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# Review of Development and Application for Laser Doppler Vibrometer

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***Abstract:***

Take Germany Polytec company, America OptoMET company and domestic Sunny company as examples, this paper introduces the products of single point laser vibrometer, multipoint laser vibrometer, high speed laser vibrometer, remote laser vibrometer, optical fiber laser vibrometer, micro laser vibrometer, scanning laser vibrometer, robot laser vibrometer, 3D laser vibrometer, etc., and their typical applications of vibration measurement which in rotating machinery, biomedical engineering, acoustic quality testing, MEMS, etc. Aiming at the problems existing in the products, the research and application development ideas are pointed out.

***Keywords**: Laser Doppler vibrometer, Development of product, Typical application, Development trend.*

## I. INTRODUCTION

In 1964, Yeh and Cummins applied Doppler technology to measure the flow velocity of particles in water, marked the laser Doppler technology from theory to application[1]. In the 1970s, Harwell Instruments Company built the first commercial scanning LDV (laser Doppler vibrometer) by installing a scanning head on a laser Doppler vibrometer[2,3]. At present, the measurement distance of LDV can be up to 300 meters, which can be applied to the test of large civil structures[4], the vibration measurement of a moving or rotating objects, the vibration modes are determined by continuous scanning along the scanning path, and can provide solutions for damage detection in the working state, material analysis and biomedical applications[5-7]. SLDV (scanning laser Doppler vibrometer) has high spatial resolution and low

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test time characteristics, which can move and measure quickly and accurately on the structure in test. The use of specific optical devices and high magnification lenses can perform vibration measurement on microscopic objects, extend the high-frequency vibration measurement bandwidth to the GHz level, and can measure the vibration of launcher or high-frequency electronic components[8]. At present, the representative manufacturers of laser Doppler vibrometers abroad include Polytec Company of the German and OptoMET Company of the United States, and domestic enterprises producing laser Doppler vibrometers mainly include Sunny Group Co., LTD. This paper mainly introduces domestic and foreign product development and typical application cases, and analyzes existing problems and development trends.

## II. PRODUCT DEVELOPMENT

### 2.1 Single-point Laser Vibrometer

The American OptoMET SWIR series universal laser vibrometers can measure the small vibration of targets with low surface reflectivity[9]. Changing objective lenses can realize the measurement of 0-300m distance, which can be used for long time monitoring and long distance measurement. The American OptoMET Nova series universal laser vibrometers can measure vibrations up to 500kHz, and can measure weak vibrations and noises. Changing the objective lenses can realize the measurement at a distance of 5mm-100m. The measurement range of high-performance laser vibrometers is 2.5nm/s-10m/s, the bandwidth is 10MHz, and the displacement resolution is 2pm[10].

Sunny company LV-IS01 laser vibrometer (tangential direction) measures the displacement velocity of the object surface in the plane perpendicular to the bisector of the two converging laser beams, that is , the transverse velocity perpendicular to the laser direction, which can be used for the measurement of tensile strength[11] and linear velocity measurement of tape drives, ultrasonic knifes and scalpels. The LV-S01 laser vibrometer (normal direction) can be equipped with a optical unit to realize functions of automatic focus, remote focus and focused access. It can be upgraded to a scanning laser vibrometer with external scanning module to realize the automatic scanning and measurement function. The LV-C01 compact laser vibrometer is compact in structure, delicate in design, easy to carry and convenient to build a test platform. Optical units can be customized to meet the application requirements of different industries.

### 2.2 Multi-point Laser Vibrometer

The Polytec MPV-800 multi-point laser vibrometer can measure up to 48 channels at the

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same time, acquire transient and non-steady vibration characteristics simultaneously, and display frequency-related and time-related working parameters of the object. The fiber optic head can be freely configured and can be parallel to the surface to be measured, and can be used for high-precision vibration measurement, such as transient events (shocks and switches events), unsteady processes (fluid machinery and valves), environmental monitoring, electric drive devices, and starting process of the internal combustion engine, and can also be used to measure sensitive or soft surfaces, with high optical sensitivity and needn't surface treatment[12].

Sunny company LV-MP type multi-point laser vibration measurement system can measure the vibration of 16 points at the same time, and can measure the transient vibration of the object. The beam arrangement can be selected according to user needs.

### 2.3 High-speed Laser Vibrometer

Polytec HSV-100 high speed laser vibrometer can measure up to 40m/s. Single-channel HSV-100 can be used as a universal high-speed vibrometer, dual-channel configuration allows differential vibration measurement, automatically compensates for the vibration of the test bench, adding additional channels can be used for multi-channel differential vibration analysis. Because the compact optical sensor head is coupled to a individual laser unit, even if space is limited, the vibration of the test workpieces can be reliably measured.

The American OptoMET Vector series high-speed laser vibrometer has a speed decoder with a measuring range of 10mm/s-10m/s; the working distance can be adjusted by changing the lens, and 6 different quick-change objective lens can achieve a working distance range of 5mm-100m; it can be used in the high frequency range of microsystem as well as the measurement target with large amplitude of structural dynamic vibration. The measurement speed of Nova series high-speed laser vibrometer can reach 24.5m/s, and the quick-change objective lens can realize the working measurement range of 0-300m; it is suitable for the measurement of vibration or high-speed motion caused by high energy or large external force.

Sunny company LV-S01-HS high-speed vibrometer is an expansion on the basis of single-point laser vibrometer, and its vibration velocity measurement can reach 20m/s. The external scanning module can be installed to realize automatic scanning, and the optical unit can be configured to realize functions of automatic focus, remote focus, and focus access. Personalized intelligent software can evaluate measurement results in real time and display changing trends, etc[13].

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### 2.4 Remote Laser Vibrometer

Polytec RSV-150 remote laser vibrometer can measure the vibration of objects beyond 300m (related to the reflection characteristics and vibration amplitude of the measured surface) and tiny displacements. It is easy to install, can be foolproof operation, needn't to layout and wiring and other tedious work[14]. With the true capability of 0Hz, it can be used for low frequency response and displacement testing of civil engineering; 25kHz bandwidth can be used for condition monitoring, such as gearboxes; it can measure any surface without cleaning the surface under test, such as the mine environment; it is not affected by the temperature of the measurement point, and can remotely measure the vibration of hot surfaces such as furnaces and pipes.

Sunny company LV-S01-LD remote laser vibrometer can measure minor deformation and vibration of objects beyond 100m, the forced vibration frequency, natural frequency and amplitude of the measurement target are given, and parameters such as impact coefficient and power spectrum can be obtained through spectrum analysis. This instrument is convenient to realize long-distance monitoring, suitable for long-term monitoring and short-term observation in fields such as unmanned and unwired in the field, and can be used for monitoring of dam deformation, subway operation, landslides, bridges, high-rise buildings and so on.

### 2.5 Fiber Laser Vibrometer

The American OptoMET fiber laser vibrometer has the characteristics of fast speed and convenient operation. Due to its innovative digital signal processing technology and high optical sensitivity, it can provide fast and simple vibration measurement in systems of high vibration frequency, remote working and small amplitude. It can be applied to vibration measurement in microsystems, aerospace and other fields. The dual-fiber SWIR vibrator consists of a SWIR vibrator and a dual-fiber head, equipped with different collimation or focusing objectives. It uses a fiber switch to multiplex multiple fiber heads, and is applied to difficult measurement conditions (rough surface), physical access difficulties, need to detect from different angles, vacuum measurement, high speed vibration measurement, etc[15].

Sunny company LV-S01-SF fiber optic laser vibrometer can measure targets at a distance of 0-10m, has strong anti-interference ability, has high resolution and large dynamic measurement range, and has a small optical head, which is suitable for vibration measurement in space-constrained areas. It can be upgraded to realize the automatic scanning function, and the optical unit is configured to realize the functions of automatic focus, remote focus, and focus access[16].

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2.6 Microscopic Laser Vibrometer

The American OptoMET Vector high-resolution laser vibrometer is specially developed to measure tiny mechanical vibrations and movements[17], with a resolution of up to 2.5nm/s, which is very suitable for sound and ultrasonic (up to 1MHz) standard measurement. Due to the use of low-noise digital decoding technology, the amplitude of the atomic level (wavetable range) can be measured.

Polytec UHF-120 ultra-high frequency vibrometer can measure vibration up to 2.4GHz[18]. The vibrometer has a small output light power, which minimizes the energy transfer from the measuring beam to the target, and it is easy to adjust the beam to the sample. In addition, the camera integrated in the vibrometer can better locate and control the measurement point.

Sunny company MLV-100 microscopic laser vibrometer can measure the vibration of small objects through a microscopic optical system[19], and can accurately measure the vibration and morphology of MEMS and other small structural components, with a laser spot up to micrometers. The vibration frequency, velocity, acceleration, displacement and other multidimensional information of the object are measured by the microscopic imaging system.

2.7 Scanning Laser Vibrometer

The American OptoMET SWIR scanning laser vibrometer has 14 scopes of measurement[20], which can flexibly and automatically scan the entire target surface. Advanced digital signal processing technology has functions such as data acquisition, three-dimensional visualization and software analysis, and can be applied to non-contact measurement of structural vibration.

Polytec PSV-500-3D three-dimensional scanning laser vibrometer, PSV-500-NH scanning laser vibrometer (portable type), PSV-500 scanning laser vibrometer has high spatial resolution, measuring area from several square millimeters to several square meters, and the scanning angle is 50°×40°. It can be applied to structural mechanics vibration measurement, and can provides a large number of annexes and analysis software for customers to choose[21].

Sunny company SLV-S02 and LV-SC300 full-field scanning laser vibrometers add two scanning mirrors in front of the single-point laser vibrometer, and the motion control system controls the deflection angle of the scanning mirrors to achieve scanning vibration measurement in X and Y direction; equipped with a camera system to achieve human-computer

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interaction; equipped with a software analysis system to achieve two-dimensional and three-dimensional animation display and data analysis[22]. This vibrometer can quickly scan the surface of objects and flexibly define measurement areas and measurement points, which can be applied for vibration measurement of large structure, high temperature, soft object, etc.

2.8 Robot Laser Vibrometer

The structure test station of Polytec robot is based on the PSV-500-3D scanning laser vibration measurement system, which overcomes the limitations of traditional contact sensor measurement[23]. The 3D scanning laser vibration measurement system is installed on a multi-DOF (degree of freedom) industrial robot, and the robot is controlled by a stable and automatically configured 3D vibration workstation to obtain the overall vibration shape of the complex structure. This technology combination shortens the test time of EMA (experimental modal analysis), and can directly import the nodes of the finite element model grid as measurement points, thereby facilitating model correction. Due to the improvement of testing efficiency, so the site testing can be carried out more effectively.

Sunny company robot laser vibrometer is installed on the robot manipulator[24], which can realize multi-directional vibration measurement of large or irregular objects such as car bodies, motorcycles, solar panels, mechanical workbenches, machine tools, and so on. Modal analysis of the measured structure can be carried out by matching the corresponding analysis software.

2.9 Rotary Laser Vibrometer

Polytec RLV-5500 rotary laser vibrometer is based on a new digital decoding technology[25], with a high signal-to-noise ratio and a speed range can up to 20,000 rpm. The newly designed optical head is more compact and easier to approach the measured target. The integrated air blowing cleaning system protects the optical components from oil and dust, and can measure the vibration of the working vehicle transmission system on a moving vehicle. The vibrometer uses optical fiber to provide laser energy for the RLV-500 optical head, which improves the accuracy of installation and positioning. The optical head has 4 working distances to choose from: 70mm, 200mm, 400mm and 600mm. Additional steering unit can be used for vertical measurement. The RLV-500 optical head integrates an air blowing cleaning system and an IP67 case, so as to meet the need of harsh working environments.

2.10 Three-dimensional Laser Vibrometer

Sunny company 3D laser vibrometers 3DLV-S01 and 3DLVS-B can simultaneously

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measure the vibration of an object in X, Y, and Z directions to obtain the 3D vibration characteristics of the object. It can realize the synchronous output of X, Y, Z three-dimensional vibration data, and has the functions of time domain analysis, frequency domain analysis, fault diagnosis, data management, and automatic report generation. It realizes ultra-wideband vibration measurement and can be used to measure the three-dimensional vibration characteristics of large equipment.

## III. TYPICAL APPLICATION

### 3.1 Rotating Machinery Vibration Measurement

LDV has the Euler method and Lagrangian method in axial vibration measurement of the rotating blade. Measurements can be made when the scanning frequency and path are synchronized with the target's overall movement, where the probe laser beam tracks a specific point on the target. It can also perform torsional vibration measurement of parallel beam structures, including motor, train wheel radial and bending (pitch/yaw) vibration measurement[26,27].

The tracking laser Doppler vibrometer (TLDV) is shown in Figure 1. The orthogonal scanning mirror in the vibrating scanning head is controlled to track a fixed point of the rotating target[28]. As an open-loop control system, it is necessary to understand the geometry of the scan head and target, and the definition of the points to be tracked. Most importantly, an encoder is needed to calculate the two scanning mirrors' angular position. TLDV's application includes rolling tires and timing belts (part of the track) and targets where vibrating parts are fixed on parts with large body movements, such as windshield wipers.

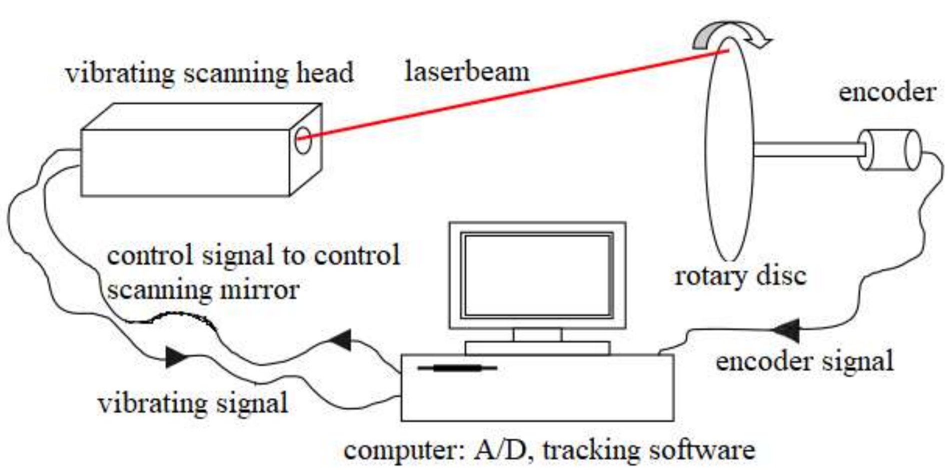

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Figure 1 Schematic diagram of TLDV system

The image-based tracking system (ITLDV) uses CCD cameras and real-time image processing algorithms to obtain the target's position signal for closed-loop control, as shown in Figure 2[29]. The same mirror observes the image through the LDV scanning head to obtain the instantaneous position of the target point relative to the laser beam, which is used as the feedback signal's error. This method overcomes the limitations of the open-loop system that requires geometric information and encoders.

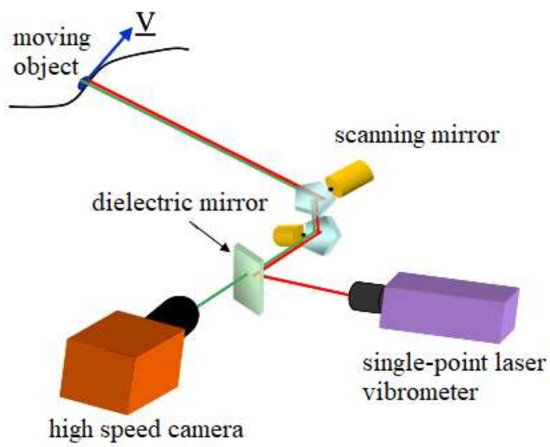


Figure 2 Schematic diagram of LDV system

Radial vibration measurement is mainly used to measure transmission systems, hard disks and their drive spindles, and monitor tool status in turning and milling. The orthogonal vibration measurement and rotation speed measurement are shown in Figure 3[30].

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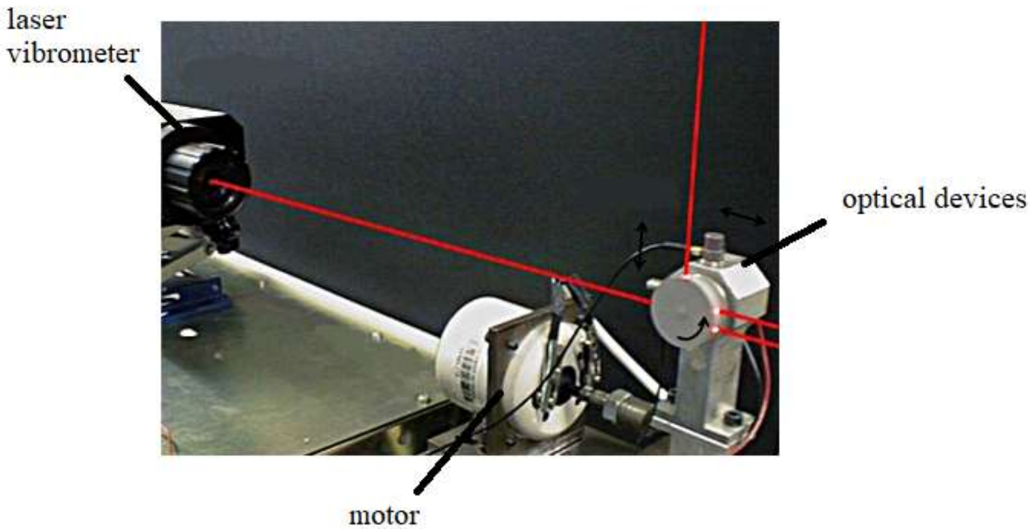


Figure 3 The orthogonal single laser beam measures the orthogonal radial vibration component, and the parallel beam instrument measures the rotation speed

Polytec PSV-A-440 has an optical reverser, which can directly measure the rotating parts' axial direction vibration. The reverser is composed of a Dove prism, and its optical working principle is shown in Figure 4[31]. The rotating device is connected to the object measured through a controller. The encoder detects the rotation speed of the object. To obtain a complete optical reverse rotation, the rotation axis of the measured object and the rotation axis of the rotation unit must match.

Figure 4 Working principle of Dove prism

As shown in Figure 5, when measuring the parameters of a compact disc (CD) that mounted on a motor with a rotary encoder, the reverser's function is to make the measuring point on the rotating measurement target static relative to the laser vibration scanner.

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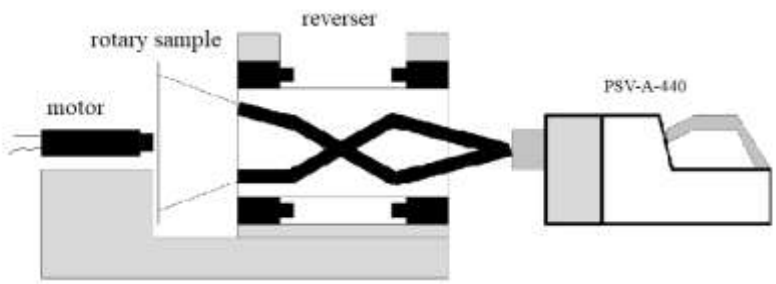


Figure 5 Typical measurement of PSV-A-440

When measuring the natural deflection shape and eigenfrequency test of CD by using the loudspeaker as a noise excitation in a static state, the vibration measurement results are shown in Figure 6. Scanning points produce an average spectrum and show the deflection shape of resonance.

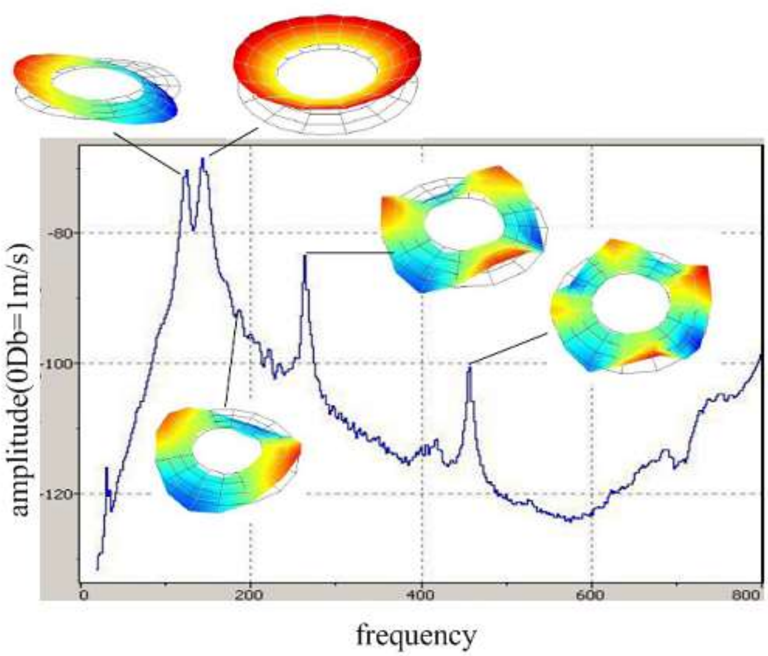


Figure 6 CD disturbance and eigenfrequency under static noise excitation

Use the reverser to test. The laser beam moves with the rotating object and stays on a fixed point on the surface. It can measure vibration in the same way as a non-moving target. The Campbell diagram (Figure 7) shows the order (straight line intersecting with the origin) of the rotational frequency, multiples and structural resonance of the forced vibration generated by

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strong excitation. The structural resonance is not a vertical line but is bent as the rotation speed increases. This relatively flexible polycarbonate material becomes harder due to increased centrifugal force. The results show that a reverse spinner can obatin the target's amplitude and hardening effect in real-time.

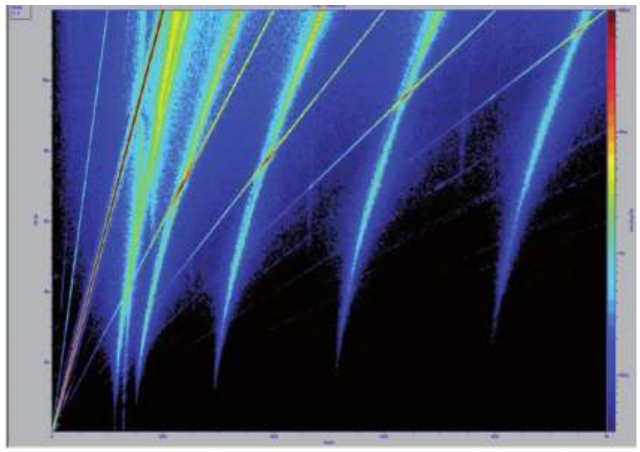

Figure 7 Application of reverser spinner measurement

3.2 Biomedical Measurement

The tympanic membrane and the three ossicles of the middle ear of mammals act as an acoustic impedance match between the air and the fluid-filled inner ear, generating electrical impulses sent to the brain. At the hearing threshold, the tympanic membrane vibration displacement is less than 0.1nm[32]. LDV can be used to study the vibration of the tympanic membrane and ossicle in a single axis and 3D.

Fruit flies listen to sounds through their antennae, which form an earpiece, just like a human eardrum. The sound causes vibration of the antennae, which is then transmitted to the sensing unit at the bottom of the antennae. It will convert the vibration into an electrical signal. The PSV-400 scanning laser Doppler vibrometer can measure the tiny, difficult to observe vibrations of the fruit flies antennae at specific measurement points. This method can systematically study the sound receiving device's vibration characteristics, as shown in Figure 8[33].

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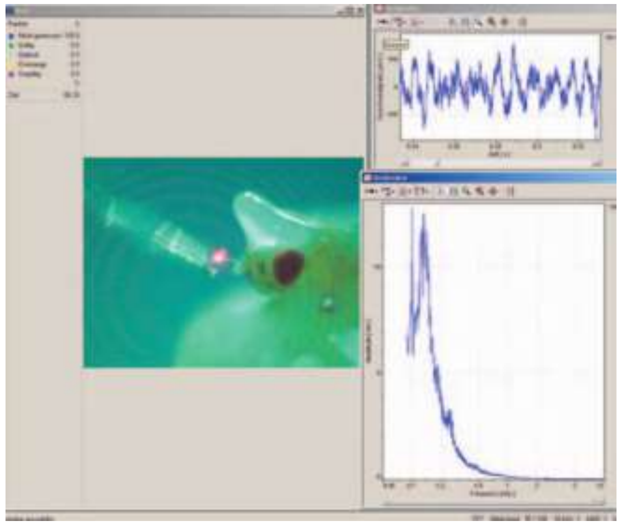

Figure 8 Vibration characteristics of fruit flies antennae.

## 3.3 Acoustic Quality Measurement

Non-contact measurement of light structures is important in acoustics, such as performance testing of microphones and ultrasonic sensors. The instrument analysis based on LDV will direct measure the sound velocity in fluid or acoustic transparent membrane. Because the LDV measures the change in the fluid's refractive index due to the sound pressure by detecting the Doppler shift resulting from the change of the optical path. The main factor that affects the measurement of refraction vibration is the integration along the laser path. This component can be demodulated with 3D tomographic reconstruction technology to obtain a complete 3D pressure field[34]. The refractive index vibration method has been used to determine the sound absorption properties of materials[35].

The balanced membrane radiator has unique visual and acoustic characteristics, and membrane performance is critical to acoustic fidelity. Polytec SLDV can perform in-situ measurements on the operating device without touching or loading the panel film, thus accelerating new speakers' development. The Polytec PSV-300 scanning vibrometer was used for vibration analysis. For sample excitation, the vibrometer generated a sine wave signal with a frequency from 150 Hz to 50 kHz, which was evenly distributed on the entire panel at 1781 measurement points to obtain velocity frequency response data.

As shown in Figure 9, it compares the operating deflection shape (ODS) at 10kHz. The left picture shows the experimental sample showing a bending mode with circular symmetry on its panel. The right picture shows the standard sample has a rotationally symmetric structure,

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destroying the circular symmetry [36]. The standard sample BMR board (with a damping material attached to the back of the mask material) shows a non-isotropic bending stiffness than the experimental sample panel. Panel manufacturers can improve the panel quality by making the panel isotropic.

Using the structural response data obtained by Polytec SLDV, the loudspeaker dynamic material properties can be identified and characterized in situ, and the inconsistency between SPL (standard PHP library) measurement and auditory testing can be clarified. The results of vibration analysis improve the understanding of BMR through the trial and error method and shorten the development time.


Figure 9 Operating deflection shape at 10kHz

3.4 MEMS Measurement

In micro electro mechanical systems (MEMS), semiconductor manufacturing technology is used to manufacture systems with mechanical and electronic coupling characteristics, such as small motors and hydraulic pumps for inkjet printers. In dynamic MEMS, applications include surface acoustic devices, micro mirror arrays and sensors. LDV can measure displacement at the pico meter level at GHz frequency [37], but LDV measurement needs to consider the size of laser spot, laser heating, specular reflection, optical interference due to complex geometry and heat dissipation, and need to observe the controlled test environment through the window.

The different thermo-mechanical properties of the materials at the MEMS package interface lead to the increase in periodic stress during normal operation. It is necessary to perform life analysis for highly miniaturized interconnects. Directly use high-frequency resonance as the pressure source to test the key parts of the package. As shown in Figure 10, the components under test are forced to produce vibration. This method will shorten the test time.

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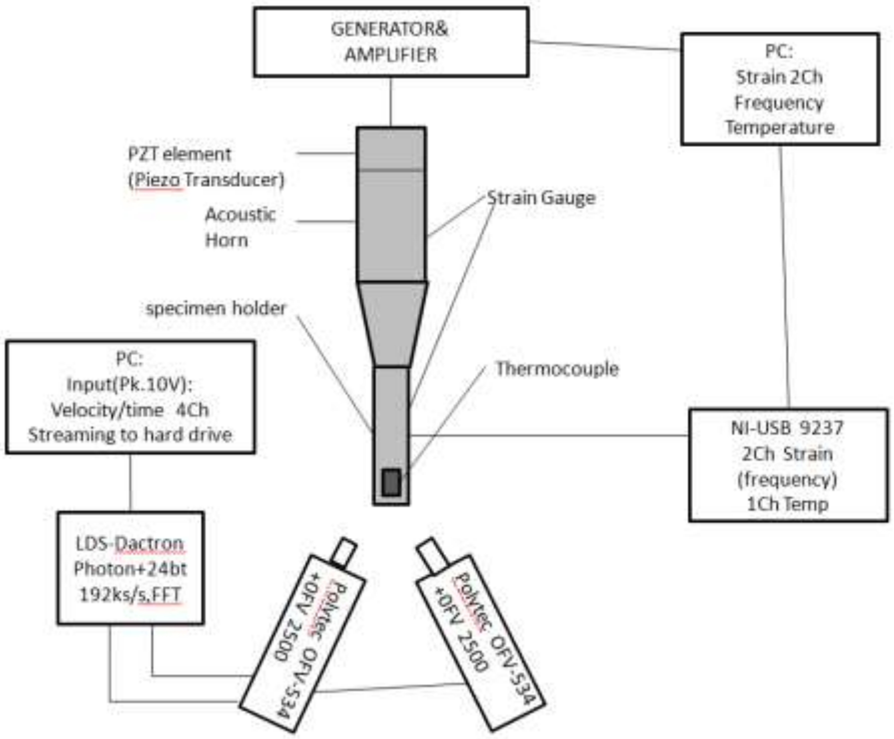


Figure 10 Schematic diagram of resonance measurement system

The collected velocity/phase difference data is used to reconstruct the relative displacement of the two vibrometers and provide the necessary information to calculate the mechanical stress acting on the interface. Since the thermal expansion difference of self-connection materials of the thermal load in normal operation, the thermal load is derived from the thermal expansion difference of the connecting materials, so a simple bimetal method is used to establish the Coffin-Manson relationship (cycle failure $N_f$ and equivalent temperature deviation $\Delta T$). The data obtained is directly compared with the industrial power cycle test results of the same sample quality as shown in Figure 11.

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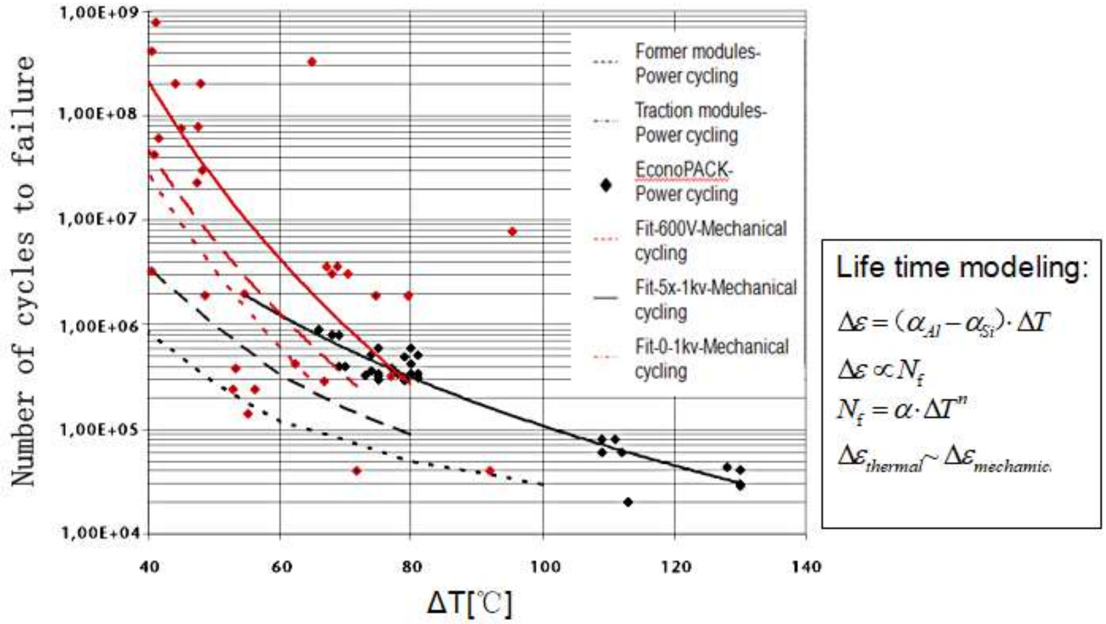


Figure 11 Curve of mechanical life and thermal life

In figure 11, the accelerated testing technique was successfully applied to the fast life estimation of various microelectronic interconnects represented by wire bonds, and the results are correlated well with the available power cycle data. Due to equipment limitations, all experiments are carried out at room temperature, and the system needs to be improved to allow isothermal testing in the temperature range of 125 to 175°C.

## IV. EXISTING PROBLEMS AND DEVELOPMENT TRENDS

### 4.1 Autofocus

3D SLDV works on a pre-defined grid composed of connecting points that form triangular elements. At these points, the system obtains the velocity data of each point in the grid. For each point on the grid, if the coordinates of the measuring point are not accurately determined, the beams will not completely intersect at the measuring point. Errors in measuring distance cause the beams to intersect "in front" or "behind" the surface. If the position of the head is not accurately determined, then the three beams will not intersect but can only approach. The interaction within a certain radius is shown in Figure 12. The accuracy of geometric measurement depends on the behind direction characteristics of the surface, and the accuracy of the head position depends on the quality of the three-dimensional alignment.

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One of the prerequisites for accurately calculating these orthogonal vibration components is that the three beams of light on the surface of the object are focused on one point, which is only possible when the precise coordinates of the measuring point are known, making 3 beams of light look like a beam of light as shown in Figure 13. This is very important for high-frequency measurements that require high spatial resolution. It can significantly reduce in-plane and out-of-plane interference. Autofocus is a direction of product development.

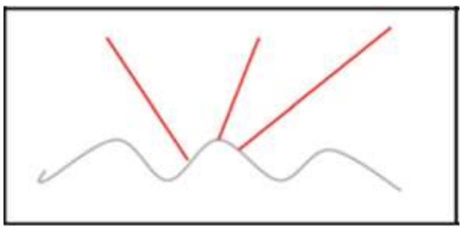

Figure 12 inexact intersection

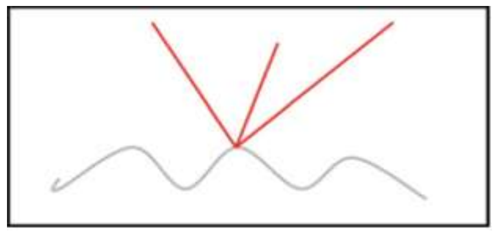

Figure 13 beam positioning accuracy

4.2 Laser Speckle and Pseudo Vibration

Laser speckle measurement technology has become the main method of vibration measurement. Many surfaces encountered in traditional engineering structures can meet the conditions, but the coherent wavelet produces destructive interference, resulting in a chaotic distribution of high and low intensity different scattering, which is called "speckle mode". The collection of light is usually the sum of several light spots, and sometimes it is necessary to make small adjustments to the position of the incident beam to avoid the impact of low intensity signals (due to low backscattered intensity, unfavorable measurement surfaces, or due to light spots) on the photodetector. This unfavorable summation may be produced by the predominance of darker spots, or the vector sum. When the spots start to move or respond to the movement of the target, the speckle effect produces "pseudo vibrations".

There are two effects on the photodetector and Doppler signal for a changing speckle cluster: amplitude modulation and phase modulation. Amplitude modulation means that the varying signal amplitude occasionally drops to a very low level, which is called "signal drop." However, even if sufficient signal amplitude is maintained, the sampled speckle will change dynamically. The phase modulation causes the photodetector to output phase noise, which causes the vibrometer to output "speckle noise", that is, "pseudo vibrations".

Both signal drops (obvious in the output) and pseudo vibrations (changes in random phase spots) will produce measurement noise in broadband, especially when the surface vibration (or total motion) that causes these effects itself is periodic, the noises generated is pseudo-random,

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and its spectrum is composed of fundamental waves and high order harmonics. High order harmonics are usually very important, and its noises are difficult to distinguished from real vibration. Solving the problem of pseudo vibration is one of the future research directions.

### 4.3 3-Dimension Measurement of MEMS

3D MEMS measurement is realized by combining out of plane LDV measurement with in-plane measurement using video microscope. It is easy to obtain the vibration information in three directions for large objects with scattering surface. However, for micro structures, optical crosstalk will be a big problem when three laser beams are used for measurement at the same time, because the three laser beams must be closely placed together to achieve the required spatial resolution (usually micrometer level), so it is necessary to solve the anti-interference technology for vibration measurement of similar MEMS devices.

### 4.4 Multipoint Measurement

When multiple points are performed non contact measure simultaneously, using multiple single LDVs is an expensive solution, such as transient vibration measurements on the fine structures. Multi beam solutions have advantages, but flexibility in beam direction is limited. The new solution is user configured multi-sensor probe connected to a central unit containing a single laser system and a multi-channel interference detection system. As shown in Figure 14, 8 sensor probes are connected to an optical unit, up to 6 optical units can be cascaded, allowing up to 48 synchronous measurement channels to be configured. In the optical unit, the output of the laser is divided into 8 measurement channels and 8 reference channels. For each measurement channel, the light is coupled to the optical fiber of its measurement head and focused on the measurement point of the target structure. The backscattered light is collected by the same lens and guided back to the optical unit for interference detection. The interference signal from each channel is demodulated by mixing.

Figure 14 8-channel vibrometer

## V. SUMMARY

This paper takes Germany Polytec company, American Optomet company and domestic Sunny company as examples, introduces the development status of single point laser vibrometer, multi-point laser vibrometer, high-speed laser vibrometer, remote laser vibrometer, optical fiber laser vibrometer, micro laser vibrometer, scanning laser vibrometer, robot laser vibrometer, 3D laser vibrometer, etc, and their typical applications of vibration measurement which in rotating machinery, biomedical engineering, acoustic quality testing, MEMS, etc. Aiming at the problems of auto focusing, laser speckle and pseudo vibration, MEMS 3-dimensional measurement, multi-point measurement and so on, the research and application development ideas are putted out.

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