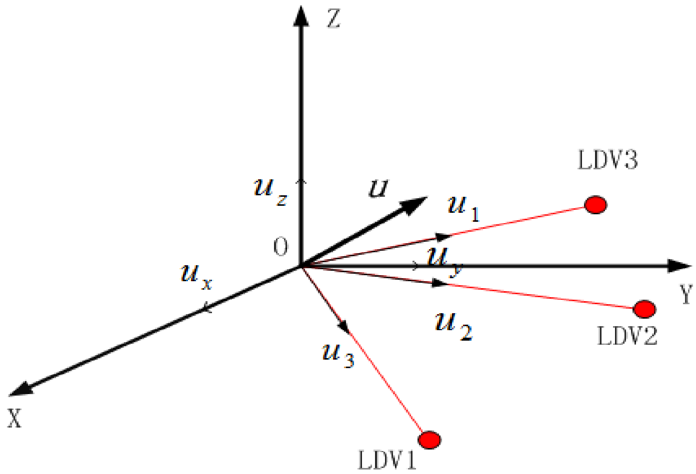


Figure 3. Schematic diagram of 3D laser test coordinate decomposition

Table 1. The angle relationship between the three laser test directions and the coordinate axis

	X	Y	Z
u_1	α_1	β_1	γ_1
u_2	α_2	β_2	γ_2
u_3	α_3	β_3	γ_3

The normal plane equation system composed of $\vec{u}_1$, $\vec{u}_2$, $\vec{u}_3$ is:

$$\begin{cases} x\cos\alpha_1 + y\cos\beta_1 + z\cos\gamma_1 = u_1 \\ x\cos\alpha_2 + y\cos\beta_2 + z\cos\gamma_2 = u_2 \\ x\cos\alpha_3 + y\cos\beta_3 + z\cos\gamma_3 = u_3 \end{cases} \tag{2}$$

Solving the system of equations, the three-dimensional vibration mode of the origin O is:

$$\begin{Bmatrix} x \\ y \\ z \end{Bmatrix} = \begin{bmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\gamma_1 \\ \cos\alpha_2 & \cos\beta_2 & \cos\gamma_2 \\ \cos\alpha_3 & \cos\beta_3 & \cos\gamma_3 \end{bmatrix}^{-1} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} \tag{3}$$

$$\mathbf{u} = (u_1, u_1, u_1)^T = (x, y, z)^T \tag{4}$$

3. Modal testing of blades based on 3D-SLDV vibration measurement technology

3.1 Pre-experimental analysis

First of all, the finite element modal analysis of the blade is carried out in order to have a general understanding of the modal parameters of the blade.

The three-dimensional modeling of a certain aero engine turbine blade is shown in Figure 4. The blade body is long and narrow with obvious torsion, and the blade surface is a complex three-dimensional curved structure. The blade coordinate system is defined as a rectangular coordinate system, X is the axial direction coincident with the engine axis, Y is the radial direction coincides with the stacking axis of the blade, and the Z axis is determined according to the right-hand rule. The blade material is DD5 alloy. According to the literature [9], some of the material properties at room temperature are shown in the table 2. Finite element modal analysis was performed on the blades using ANSYS software. The finite element meshing of the blades is shown in Figure 5, with 2828085 nodes and 1890153 elements. The boundary conditions of vibration calculation are consistent with the actual installation boundary conditions, that is, the fixed constraints are established on both sides of the blade tenon, and the first 6 modal parameters of the blade are calculated.

Table 2. Material properties of DD5 alloy

T(°C)	ρ (g/cm^3)	Elastic Modulus (GPa)	Poisson's ratio
20	8.656	142.24	0.332

Figure 4. 3D modeling of the blade

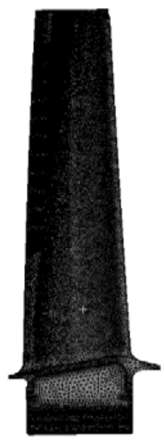


Figure 5. The finite element modeling of the blade

The first 6 natural frequencies of the finite element calculation are shown in Table 3, and the corresponding first 6 vibration modes are shown in Figure 6.

Table 3. Description of the first 6 natural frequencies and mode shapes of blades based on finite element analysis

Mode	Natural frequency/Hz	Mode description
1	573	1st Flap
2	1562	1st Edgewise
3	2563	2nd Flap
4	3919	1st torsion
5	5380	Coupling of 2nd Edgewise and 3rd Flap
6	6355	Coupling of 1st torsion 2nd Edgewise and 3rd Flap

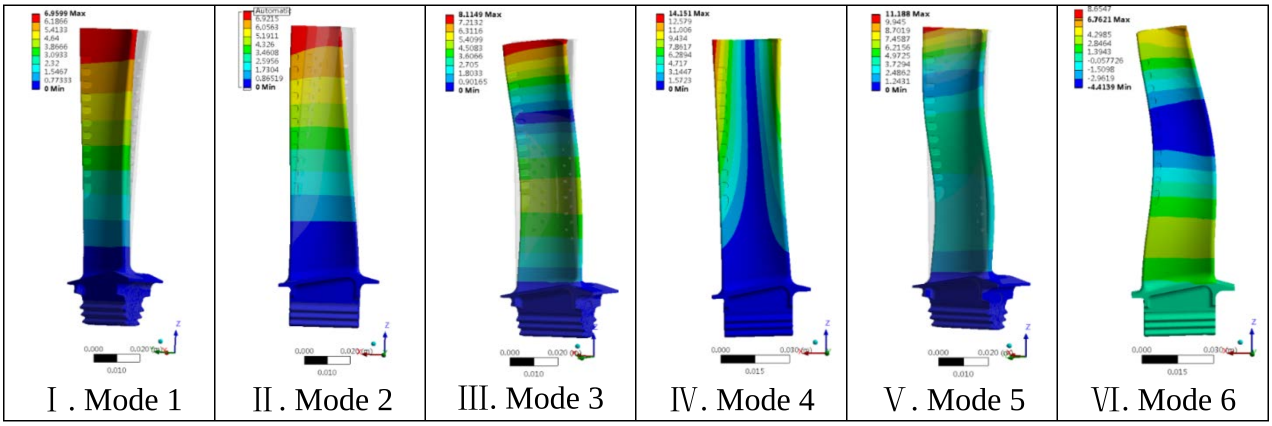


Figure 6. The first 6 mode shapes of blades

From the results of the finite element analysis, it can be seen that the first 6-order frequency of the turbine blade is <6500 Hz. Except for the second-order vibration which is an axial vibration, most of the other vibration modes appear as circumferential vibration. According to the vibration mode results, in the subsequent experimental mode, the excitation point needs to avoid the vibration mode nodes to ensure that all blade modes can be excited.

3.2 Test system

The test used Polytec Scanning Vibrometer (PSV) PSV-500-3D to collect the three-dimensional full-field vibration signal of the blade. In this test, the DYTRAN hammer is used to excite the blade.

The test boundary conditions will be consistent with the boundary conditions of the finite element modal analysis: that is, the two sides of the blade tenon are fixed. Before the formal test, the blade installation torque needs to be calibrated. Install the blade on the experimental platform, gradually increase the installation torque from 80Nm with 10Nm as the gradient, and measure the natural frequency of the blade under the torque by hammering test. The installation torque when the fourth-order frequency change of the blade does not exceed 0.5% is taken as the installation torque of the modal test. The test results are shown in Table 4. According to the test results, 110Nm is selected as the installation torque of the blade modal test.

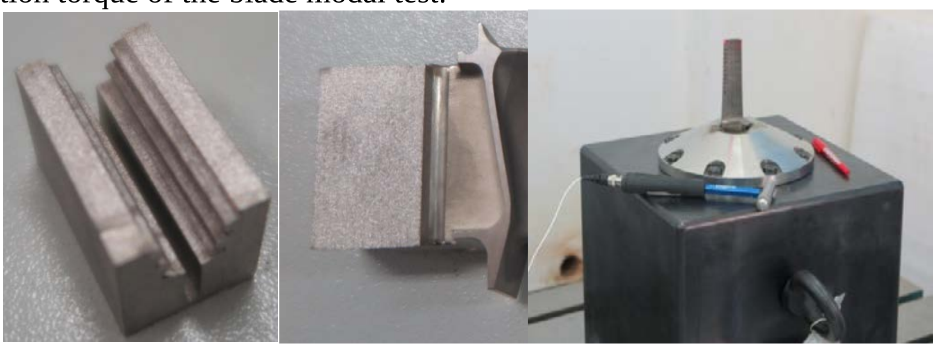


Figure 7. Blade installation status

Table 4. Calibration installation torque

Torque (Nm)	Natural frequency /Hz				4th order frequency change ratio
	1st order	2nd order	3rd order	4th order	
80	522	1379	2499	3715	-
90	523	1384	2506	3736	0.57%
100	554	1388	2510	3755	0.51%
110	554	1390	2514	3760	0.13%
120	554	1390	2515	3763	0.08%

3.2 1D-SLDV modal test of turbine blades

For the 1D-SDLV modal test of turbine blades, only one laser scanning head of the PSV system is needed, which means that the laser scanning head is used as a general laser displacement sensor to collect the response. The test site is shown in Figure 8. The turbine blade is regarded as a plane perpendicular to the laser test direction throughout the test, regardless of the curvature of the blade surface.

Figure 8. 1D-SLDV modal test

After completing the 1D modal test, the first 6th order natural frequency of the turbine blade is obtained through modal parameter identification, as shown in Table 5, and the first 6th order vibration mode of the blade is shown in Fig. 9. The actual blade is a three-dimensional curved surface structure, and each measurement point has vibration responses in three directions of XYZ. However, in the 1D test, the response signal measured by the Top head is only a unidirectional vibration response along the laser direction, and vibration decomposition cannot be performed. The test results only have a certain reference value of frequency, and the vibration type can only reflect the circumferential vibration of the blade in the laser direction, and cannot truly reflect the actual vibration state of the structure.

Table 5. Description of the first 6 natural frequencies and mode shapes of turbine blades based on 1D-SLDV test

Mode	natural frequency /Hz	Mode description
1	554	1st Flap
2	1390	2nd Flap
3	2515	2nd Flap
4	3760	1st torsional
5	5246	3rd Flap
6	6221	3rd Flap

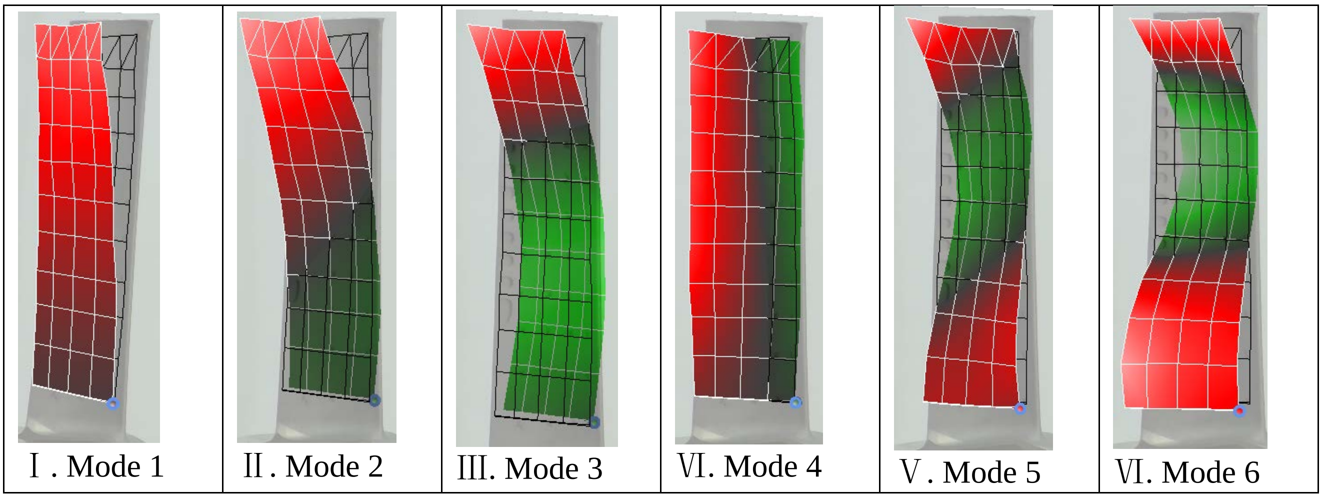


Figure 9. The first 6 mode shapes of turbine blades based on 1D-SLDV test

3.3 3D-SLDV modal test of turbine blades

Three laser heads are used for 3D-SLDV modal test, and the vibration response at the same point is measured from three different laser incidence directions. After the test is completed, the test data can be coordinate transformed to obtain the vibration speed of the point in the XYZ direction.

The relative positions of the three laser heads of the 3D-SLDV modal test arrangement are shown in Figure 10. In order to compare with the 1D test results, the measurement point arrangement, excitation method and A / D settings of the 3D test will be consistent with the 1D test, and the response signal will be collected by the PSV-500-3D vibration measurement system.

Figure 10. 3D-SLDV modal test

According to the coordinate system defined in this paper, the laser test direction is perpendicular to the surface of the leaf pot, that is, the XY plane. The frequency response functions of the blades in the X, Y, and Z directions are shown in Figure 11. It can be seen from Fig. 11 that the Z-direction, the circumferential vibration of the blade is the largest, the Y-direction, the axial vibration is the second largest, and the X-direction, the radial vibration is the smallest.

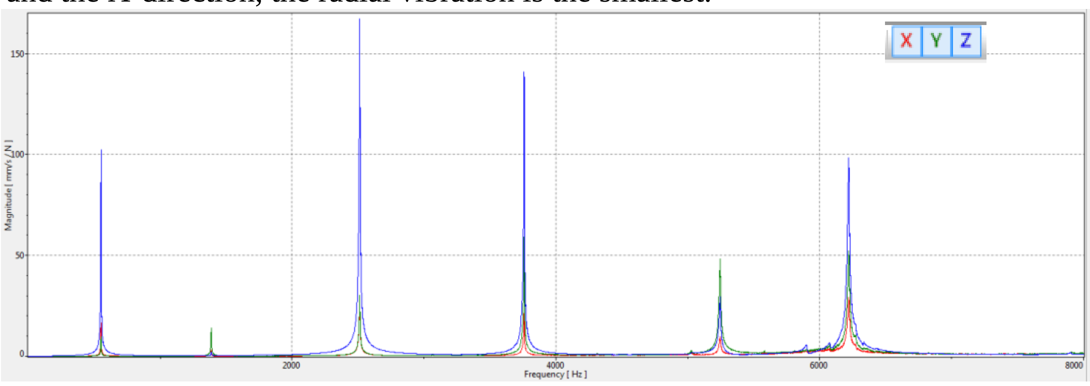


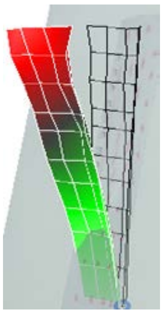
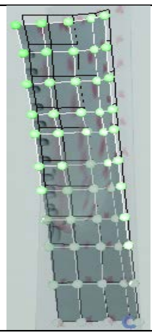
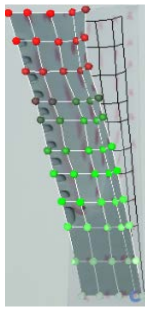
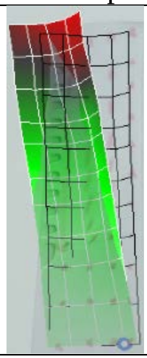
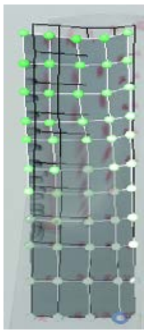
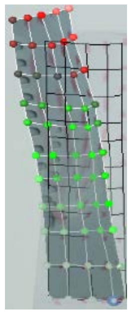
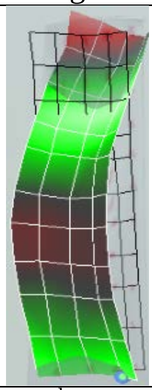
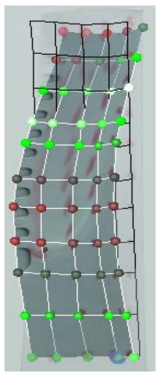
Figure 11. XYZ frequency response function

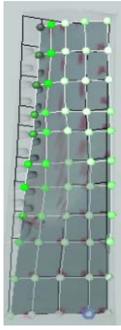
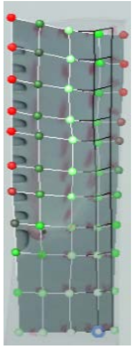
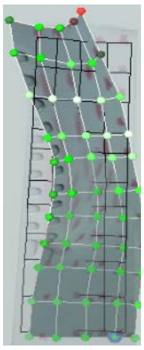
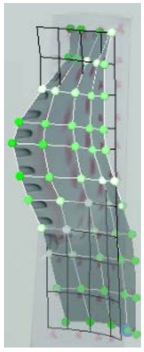
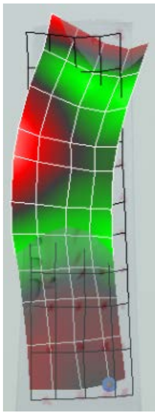
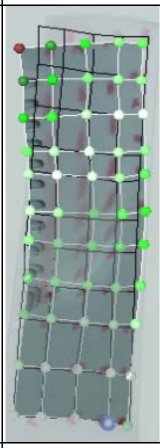
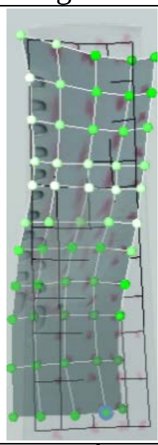
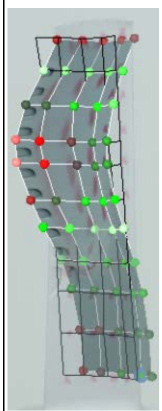
The first 6 natural frequencies and mode shapes of the 3D-SLDV modal test are obtained through modal parameter identification, and the mode shapes are decomposed into three directions of X, Y, and Z, respectively. The modal parameters of the 3D-SLDV test are shown in Table 6, and the modal shapes are shown in Table 7.

Table 6. Description of the first 6 natural frequencies and mode shapes of turbine blades based on 3D-SLDV test

Mode	Frequency/Hz	Description of the mode shapes
1	554	1st Flap
2	1390	1st Edgewise
3	2515	2nd Flap
4	3760	1st torsion
5	5246	Coupling of 2nd Edgewise and 3rd Flap
6	6221	Coupling of 1st torsion 2nd Edgewise and 3rd Flap

Table 7. The first 6 mode shapes of turbine blades based on 3D-SLDV test

Modal order	XYZ	X	Y	Z
1				
	1st Flap	Static	Static	1st Flap
2				
	1st Edgewise	Static	1st Edgewise	Static
3				
	2nd Flap	Static	Static	2nd Flap

4				
	1st torsion	Static	Static	1st torsion
5				
	Coupling of 2nd Edgewise and 3rd Flap	Static	2nd Edgewise	3rd Flap
6				
	Coupling of 1st torsion 2nd Edgewise and 3rd Flap	1st torsion	2nd Edgewise	3rd Flap

It can be seen from Table 7 that the 3D-SLDV test can identify the three-dimensional vibration of the blade, decompose its mode shapes in the XYZ direction of space, and determine the vibration coupling mode of higher-order mode shapes. From this, we can know that the 3D-SLDV modal test is unmatched by the 1D modal test.

3.4 Comparison and analysis

The 3D-SLDV test results of the blade were compared with the 1D-SLDV modal test results and the finite element modal analysis results, as shown in Table 8 and Table 9.

Table 8. Comparison of 3D-SLDV and 1D-SLDV test results

Mode	Frequency /Hz		Relative error/%	Modal shape	
	1D-SLDV	3D-SLDV		1D-SLDV	3D-SLDV
1	554	554	0	1st Flap	1st Flap
2	1390	1390	0	2nd Flap	1st Edgewise
3	2515	2515	0	2nd Flap	2nd Flap

4	3760	3760	0	1st torsional	1st torsion
5	5246	5246	0	3rd Flap	Coupling of 2nd Edgewise and 3rd Flap
6	6221	6221	0	3rd Flap	Coupling of 1st torsion 2nd Edgewise and 3rd Flap

Table 9. Comparison of 3D-SLDV test results and finite element analysis results

Mode	Frequency /Hz		Relative error/%	Modal shape	
	FEA	3D-SLDV		FEA	3D-SLDV
1	573	544	-3	1st Flap	1st Flap
2	1562	1390	-11	1st Edgewise	1st Edgewise
3	2563	2515	-2	2nd Flap	2nd Flap
4	3919	3760	-4	1st torsion	1st torsion
5	5380	5246	-2	Coupling of 2nd Edgewise and 3rd Flap	Coupling of 2nd Edgewise and 3rd Flap
6	6355	6221	-2	Coupling of 1st torsion 2nd Edgewise and 3rd Flap	Coupling of 1st torsion 2nd Edgewise and 3rd Flap

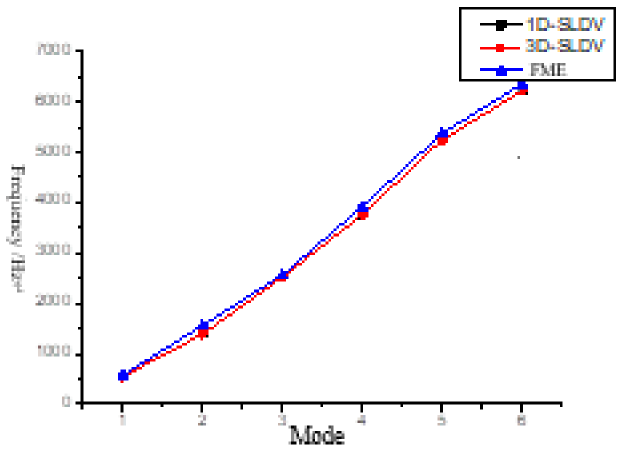


Figure 12. Frequency difference

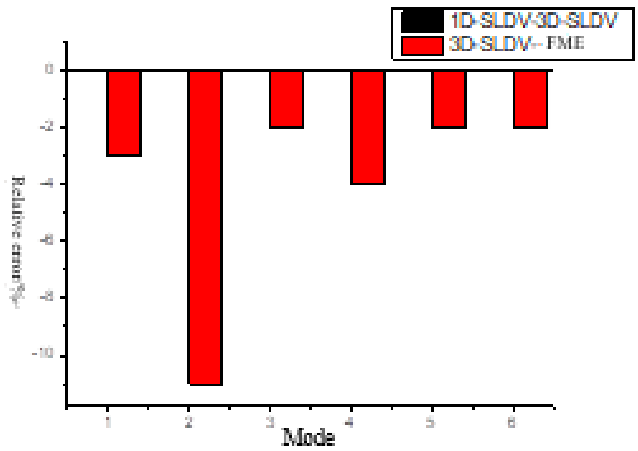


Figure 13. Relative error

The results show that the 3D-SLDV modal test has a good correlation with the 1D-SLDV modal test in the circumferential vibration mode. And because the laser test is a non-contact test without any additional mass, the frequency error between the 1D-SLDV test and the 3D-SLDV test is 0. However, because the 1D-SLDV modal test cannot measure the axial vibration of the blade, the correlation of the axial mode shapes of the two modal tests is poor.

Compared with the finite element modal analysis, the 3D-SLDV modal test shows that the frequency is relatively small. This may be because the actual test boundary conditions cannot reach the fully fixed finite element boundary conditions. Except for the second-order natural frequency, the relative errors of the remaining test frequencies are all within 5%, and the 3D-SLDV modal test completely matches the first 6th-order mode shapes of the finite element modal analysis.

It can be considered that the 3D scanning laser Doppler modal test method can obtain the three-dimensional full-field vibration mode of the blade, and can realize the accurate test of the modal parameters of the light and small structure without additional mass and additional rigidity.

4. Conclusion

In this paper, based on the three-dimensional scanning laser Doppler theory, a three-dimensional modal test of an aero-engine turbine blade is achieved. The main conclusions are as follows:

Finite element modal calculation is performed on the blade to obtain its first 6 natural frequencies and modal shapes, which provides guidance for experimental modal testing.

The 1D-SLDV modal test was carried out on the blade. The test results showed that 1D-SLDV can obtain the first 6 modal parameters of the blade. However, since the vibration response of the blade can only be collected in one direction, there is a mismatch between the modal shape of the 1D-SLDV test and the modal shape of the real structure.

Based on the 1D-SLDV test, the blade was subjected to 3D-SLDV modal test. The first 6th order 3D mode shapes of the blade are decomposed into three directions of X, Y, Z, respectively, to determine the coupling mode of the complex mode of the blade. The results show that the 3D scanning laser Doppler modal test method can obtain the three-dimensional full-field vibration mode of the blade, and can realize the accurate test of the light-weight and small-scale structure without the influence of additional mass and additional rigidity.

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