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THE DEVELOPMENT OF THE POTENTIAL AND ACADEMIC PROGRAMMES OF WROCŁAW UNIVERSITY OF TECHNOLOGY

Automotive Engineering

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Testing of vehicle elements and assemblies

Application of the holographic interferometry for a valve cover displacement determination

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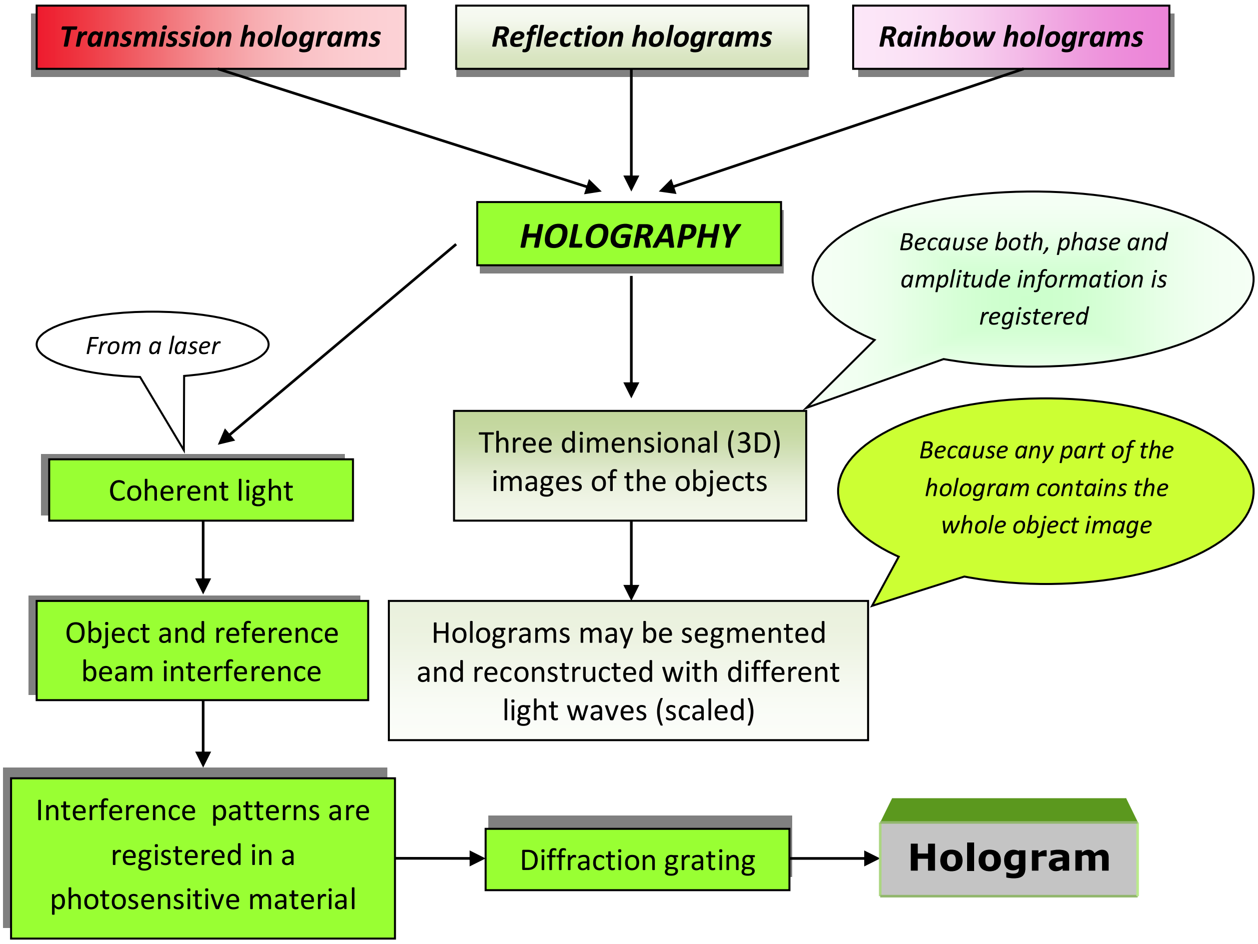
Introduction

Holography is a method of recording an image on a proper recording material with phase and amplitude registration. It means that a complete optical wave field is recorded. Holography is also called "lens less photography" because an image is captured not as an image focused by an optical system on a film, but as interference patterns at the registration material.



Typically, a coherent light from a laser is reflected from an object and combined at the holographic (photosensitive) plate with the light from the reference beam – fig. 1.

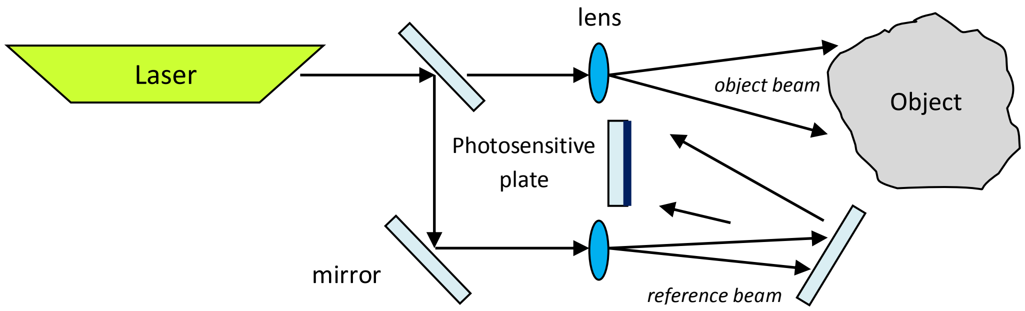


Fig. 1 A scheme of the reflected light hologram registration set-up

The superposition of these two beams results in a fringe pattern which is recorded by the thin layer of the photosensitive material (high resolution – order 2000-3000 lines/mm is needed). These fringes produce a random diffraction grating with any similarity to the object's image. The registered interferometric fringes are not visible to the normal (unaided) observation. The distance between the fringes is approximately ~ 5.0 x 10^{-4} mm.

The processed hologram is used for the reconstruction of a three-dimensional image of the real object (thanks to the recorded phase information). There are two possibilities to obtain: the virtual image or the real image – fig.2.

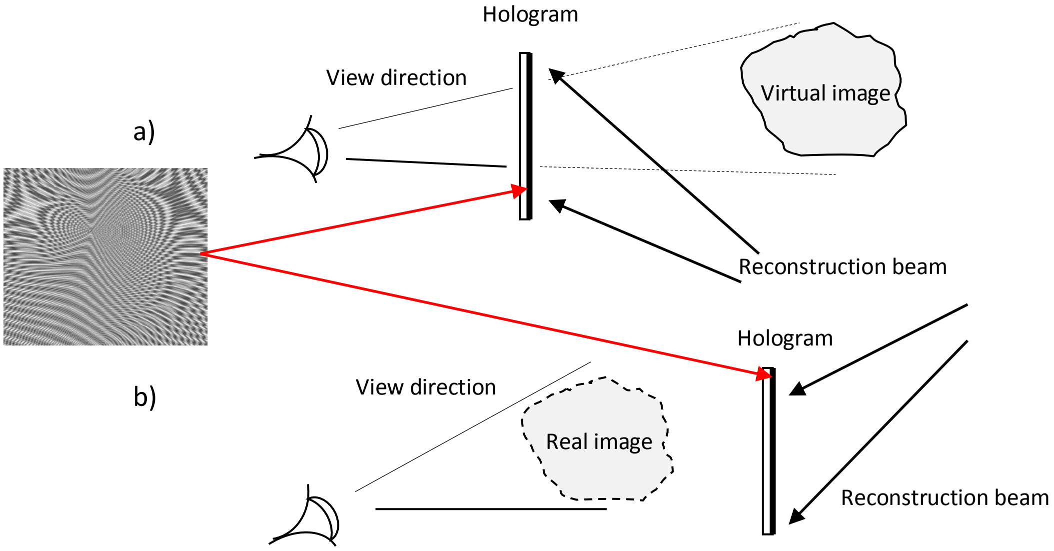


Fig. 2 The hologram reconstruction scheme: a) virtual image,
b) real image obtaining

The image observed in the scheme fig. 2a will appear behind the hologram as the virtual image of the original object, the second one (fig. 2b) – will appear in front of the hologram as the real image. Both the images are reconstructed because the coherent light (laser's) beam is diffracted when it passes the hologram. The diffracted light rays interfere in the space and reconstruct the three-dimensional object's image with all optical phenomena that characterized the original waves fronts during the registration of the hologram. The evident effects which an observer may see during viewing the position change are the parallax effects.

Fig. 3 Examples of the holograms

Holographic interferometry

Holographic interferometry uses the property of the holographic image recording for the measurement of small path-length differences of light rays reflected from the object's surface or going through the transmission medium. This technique is similar to the holography except that two or several holograms of the object are recorded on the same plate of the photosensitive material. If the reflected surface of the object is deformed between exposures, after the plate processing, during the reconstruction of the hologram the registered images of the object are formed in the space. They interfere with each other and produce interference fringes (bright and dark). These fringes represent the lines of the equal displacement along the viewing axis. The distance between levels is approximately half-wavelength.

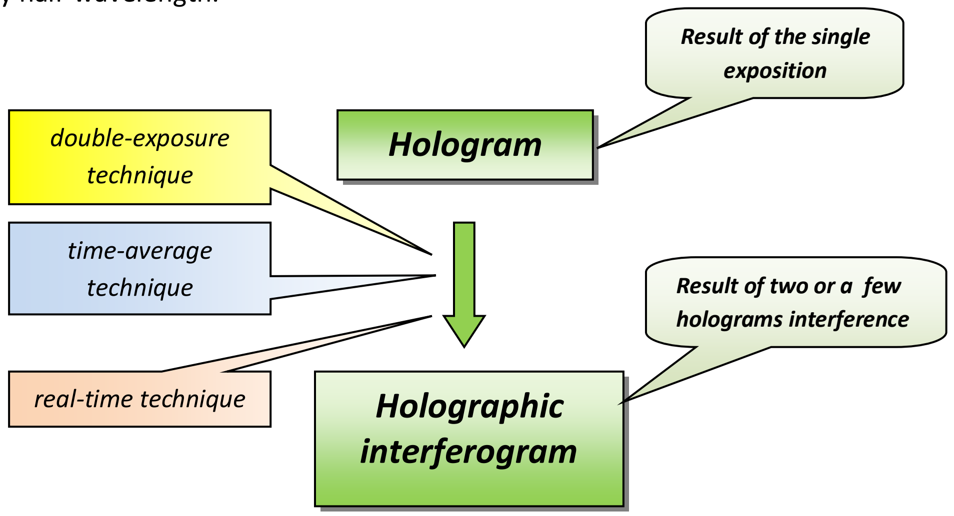


Fig. 4 Techniques of the interferometric holography

The holographic interferometry is realised in one of the three techniques:

- ***double-exposure technique*** – consists of recording of the two successive holographic exposures of an object in two different states (for example under two loading states) on the same photosensitive plate; this is the most often used technique even for impact loading cases,
- ***time-average technique*** – a single recording is made on the photosensitive plate during several cycles of the object vibration (an ensemble of images are recorded),
- ***real-time technique*** – this technique consists of a registration of a single hologram of an object in an unstressed state and, after processing the plate, replacing it in exactly the same position in which it was recorded; then the observation of the object is provided through the registered hologram.

For ***double-exposure technique*** the reference and object beam wavefronts during both exposures are additive in the plane of the registration (emulsion layer on the plate) and the light intensity distribution is expressed as:

$$I = |U_{01}|^2 + |U_{02}|^2 + |U_r|^2 + U_r^*(U_{01} + U_{02}) + U_r(U_{01}^* + U_{02}^*) \quad (1)$$

The functions in eq. (1) describe the wavefronts:

U_{01}, U_{02} – object beam wavefront during first and second exposure respectively,

U_r – reference beam wavefront, U_{01}^*, U_{02}^*, U_r^* - the complex conjugate functions.

The plate (after processing) should be illuminated with a wavefront identical to the reference beam. The reconstructed wavefront is proportional to the image wavefront U_i and is a vector sum of the U_{01} and U_{02}. Taking in to the consideration the assumption about the small value of the object displacements compared to the spatial dimensions of the object, the object fields are represented as:

$$U_{01} = A_0 \exp(ik\Phi_{01}), \qquad U_{02} = A_0 \exp(ik\Phi_{02}) \tag{2}$$

and the intensity distribution in the reconstructed image is:

$$I_{ide} = \left|U_{image}\right|^2 \propto 2|A_0|^2\{1 + \cos[k(\Phi_{01} - \Phi_{02})]\} \tag{3}$$

where: $k = 2\pi/\lambda$ – wave number (<u>*λ is the wavelength of the light used for an image reconstruction*</u>)

$\Phi_{01} - \Phi_{02}$ – phase change is the result of the object displacement between exposures (additional path length of the object beam).

It is assumed that the object displacement z_1 is perpendicular to it's surface and additionally:

α is the angle of the incident object beam during the interferogram registration (measured from the normal to the object surface), β is the angle of the image observation during the reconstruction (measured from the normal to the object surface), then the intensity (3) can be expressed as:

$$I_{ide} \propto 4|A_0|^2 cos^2\frac{1}{2}[kz_1(\cos\alpha + \cos\beta)] \tag{4}$$

The equation (4) describes the interference fringes observed on the reconstructed image of the object. Assuming N as interference fringe order (bright fringe has integral value $N = 0, 1, 2, \ldots$), the displacement z_1 can be calculated using the relation:

$$z_1 = \frac{N\lambda}{(\cos\alpha + \cos\beta)} \tag{5}$$

This equation may be often simplified if the angles α and β are small:

$$z_1 = \frac{N\lambda}{2} \tag{5a}$$

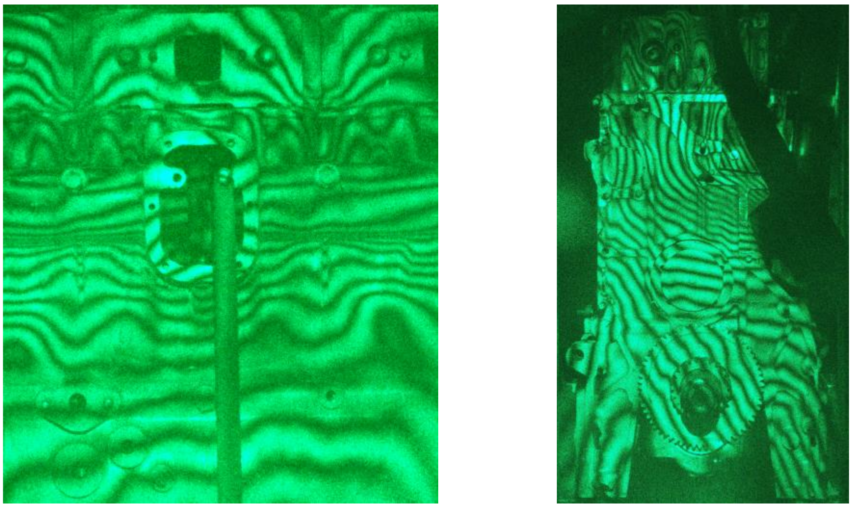


Fig. 5 Examples of the double-exposure holographic interferograms of the Diesel engine block deformations under thermal loading (simulation of the cooling liquid flow): a) side wall, b) front wall

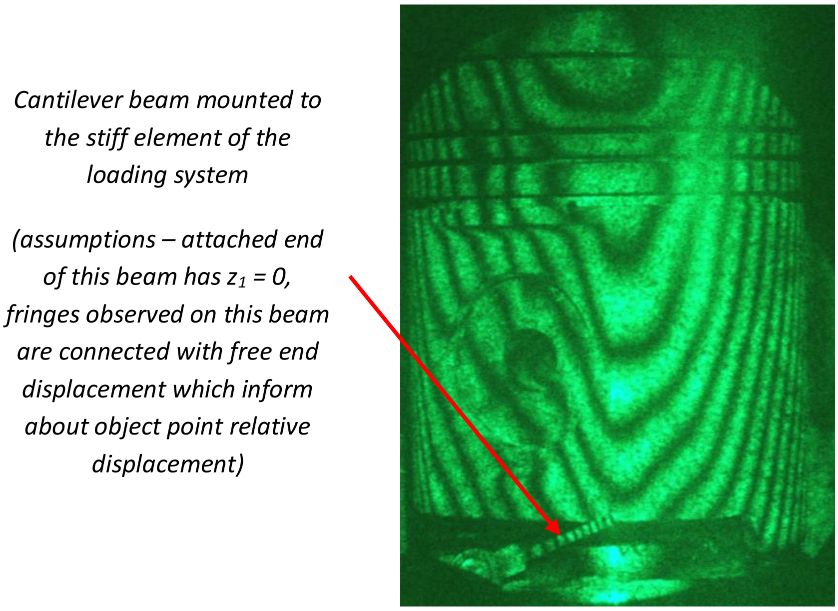


Fig. 6 The double-exposure holographic interferogram
of the Diesel piston skirt

The interferometric fringes presented above are passing by those points of the object's surface image where $z_1 = const$. For determination of the z_1 distribution, a proper numbering of the fringes is necessary, especially the interferometric fringe $N = 0$ identification has a great importance. In many experiments the boundary conditions are well known and the points with zero-value of z_1 displacement may be caslly determinated and in consequence, the localisation of the zero-order fringe is achieved. Another solution of this problem is application the "calibration" beam – fig. 6. Using this device, the information about relative (to the beam mounting) displacement is known and the localisation of the zero-order fringe is possible. There are several optical techniques of the zero-order fringe localisation. The simpliest one is based on the optical phenomena connected with changing of the observation directions of the reconstructed image - the zero-order interferometric fringe does not change the localisation. The same effect will be observed during changing of the reconstruction beam directions.

The ***time-average technique*** assumes that the exposure time in recording of the cyclically vibrated object hologram is longer than one period of the cycle. Practically, during one exposure an ensamble of images of the object's surface in different states of motion (and deformation) is registered. During the hologram reconstruction an interference of the several images occurs and produces the interference patterns connected with the object's surface deformations. If the object is under a cyclic vibration with a frequency ω and amplitude z_2, the object wavefront is:

$$U_0 = A_0 \exp\,(ik\gamma z_2 cos\omega t) \tag{6}$$

where γ is a function of the incident (during registration) and observation (during reconstruction) angles. The wavefront during reconstruction is expressed as:

$$U_{ta} \propto \frac{1}{T}\int_0^T U_0 dt = \frac{A_0}{T}\int_0^T \exp(ik\gamma z_2 cos\omega t)\, dt \tag{7}$$

The intensity of the image is:

$$I_{ta} = |U_{ta}|^2 \propto |A_0|^2 \left| \frac{1}{T} \int_0^T \exp(ik\gamma z_2 cos\omega t)\, dt \right|^2 \tag{8}$$

Using zero-order Bessel function, the equation (8) has a simple form:

$$I_{ta} \propto |A_0|^2 J_0^2[k\gamma z_2] \tag{9}$$

Introducing the same definitions of the α and β angles as in the eq. (4), the light intensity of the reconstructed image is:

$$I_{ta} \propto |A_0|^2 J_0^2[k(cos\alpha + cos\beta)z_2] \tag{10}$$

The effect of the light intensity modulation by square of the Bessel function can be observed directly in the reconstructed image. It is a well known effect that the cyclic vibration causes object regions to have no motion (i. e. nodes). Those regions have the highest intensity of light – fig. 7.

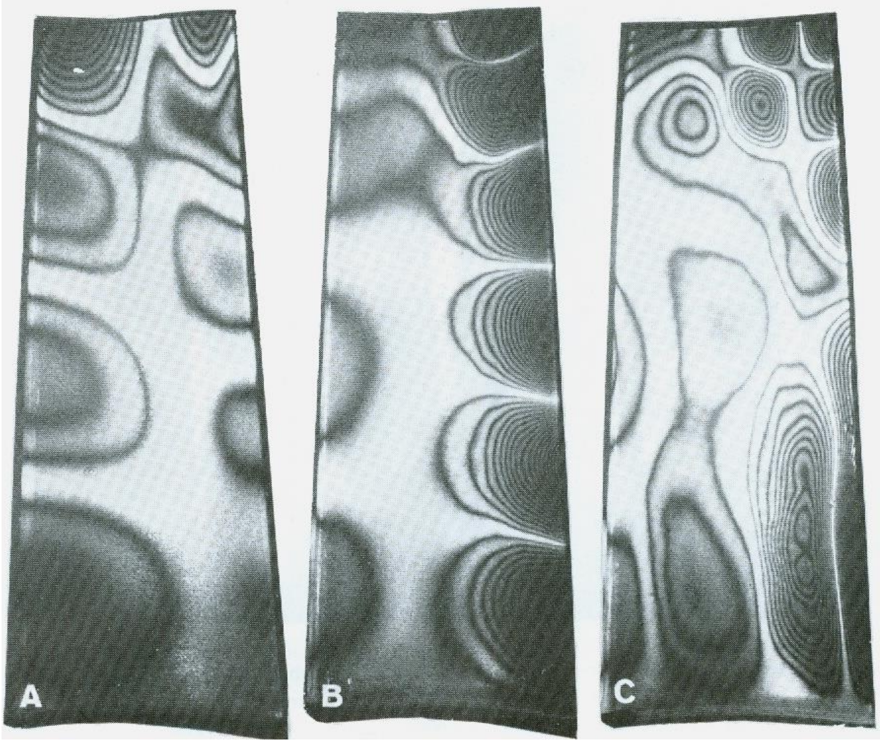


Fig. 7 Time-average interferograms of the turbine blade
for different frequencies (A < B < C)

Using time-average technique determination of the vibration amplitude and the location of the nodes in cyclic vibration motion can be achieved.

The ***real-time technique*** is rarely used. It relies on making one-exposure hologram for an object in the initial state, processing the holographic plate, and replacing this plate exactly in the same position in which it was during the hologram recording. The precision of the positioning must be in the order of the wavelength and the same reference beam must be used! Then, the reconstruction of the hologram leads to the inerference of the registered image with the actually produced one in the identical optical arrangement as during the hologram registration. If the object surface's is deformed, the interference patterns appear in the image observed through the holographic plate. Those "live" fringes are registered for example photographically. For static displacement, the equation describing the light intensity distribution in the reconstructed image is identical with the eq. (4), i. e.: $I_{de} = I_{rt}$.

Holographic interferometry requirements

Holographic interferometry is applied for accurate measurements, mostly for displacement determinations. Assuming that adjacent bright and dark fringes ($\Delta N = ½$) are connected at the difference of the displacement perpendicular to the object's surface $\Delta z \approx \lambda/2$, the high *vibration stability* of the equipment is necessary. It is especially necessary for those optical set-ups which are rigged with continuous wave (cw) lasers (commonly He-Ne or argon ion laser) with a relatively low power output. Non-controlled movements or vibrations of the optical elements and the tested object during exposures decrease the fringes contrast. In the extreme case the hologram registration may be unsuccessful. The stability limit will be lower for a higher power of coherent light (and, in consequence, a shorter time of the exposure) emitted by cw or pulsed lasers. Practically, the most important thing is isolation of the measurement arrangement from the random vibration, including air flow, sound incidents and other influences which may occur during an interferogram registration.

Lasers are the electromagnetic radiation sources where the emitted light has special properties, known as *spatial* and *temporal coherence*. A spatially coherent light beam with a plane wavefront has the same phase over a plane perpendicular to the propagation axis. For a spherical wavefront beam, the phase is the same over a sphere surface with radii placed at the light source. Thus the spatial coherence is a measure of the phase uniformity of a wavefront. The temporal coherence describes the correlation relationship between wavefronts observed at different moments in time. Usually, this kind of coherence is expressed as the *coherence length*, i.e. the difference of the length of the two beams emitted from one source (laser) which may interfere, or, in other words the propagation distance from the coherent source to a point where the laser's light lost the possibility of interference. For holography the temporal coherence, which is inversely proportional to the frequency bandwidth of the light source is more important. In consequence, the monochromatic (single frequency) source has an infinite coherence length. The most popular sources in holographic applications, i.e. helium-neon (He-Ne) and argon ion lasers, have unwanted frequency bands generated in gas medium. This effect is more evident in argon ion laser, where in the laser cavity internal etalon must be placed for decreasing the influence of the wide frequency bandwidth.

Other requirements are connected with the photosensitive plates used for the holographic application. Generally, a hologram requires recording with a high fringe frequency. In consequence, the emulsion must be characterised by a high resolution. The necessary resolution can be calculated using the equation:

$$\nu = [2\sin(\Theta/2)]/\lambda \qquad (11)$$

where Θ is the angle between the reference and object beams and λ is the light wavelength used for the interferogram registration.

For high resolution materials the low photographic sensitivity is observed. Thus the long time of expositions or a higher power of the laser must be applied. Commonly, the silver halide or dichromated gelatine materials are used for holographic plate producing with a resolution of 3000 – 5000 lines/mm, with an average grain size of 8 – 40 nm and spectral sensitivity proper for the light emanated by the laser which will be used for registration. It is a well known fact that a holographic emulsion (like photographic) is a square law detector of the light intensity. The relationship between the optical density and the exposure time is represented by Hurter-Driffield curve. Presently, density vs. energy curve is used more often – fig. 8.

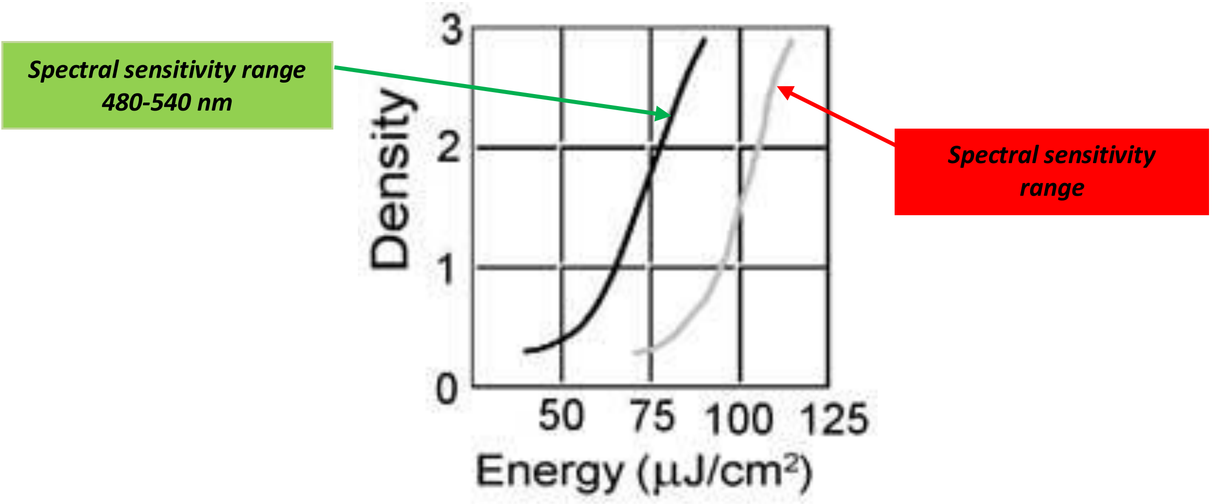


Fig. 8 Example of the optical density vs. energy curves
for silver halide emulsions

After exposures, a holographic plate is processed similarily to the photographic materials – fig. 9.

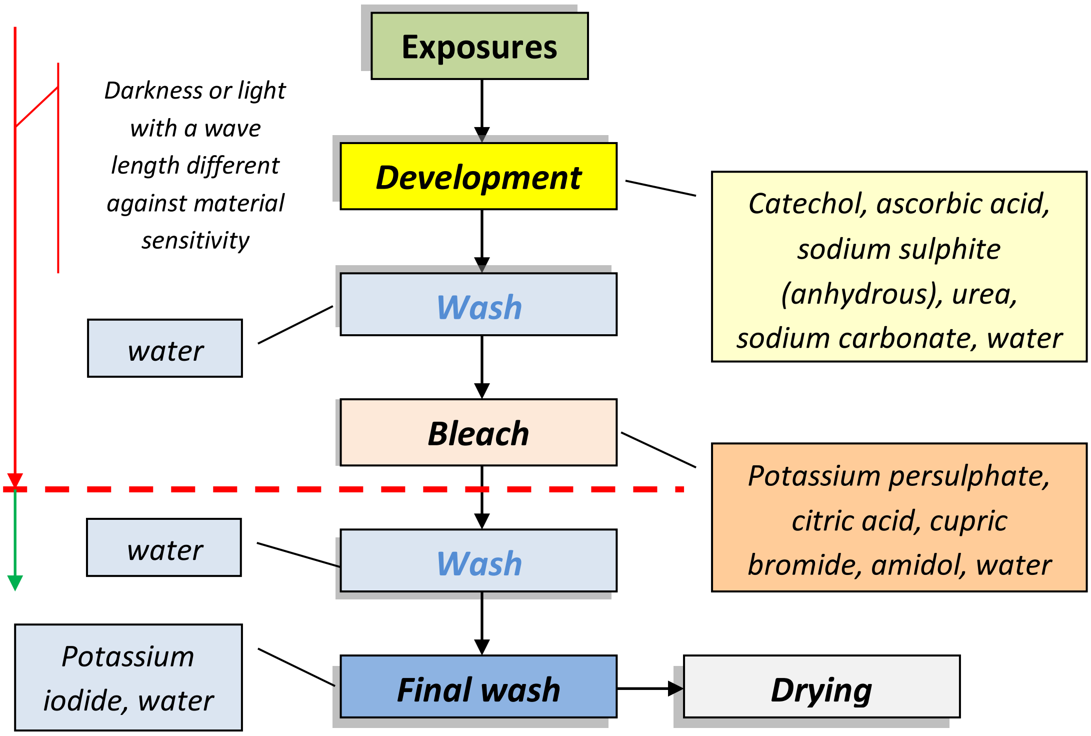


Fig. 9 Typical holographic plate processing

Examples of the holographic interferometry applications

➢ *Crack detection*

Holographic interferometry has been used for qualitative and quantitative analysis of the solid body fracture. If a crack appears near or on the body surface the displacement field around the crack is changing (fig. 10), especially for anti-plane shear mode loading of the crack edges loading case.

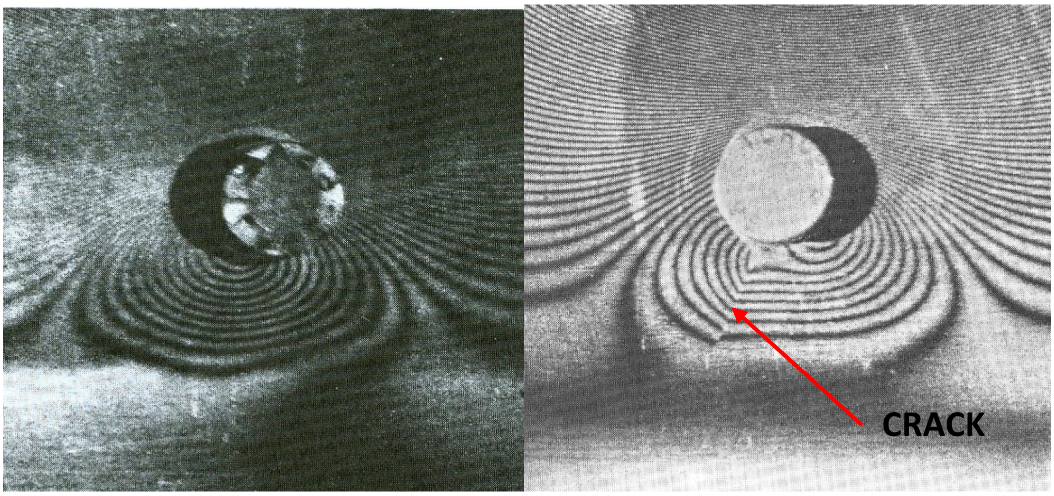


Fig. 10 Reconstructed images of the interferometric fringes around a hole:
a) before, b) after crack propagation from the hole edge

➢ *Inspection of the sandwich and laminate structures*

Detection of the disbond area in laminate and sandwich constructions plays a great role in suitability evaluation of the produced object. Holographic non-destructive testing of such constructions is provided using heat, vibration or pressure stressing, which causes greater displacements in the region of disbonding and - in consequence – specific distributions of the interferometric fringes (fig. 11 and fig. 12).

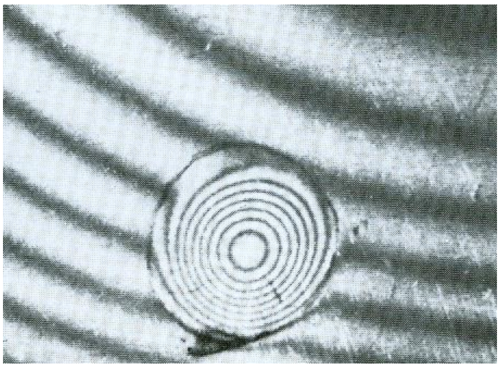
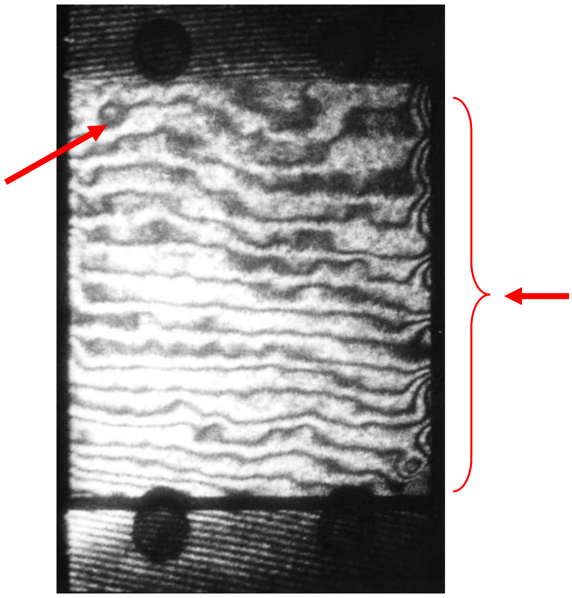


Fig. 11 Detection of the disbond area (aluminium face sheet bonded to the honeycomb core) – fringes image is an effect of the pressure stressing



Buckling effect
"one cell level"

Buckling of the face edge
("opened honeycomb cells")

Fig. 12 Detection of the local buckling areas (compressed sandwich plate – aluminium faces bonded to the aluminium honeycomb core)

- ***Determination of the object deformations***

Holographic interferometry is useful for measuring small, especially out-of-plane components of the displacement vector. For example, radial displacements of the piston skirt caused by thermal loading of the piston head are presented in fig.13. Three different bimaterial constructions of the piston were compared with the monomaterial version of the piston. Geometrically all the tested pistons were identical.

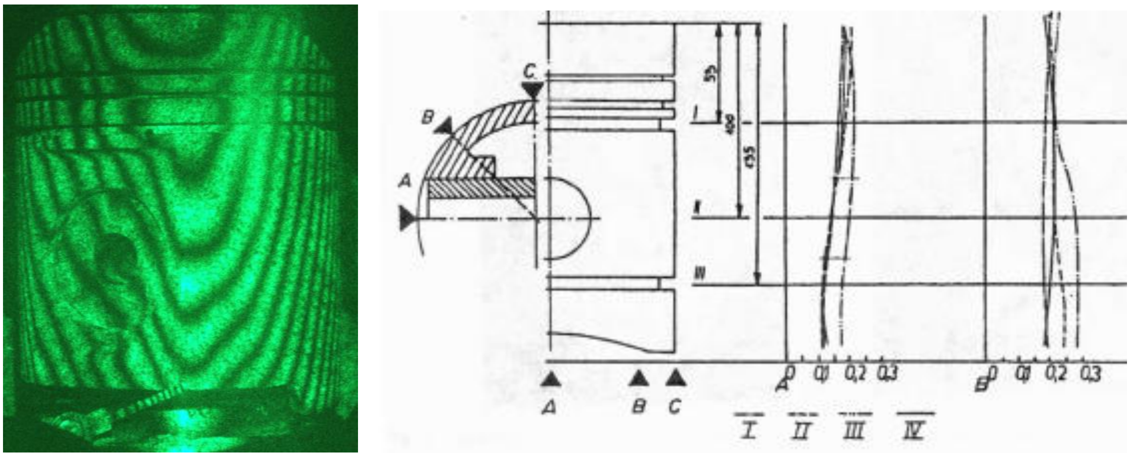


Fig. 13 Radial deformation of the piston skirt in A and B cross-section
(presented interferogram was registered for B cross-section displacement determination)

A similar application is presented below. A sandwich plate deflection under quasi-point loading acting perpendicularly to the plate surface was analysed using the holographic double-exposure technique – fig. 14. The experimental results of those measurements were compared with FEM analysis.

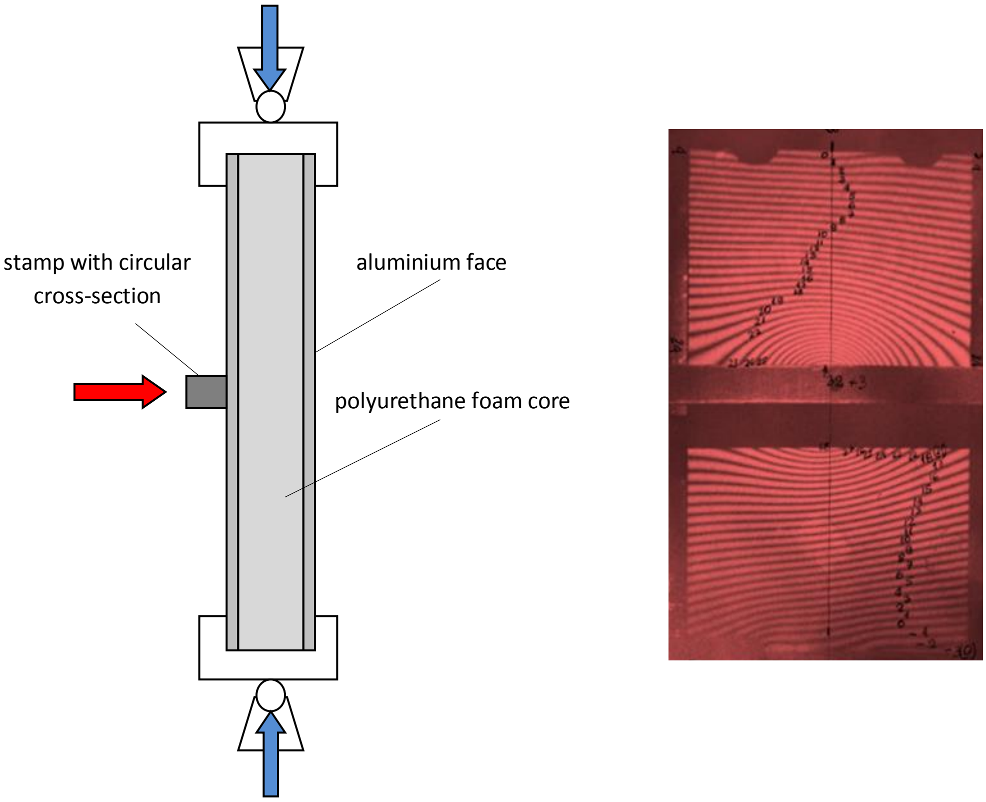


Fig. 14 Deflection of the sandwich plate testing: scheme of the loading (right) and interferometric fringes image (left)

Pressure limiting valve (PLV)

Compressed (pneumatic) air brake systems are typically used in heavy truck, buses, trailers and semi-trailers. Different valves are applied for controlling the air flow and pressure in those systems. One of them is the pressure limiting valve which limits pressure in a system, for example, it preserves compressed air tank of the trailer from overpressure – fig. 15.

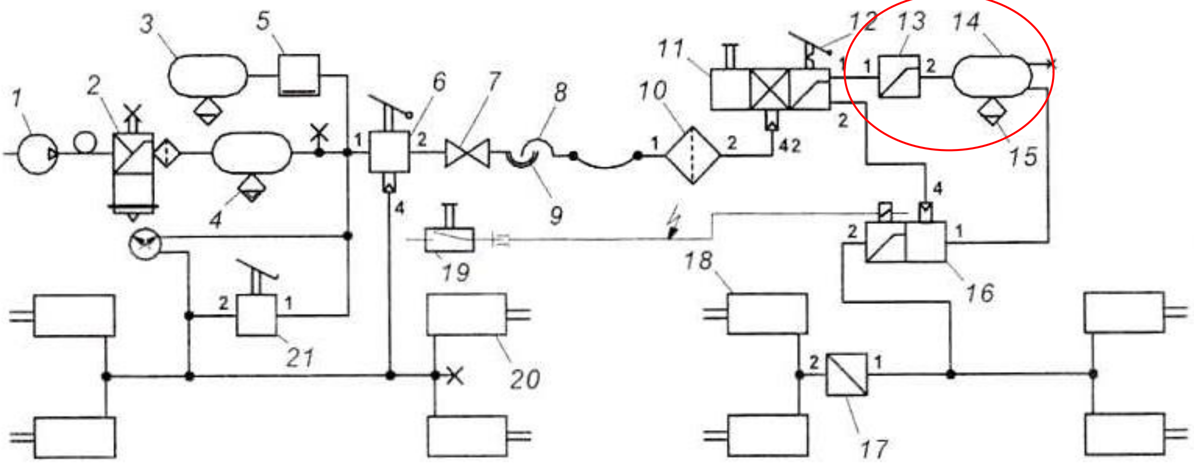


Fig. 15 Example of the compressed air brake system of the truck and trailer (13 – PLV, 14 – air tank of the trailer)

The PLV operation is simple. It can be explained on the example of the valve (BOSCH) presented in fig. 16.

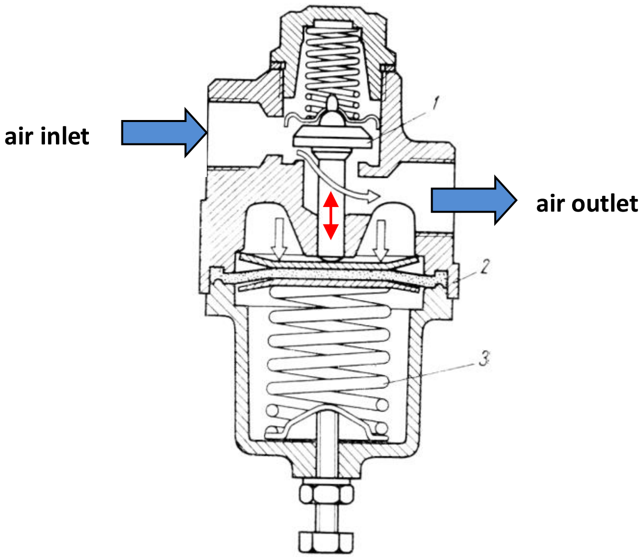


Fig. 16. The PLV valve (BOSCH)

A typical set up of the pressure limiting valve involves a spring (3) and a diaphragm (2) that are connected to a valve lifter (1) or other device that regulates the flow opening in the valve. The spring is adjusted to the desired outlet pressure by compression or relaxation (using for example a screw). The incoming air pressure reacts against the spring/diaphragm force to create an equilibrium of forces. If the incoming pressure goes up, the force on the diaphragm grows and causes the increasing of the spring load. This will move the valve lifter to close off the flow area. When the inlet pressure goes down, the load on the diaphragm decreases and the spring extends and causes the lifter to open the flow area.

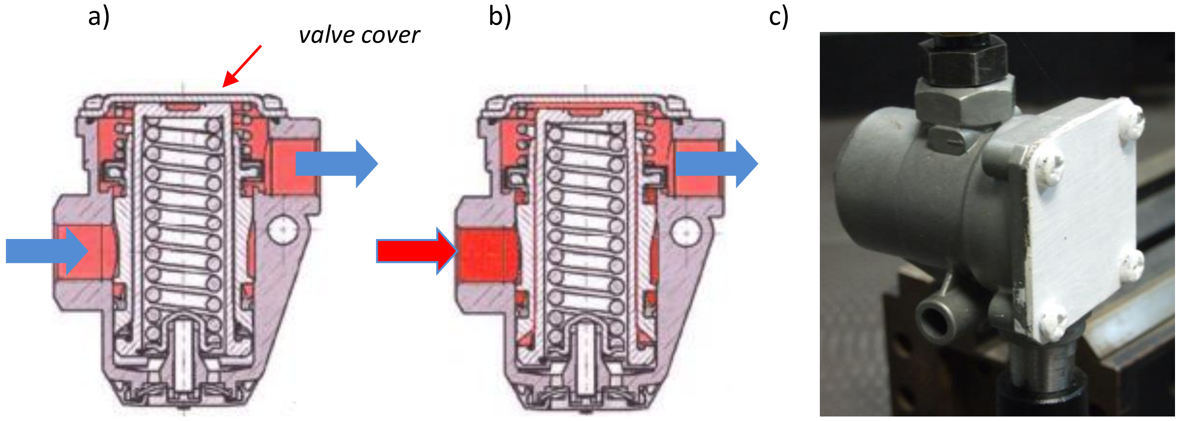


Fig. 17 The PLV valve (8 bar): a) opened air flow, b) stopped air flow, c) view of the valve on the testing stand (white painted cover will be tested)

Practical tasks

The following activities will be carried out:

- presentation of practical information about the methodology of the valve cover testing,
- preparation of the optical arrangement for a double-exposure interferogram registration,
- interferogram making for hydraulic loading of the valve,
- reconstruction of a registered interferogram, localisation of the zero-order interferometric fringe,
- determination of the cover deflection in a chosen cross-section,
- preparation of a report (its range will be determined by the lecturer).

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