Abstract

This paper introduces laser Doppler vibrometry as a modern technique for measuring objects dynamics. It explains all the needed physical and data processing background which brings to the velocity and displacement information. The dynamic parameters of the object are given by modal testing, which is presented in addition.
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Chapter 1

Introduction

Laser Doppler vibrometry (LDV) is a velocity and displacement measurement technique. Its theoretical bases were only presented in the second half of the 20th century in spite having had all the needed physical knowledge for a long time. LDVs relatively late development is related to the late laser development which is its basic component (the first working laser was demonstrated in 1960). The use of LDV is nowadays spread in a variety of fields. It is used for the analysis of all kinds of vibrating systems, speed and position measurement. A typical modern vibrometer is composed of the a sensor head unit and a controller unit (1.1).

The LDV measurement is non-contact and that is its biggest advantage. Therefore the tested part stays uninfluenced during the measurement bringing a much more reliable picture of its own properties. Because of this it is possible to observe dynamics on a very broad scale down to micron size. Alternatives to the LDV are accelerometers which supply a better sensitivity and are less sensitive to vibrations of the environment because they are not part of it. On the other hand this is a contact method that influences the measurement object with its own mass. Another disadvantage of the accelerometers are problems with fixation which also makes the change of the observation point complicated [1].

The basic component of a LDV aperture is a laser beam focused on the tested structure which’s movement causes the presence of the Doppler effect in the laser reflection. If the object supplies a proper reflection, it is possible to calculate its displacement and velocity. How exactly this is done will be explained in the second chapter while modal testing will be presented in the third chapter.

Figure 1.1: An example of a modern vibrometer from Polytec. Composed of a sensor head and a controller (processing unit) [2].
Chapter 2

Laser Doppler vibrometry

Before entering into the in-deep explanation of LDV the understanding of its basic component is needed. Therefore the properties of the laser and the Doppler effect should be discussed.

2.1 Laser

The word "LASER" is an acronym (Light Amplification by Stimulated Emission of Radiation) which also explains how it works. The basic principle is the principle of the induced emission of photons. The laser consists of a resonant optical cavity which contains the lasing material (gain medium) which supplied with energy places some of its particles into excited quantum states. The pumping of energy is usually done with electrical current, light flashes or even with lasers. The excited particles release the additional energy by emitting photons (2.1) spontaneously or stimulated by other photons with proper energy. The cavity has therefore mirrors on each end that are repeatedly reflecting light. The length of the cavity defines the wavelength of the reflecting light and must be tuned to the difference of quantum energy levels of the gain medium. If so, the light in the cavity is amplified. In addition one of the reflecting mirrors is partially transparent letting some of the light out of the cavity in the form of a beam [3].

The cavity dimensions do not only well define the emitted light wavelength (monochromatic), but the cavities bounds make the laser a coherent light source (reflection boundary condition). Why a monochromatic and coherent light source is needed will be explained later, but that are exactly the properties of a laser. The lasers used for LDV are usually helium-neon with the wavelength $0.6328 \, \mu m$ (the following text will refer to it on many occasions).

2.2 Doppler effect

This physical phenomena was firstly observed by the Austrian physicist Christian Doppler. It describes the relative change in wavelength and frequency of a wave when the observer and the source are moving. The waves can be grouped according to the medium/non-medium propagation and in both cases the Doppler effect can be observed (2.2). But when talking about waves propagating in medium relative velocities of the source and of the observer comparing the medium must be taken into account. On the other hand only the relative difference in velocity between the observer and the source is important for the electromagnetic waves.
LDV uses a laser which is an electromagnetic wave. The light source is fixed and the observation object is moving. The object would measure a different frequency \( f' \) as it is emitted

\[
f' = f \left( \frac{c}{c \pm v} \right).
\]

\( f \) stands for the emitted wave frequency, \( c \) \((299792458 \text{ m/s})\) for its propagation velocity and \( v \) for the velocity of the object. The \( \pm \) sign in the denominator depends on the way the observed object is moving. If it moves away from the source the plus sign should be taken and the frequency is being lowered. It is the way around for moving toward the source.

Light speed is very big compared to the speed of the observed object. Therefore the equation can be evolved in a Taylor series

\[
f' = f \left( \frac{c}{c \pm v} \right) \approx f \left( \frac{c \mp v}{c} \right) = f \left( 1 \mp \frac{v}{c} \right) = f + f_d
\]

(2.1)

The frequency shift is denoted with \( f_d = f \frac{v}{c} \) (Doppler frequency). Equation (2.1) expresses the frequency the moving object would measure, but in the LDVs case the reflected light is observed. Therefore the Doppler effect must be taken into account again. Now the source is moving and the observer is fixed and the overall frequency shift doubles

\[
f_d = 2f \frac{v}{c} = \frac{2v}{\lambda}
\]

where \( \lambda \) is the wavelength of the laser.

### 2.3 Vibrometer

At this point all the needed physical background is explained and the explanation of LDV is possible [2]. Measuring the frequency of the reflected laser would give the velocity of the object. Unfortunately the laser has a very high frequency \((\omega = 4.74 \cdot 10^{14} \text{Hz for the he-ne laser})\) and a direct demodulation is not possible. The solution is to observe the interference between the reflected and the original light. An optical interferometer is therefore used to mix the scattered light coherently with the reference beam. The photo detector measures the intensity of the mixed light of which the beat frequency is equal to the difference frequency between the reference and the measurement beam. Such an arrangement can be a Michelson interferometer (2.3).

A laser beam is divided at a beam splitter into a measurement beam and a reference beam which propagates in the arms of the interferometer. The distances the light travels between the beam splitter and each reflector are \( x_r \) for the reference beam and \( x_m \) for the measured object. The
corresponding optical phases of the beams in the interferometer are \( \varphi_r = 2kx_r \) and \( \varphi(t)_m = 2kx_m \), where \( k = 2\pi/\lambda \). In LDVs case only the reflected phase is time dependent while the reference phase is fixed because the distances are not changing. The phase difference between the mixed beams is introduced \( \varphi(t) = \varphi_r - \varphi_m = 2k\Delta L \), where \( \Delta L \) is the vibrational displacement of the object and \( \lambda \) the wavelength of the laser light.

Mathematically both beams can be treated as free waves.

\[
E_r = E_{r0}e^{i(\omega_r t + \varphi_r)}
\]

\[
E_m = E_{m0}e^{i(\omega_m t + \varphi_m)} = E_{m0}e^{i((\omega_r + \omega_d) t - \varphi(t))} = E_{m0}e^{i(\omega_r t + \varphi_r)}e^{i(\omega_d t - \varphi(t))}.
\]

The photo detector measures the time dependent intensity \( I(t) \) at the point where the measurement and reference beams interfere.

\[
I(t) = |E_m + E_r|^2 = I_m + I_r + 2\sqrt{I_mI_r} \cos(\omega_d(t) - \varphi(t))
\]

Introducing \( K \) is a mixing efficiency coefficient and \( R \) is the effective reflectivity of the surface the intensity equation becomes

\[
I(t) = I_mI_rR + 2K\sqrt{I_mI_r}R \cos(\omega_d(t) - \varphi(t)).
\]

If \( \Delta L \) changes continuously the light intensity \( I(t) \) varies in a periodic manner. A phase change \( \varphi \) of \( 2\pi \) corresponds to a displacement \( \Delta L \) of \( \lambda/2 \). Now it is obvious why for LDV a laser is needed. Having a monochromatic and coherent light source is important for having a well defined phase and wavelength.

From the phase of the intensity it is possible to calculate the displacement. But getting the phase information is not that easy. As object movement away from the interferometer generates the same interference pattern as object movement towards the interferometer, this setup cannot determine the direction the object is moving in. By changing the measurement setup, there are two ways to introduce directional sensitivity (Homodyne and Heterodyne). In the next two sections both of them are explained.

### 2.3.1 Heterodyne interferometer

An acousto-optic modulator (called also Bragg cell, see Appendix: Acousto-optic modulator) is placed in the reference beam (2.4), which statically shifts the light frequency by typically \( f_b = 40 \text{ MHz} \). By comparison, the frequency of the laser light is \( 4.74 \cdot 10^{14} \text{ Hz} \). The frequency shift causes a modulation frequency of the fringe pattern of 40 MHz when the object is at rest. This way the objects zero velocity position is transposed and directional sensibility is introduced. If the object moves towards the interferometer, the modulation frequency is reduced and if it moves away the frequency is raised. This means that it is now possible not only to detect the amplitude of movement but also to clearly define its direction.
A mathematical formulation of a heterodyne interferometer can be done. The reference frequency \( f \) changes and therefore the frequency difference changes

\[
\Delta f = f - f' = -f_d \quad \rightarrow \quad \Delta f = f + f_b - f - f_d = f_b - f_d
\]

and the intensity at the detector becomes

\[
I(t) = I_m I_r R + 2K \sqrt{I_m I_r R} \cos(2\pi [f_b - f_d]t - \varphi(t)) \tag{2.2}
\]

Now the \( \cos \) part of the intensity never varies with negative frequencies and therefore directional sensibility is introduced.

### 2.3.2 Homodyne Interferometer

The second solution known as the quadrature homodyne interferometer can be designed by adding wave retardation plates, a polarizing beamsplitter and an additional detector [2]. The interferometer polarizes the laser to a 45° inclination. The light in the reference arm passes twice through the \( \lambda/8 \) retardation plate and the light coming back to the beam splitter is circularly polarized. This can be described as the vector sum of two orthogonal polarization states (2.5).

\[
\begin{align*}
\text{Figure 2.5: A heterodyne interferometer. The additional Bragg-cell produces a frequency shift in the reference laser beam.} \\
\text{A mathematical formulation of a heterodyne interferometer can be done. The reference frequency (} f \text{) changes and therefore the frequency difference changes} \\
\quad \Delta f = f - f' = -f_d \quad \rightarrow \quad \Delta f = f + f_b - f - f_d = f_b - f_d \\
\text{and the intensity at the detector becomes} \\
\quad I(t) = I_m I_r R + 2K \sqrt{I_m I_r R} \cos(2\pi [f_b - f_d]t - \varphi(t)) \tag{2.2} \\
\text{Now the } \cos \text{ part of the intensity never varies with negative frequencies and therefore directional sensibility is introduced.} \\
\text{2.3.2 Homodyne interferometer} \\
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\text{Figure 2.5: A homodyne interferometer. The additional polarizer, } \lambda/8 \text{ plate, a beam splitter and a photo detector are inserted into the measuring system.} \\
\text{A polarizing beamsplitter placed in front of the detectors 1 and 2 separates the two orthogonal components. The result is a quadrature relationship at the detectors (sine and cosine output). Out of the interference patterns of the reflected signal with both signal components the direction of} 
\end{align*}
\]
the movement can be calculated. Between the sine and cosine component is a $90^\circ$ phase difference
and therefore different movement directions cause a different interference pattern at least with
one of the reference component.

A quadrature homodyne interferometer is much easier to design as simple low frequency photo
detectors and amplifiers can be used, but non-linear behavior of the used elements on the other
hand causes harmonic distortions of the measurement signal. Because of this Homodyne interfer-
ometers are usually used for LDVs.

\subsection*{2.3.3 Measuring objects with multiple degrees of freedom}

Introducing the directional sensibility it is now possible to detect the movement parallel to the laser
beam. In the case the movement is not only in the beam direction only the parallel component
is measured. It is possible to measure motion in more direction using multiple LDVs in different
setups 2.6.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_6.png}
\caption{Different measuring setups allow to analyse more complex movements using multiple
LDVs [2].}
\end{figure}

\subsection*{2.4 Signal processing}

In the Homodyne case the interference frequency is proportional to the surface velocity and the
phase change $\Delta\varphi$ is proportional to the displacement of the object. Typical performances of a
modern LDV are presented in the lower table. How the the displacement and velocity is calculation
out of the measured intensity must be explained.
<table>
<thead>
<tr>
<th>Frequency</th>
<th>from</th>
<th>to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration Amplitudes</td>
<td>0</td>
<td>30 MHz</td>
</tr>
<tr>
<td>Vibration Velocities</td>
<td>2 pm</td>
<td>10 m</td>
</tr>
</tbody>
</table>

### 2.4.1 Velocity estimation

Typical frequencies that should be analysed are moving between 30 MHz and 50 MHz. That is in the RF range, which is defined between 3 Hz and 300 GHz.

The analogue way to do the decoding is to use a PLL (phase locked loop). PLL is a control system that generates a signal that has a fixed relation to the phase of a "reference" signal. In LDV’s case the interference intensity signal is used for the "reference". The phase-locked loop circuit responds to the frequency and to the phase of the input signals, automatically raising or lowering the frequency of a controlled oscillator until it is matched to the reference in both frequency and phase. From the voltage on the oscillator the frequency is read.

Digital demodulation is another way to measure the frequency. Firstly the signal must be digitalised with an AD converter. For this purpose high speed converters should be used because high frequencies are present. Out of the data stream the velocity information is taken with the use of numerical methods (convolution, FFT).

### 2.4.2 Displacement estimation

To measure displacement the fringe counting technique is used. As displacement by half the laser wavelength (λ/2 = 316 nm for He-Ne lasers) changes the phase by 360 degrees. By counting the "zero-crossings" the laser vibrometer measures how far the object has moved, in increments of λ/2 per cycle. The information about the direction of the movement should be taken from the velocity information.

In the case of digital LDVs the data is interpolated. Doing so the determination of "zero-points" is done with a better resolution that leads to a better accuracy of the displacement measurements. Another way to increase the resolution is to arrange multiple reflections from the object. In that case bigger frequency shifts and phase changes are detected for the same movement. This way resolutions of λ/160 (2 nm for He-Ne laser) are achieved. It should be noted that, the higher the phase multiplication becomes the lower the measurable velocity and vibration frequency of the object will be.

### 2.5 Scanning vibrometer

Scanning vibrometers use a single point vibrometer (discussed until now) for analysing bigger areas of an object. The measurement system is equipped with an additional video camera which is connected to the control unit. Through a computer based user interface the scanning area is selected with the help of smart picture recognition algorithm (2.7).

The sensor head of the vibrometer is equipped with a moving mirrors mechanism driven by the control unit that scan the selected area in discrete points. Each point is being measured for a certain time period which defines the precision of the frequency estimation. Simultaneously the displacement and the velocity is measured and stored in the computer memory. After the measurement the data can be presented graphically making a very good picture of an object’s dynamics. With scanning vibrometers amazing pictures are produced with all the precision that the LDV technique is offering (2.8).

When using scanning vibrometers a basic assumption is made: the vibrating object is vibrating in the same way all during the measurement. This is the assumption of stationary vibration.
Figure 2.7: Through a computer based interface it is possible to estimate the scanning area. The picture shows the interactive grid which defines the measurement points on a cars mudguard [2].

Figure 2.8: Scanning LDVs are broadly used in different industrial fields. Amazing surface scans give very clear pictures of the properties of an object [2].

2.6 Surface properties

LDVs operate on a variety of surfaces [2]. It is important that the amount of light scattered back from the different surfaces is sufficient for further signal analysis. Specular surfaces obey the law: angle of incidence is equal to the angle of reflection. When making measurements from such surfaces the optics of the LDV need to be aligned such that the reflected light returns within the aperture of the collecting optics (2.9). Diffuse surfaces scatter the incident light over a large angular area. In this case bigger measuring angles are possible if there is a satisfying intensity of the reflected light.

It is possible to increase the reflection of the surface in the laser's beam direction using retro-reflective tape or paint. This material consists of small glass spheres (approximately 50 µm in diameter) that are glued with an elastic epoxy to the base material. Each sphere acts as a small "cats eye" scattering light back along the path of the incident beam.
Chapter 3

Modal testing

Modal analysis is defined as the study of the dynamic characteristics of a mechanical structure [8]. The observed object is exposed to controlled excitations and its response is observed, analysed and formulated in a very specific way (3.1). The best way to measure the objects response is with a laser Doppler vibrometer. Therefore this chapter can be understood as an important example of the LDV usage.

![Modal testing procedure schematics](image)

Figure 3.1: Modal testing procedure schematics.

3.1 Measurement

The modal analysis begins with the measurement. The basic principle is to induce a force to the object and measure its response to it. The excitation is usually made with an impact hammer with a force sensor or with a shaker. A shaker is controlled by an external signal and delivers the excitation force to the object. For this purpose usually electro-dynamic or hydraulic shakers are used, which typically produce maximum forces from 10 to 5000 N with a typical frequency limit.
between 5 and 20 kHz. A shaker can deliver sinus sweep and random noise excitations while a hammer produces impact excitations.

The data of interest is the response (displacement, velocity, acceleration) and the excitation force. The response data is delivered by a LDV or accelerometer which were already discussed. On the other hand the excitation force information comes from a force transducer. The piezoelectric types of transducers, which measure force and acceleration, are the most widely used for modal testing. Piezoelectricity is the ability of some materials (notably crystals and certain ceramics) to generate an electric potential in response to applied mechanical stress (3.2). The word is derived from the Greek piezein, which means to squeeze or press. A general test configuration is presented on Figure 3.3.

Figure 2.9: A highly reflecting surface. The observed surface must be nearly perpendicular to the laser beam.

Figure 3.2: Piezoelectric material generate an electric potential in response to applied mechanical stress.

Figure 3.3: General test configuration including all the main parts [8].

The first step in setting up a structure for frequency response measurements is to consider the fixturing mechanism necessary to obtain the desired constraints (boundary conditions). This is a key step in the process as it affects the overall structural characteristics. Analytically, boundary conditions can be specified in a completely free or completely constrained sense. In testing practice, however, it is generally not possible to fully achieve these conditions. The free condition means that the structure is floating in space with no attachments to ground and exhibits rigid body behavior at zero frequency. Physically, this is not realizable, so the structure must be supported in some manner. The constrained condition implies that the motion is set to zero, which is also impossible to achieve.

In order to approximate the free system, the structure can be suspended from very soft elastic cords or placed on a very soft cushion. By doing this, the structure will be constrained to a degree and the rigid body modes will no longer have zero frequency. However, if a sufficiently soft support system is used, the rigid body frequencies will be much lower than the frequencies of the flexible modes and thus have negligible effect.

The implementation of a constrained system is much more difficult to achieve in a test environment. To begin with, the base to which the structure is attached will tend to have some motion of its own. Therefore, it is not going to be purely grounded. Also, the attachment points will have
some degree of flexibility due to the bolted, riveted or welded connections. One possible remedy for these problems is to measure the frequency response of the base at the attachment points over the frequency range of interest. Next thing is to verify that this response is significantly lower than the corresponding response of the structure, in which case it will have a negligible effect.

Finally the measurement can start. The hole process is managed by the controller which sets the input excitation and measures the output response simultaneously according to the will of the user. The excitation signal is connected to an amplifier which assures enough power for the shaker. The force and the response is acquired during the experiment and afterwards objects parameters are estimated out of it.

3.2 Parameters estimation

Knowing the excitation force and the response of the object, its dynamic properties can be estimated (3.4). Finding its transfer function brings the value of the system’s damping factors, moving mass and stiffness parameters. The transfer function of a system is defined as the Laplace transformation of the ratio of the input and output signal

\[ G(s) = \frac{Y(s)}{X(s)} = \frac{\mathcal{L}\{y(t)\}}{\mathcal{L}\{x(t)\}}. \]

All real systems of finite extent have an infinite number of possible vibration modes [10]. Suppose that the equation describing wavelike propagation in the oscillator has the form

\[ L\Phi - \frac{\partial^2 \Phi}{\partial t^2} = 0 \] (3.1)

where \( L \) is a linear differential operator. The equation can be written in form of eigenfunctions

\[ L\Phi_j + \omega_j^2 \Phi_n = 0. \]

Extending equation 3.1 by adding a a force unit magnitude on right at frequency \( \omega \) applied at point \( r_0 \) this equation becomes

\[ LH_\omega + \omega^2 H_\omega = -\delta(r - r_0) \] (3.2)

where \( \delta(r - r_0) \) is the Dirac delta function and \( \Phi \rightarrow H_\omega(r, r_0) \), which is the Green function for the system at the frequency \( \omega \). Assuming the expansion

\[ H_\omega(r, r_0) = \sum_j a_j \Phi_j(r) \]

and substituting this into 3.2

\[ \sum_j a_j (\omega_j^2 - \omega^2) \Phi_j(r) = \delta(r - r_0) \] (3.3)

it is possible to express \( a_j \) by multiplying both sides of 3.3 with \( \Phi_j(r) \) and integrating over the hole volume of the resonator using the orthonormality condition. Now it is possible to express the Green function

\[ H_\omega(r, r_0) = \sum_j \frac{\Phi_j(r_0) \Phi_j(r)}{\omega_j^2 - \omega^2} \] (3.4)
This is the equation on picture 3.1 and is expressing the transfer function dependence of the measurement and excitation point. If both points are chosen to be the same the "driving transfer function" is measured, otherwise we talk about "cross transfer function.

The transfer function must fit the measured data in the form of a rational function which has a well understandable physical background. By fitting the response with a rational function the linearity assumption is made. On one hand linearity is limiting to harmonic solutions which are nothing else than a supposition and no shocking results can be achieved. But luckily this assumption is easy to verify. A linear system can respond only by the frequency it was excited with and only phase and amplitude changes can occur. If this is not true the linearity assumption is inappropriate.

Modal testing can help making improvements on vibrating systems. If one mode of the system vibration is in our interest its natural frequency, its damping factor and stiffness coefficients can be calculated. That means knowing the objects dynamic properties in the form of a differential equation (3.5). That gives the opportunity to make corrections to the system based on understanding and knowledge.

\[
m\ddot{x} + c\dot{x} + kx = f(t) \tag{3.5}
\]

\[
\omega_n = \frac{k}{m}, \quad 2\zeta\omega_n = \frac{c}{m}
\]
Chapter 4

Conclusion

LDV is a very sophisticated measurement technique becoming a standard for measuring displacements and velocities. Its main advantages are the non-contact nature, its wide frequency measurement capability, a very high precision, the ability to measure distant objects and its simplicity to change the measurement point. All the advantages make it indispensable for analysis in many different fields. Its commercial success makes it even more affordable and broadly used.

The example of modal testing usage was made which gave a close look at the dynamics. The parameters can be understood and changes to the object can be made easily. Resonances can be moved from the operating regime and other vibration-connected corrections can be made. Because of its high practical value, modal testing is broadly used in many industry fields.
Chapter 5

Appendix: Acousto-optic modulator

An acousto-optic modulator, also called a Bragg cell, uses the acousto-optic effect to diffract and shift the frequency of light using sound waves [9]. A piezoelectric transducer is attached to a material such as glass and an oscillating electric signal drives the transducer to vibrate, which creates sound waves in the glass.

These can be thought of as moving periodic planes of expansion and compression that change the index of refraction. Incoming light scatters off the resulting periodic index modulation and interference occurs.

A diffracted beam emerges at an angle $\theta$ that depends on the wavelength of the light $\lambda$ relative to the wavelength of the sound $\Lambda$

$$\sin \theta = \frac{m \lambda}{2 \Lambda}$$

where $m = \ldots -2, -1, 0, 1, 2, \ldots$ is the order of diffraction. Diffraction from a sinusoidal modulation in a thin crystal solely results in the $m = -1, 0, +1$ diffraction orders 5.1.

The light is scattering from moving planes. A consequence of this is the frequency of the diffracted beam $f$ in order $m$ will be Doppler-shifted by an amount equal to the frequency of the sound wave $F$.

$$f \rightarrow f + mF$$

A typical frequency shift varies from 27 MHz, for a less-expensive AOM, to 400 MHz, for a state-of-the-art commercial device. In addition, the phase of the diffracted beam will also be shifted by the phase of the sound wave.
Bibliography