Laser Vibrometry

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Artikel auf Deutsch

A laser Doppler vibrometer (also laser vibrometer or LDV) is an optical measuring instrument that quantifies mechanical oscillations.

1 Operating principle
2 Physical and technical fundamental principles
   2.1 Doppler effect in LDV
   2.2 Function of the Bragg cell
3 Practical application knowledge
   3.1 Measurement modi
   3.2 Velocity measurement
   3.3 Displacement measurement
   3.4 Accuracy and limits of the measuring range
   3.5 Advantages and disadvantages
   3.6 Advantages
   3.7 Disadvantages
   3.8 Applications
4 Requirements for LDV lasers
5 Conceptual distinction
   5.1 Laser interferometer
   5.2 Laser scanning vibrometry
   5.3 Laser Doppler anemometry (LDA)
6 Literature
7 References
8 Weblinks

Fig. 1: Polytec single-point vibrometer sensor head and vibrometer controller

Operating principle

The laser beam is divided into two partial beams - a test beam and a reference beam (cf. Fig. 2 bottom). The test beam hits the oscillating surface of the target. There, it is modulated in frequency and phase in accordance with the laws of the Doppler effect (see Physical and technical fundamental principles). The reference beam does not leave the LDV. It is guided via a Bragg cell (see Physical and technical fundamental principles) to the photodetector where it is interfered with the reflected test beam. A frequency modulated voltage which is directly proportional to the velocity of the target is generated at the BNC connector of the LDV. The measurements can be further analysed with FFT.
Physical and technical fundamental principles

**Doppler effect in LDV**

In the event of an electromagnetic wave (in this case a laser light) hitting a dynamic particle (in this case the target), the frequency as well as the phase change proportionally according to their relative velocity. The new frequency is given by the formula

\[
    f_t = f_0 \sqrt{\frac{c + v}{c - v}}
\]

with \( f_t \) new frequency,

\( f_0 \) initial frequency,

\( c \) velocity of light within the medium,

\( v \) velocity of the moving object.

As the velocity of the target is very slow compared with the velocity of light, the frequency shift is also relatively small. The following relation exists:

\[
    \Delta f = \frac{2v}{\lambda}
\]

Here it is assumed that the velocity \( v \) of a relative movement towards each other is positive.

Example calculation:

- given: HeNe laser with \( \lambda = 633 \text{ nm} \), the membrane oscillates with \( v_{\text{max}} = 10 \text{ m/s} \)
- quested: maximum frequency shift
- solution: \( \Delta f = 31.6 \text{ MHz} \)

In comparison: The frequency of the HeNe laser is \( f_{\frac{\lambda}{\Delta}} = 474 \text{ THz} \)

**Function of the Bragg cell**
The velocity of the target can be determined by the interference pattern of both beams but not the direction of the movement. The Bragg cell is a acousto-optic modulator and shifts the frequency of the reference beam by 40 MHz. That means that a static object appears at the detector an interference pattern with a modulation frequency of 40 MHz. As the object moves towards the interference pattern, the modulation frequency increases - and decreases if the object moves away from the interference pattern. This enables a change in direction.

Practical application knowledge

**Measurement modi**

**Velocity measurement**

Velocity measurement is particularly suitable for high frequencies. Despite a low oscillation amplitude, high velocities are achieved at high frequencies. The given formula is:

\[ v = 2\pi f s \]

with \( v \) maximum velocity of the membrane,

\( s \) maximum amplitude of the oscillating membrane

With this formula, a conclusion can be drawn from the measured velocity to the displacement of the target. Generally, a vibrometer can also measure the displacement directly. More about that in the following measurement mode.

**Displacement measurement**

Displacement measurement should be used particularly for frequencies smaller than 1 Hz. This implies a large amplitude and low velocities. In this measurement mode, the Doppler effect is not used as with the velocity measurement, but determined from the light-dark transitions while passing through the interference pattern on the photodetector. [1]

**Accuracy and limits of the measuring range**

- achievable displacement resolution: 2 pm
- velocity resolution: up to 2 nm/s
- max. measurable frequency: several MHz
- working distances: mm to > 100 m

Through the influence of the device parameters with one another, maximum accuracies and limits cannot be achieved at the same time.

**Advantages and disadvantages**

**Advantages**

- transportable/on site analyses possible
- non-contact measurement possible (especially if the assembly of a sensor had too much influence on the vibrational spectrum)
- distances of several metres between the target and the LDV possible. (Dependent on the parameters of the device such as laser power and coherence length as well as on the measurement conditions: Reflectivity of the target, light absorption of the medium between the LDV and the target.)
- insensitive to electromagnetic interferences [2]
- oscillation measurement on rotating or glowing surfaces [2]
- calibration free in application
- large measurable frequency range/almost all technically relevant frequencies are measurable
- linear amplification of measured frequencies/no resonant frequencies such as with other oscillation sensors (e.g. piezo sensors)

**Disadvantages**

- compliance with safety regulations for laser application is required (e.g. wearing safety glasses)
- material limitations: To achieve good measurements, the target’s surface has to be sufficiently reflective. It is not possible to measure transparent materials, whereas the different degrees of transmission of a material in relation to the wavelength of the light has to be noted. A for the human eye transparent material can be impermeable for electrical waves beyond the visible range of about 380 - 780 nm. A thin film glued on to the target’s surface can sometimes solve the problem
- point measurement
Applications

- Acoustic: Diagnoses of speaker and musical instrument performance [3]
- Automotive industry: Vibration analysis of individual components and the entire vehicle
- Biological: Analysis of communication of animals e.g. bees
- Engineering: Testing and long-term monitoring of the oscillatory behaviour of buildings and bridges, surface inspection of structures with unmanned aerial vehicles
- Turbine construction and mechanical engineering

Requirements for LDV lasers

Pre-requisites for all interferometric measurements are a high quality of the beam and a large coherence length of the light source. Some laser types have proved particularly suitable - for example the HeNe laser. It can have a coherence length of 100 m (328 ft). The most often used wavelengths are 632.8 nm and 1152.3 nm. The argon-ion laser is also very popular. Its coherence length is somewhat smaller than of the HeNe laser but with up to 100 m it is still very large. It's typical utility wavelengths are 514.5 nm and 488.0 nm. Both lasers operate in the visible range.

Conceptual distinction

Laser interferometer

The laser doppler vibrometer is a type of laser interferometer. Laser interferometers are generally qualified by making use of overlapping waves (interference).

Laser scanning vibrometry

Extensive application of a laser Doppler vibrometer due to scanning the target with a laser beam and integrated mirrors, and thus carrying out several point-by-point measurements.

Laser Doppler anemometry (LDA)

Determination of the particle velocity in fluids.

Literature


References

1. Grundlagen der Vibrometrie.

Weblinks

- https://de.wikipedia.org/wiki/Akustooptischer_Modulator
- https://en.wikipedia.org/wiki/Laser_Doppler_vibrometer
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