Photonics-Enabled Technologies

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

OP-TEC

Optics and Photonics Series

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Photonics-Enabled Technologies: Manufacturing

OPTICS AND PHOTONICS SERIES

STEP (Scientific and Technological Education in Photonics), an NSF ATE Project

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PREFACE

This module is one of four pertaining to manufacturing as a *photonics-enabled* technology. The combined series on photonics-enabled technologies (comprising both STEP and OP-TEC materials) consists of modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used as a unit or independently, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this document was prepared by Jack Ready (consultant) and edited by Leno Pedrotti (CORD). Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

INTRODUCTION

This module continues the discussion begun in the last module (Manufacturing, Module 3) on the use of lasers for testing and measurement in an industrial environment. It emphasizes the use of interferometric and holographic principles for measurement and for nondestructive testing.

In this module you will study the use of interferometric techniques for measurement and control of the motion of machine tools used to manufacture products.

This module also describes holographic methods for detecting defects in manufactured products, for analysis of strain and for analyzing vibration of surfaces, in general describing measurements in industry that would be difficult to perform by other means.

PREREQUISITES

The following modules in Courses 1 and 2 form an ideal background for a study of modules devoted to lasers in manufacturing. However, one can begin a study of this module—*Lasers in Testing and Measurement: Interferometric Methods and Nondescructive Testing*—after a study of modules 1-2, 1-3, 1-6, and the manufacturing modules listed on the following page.

Course 1: *Fundamentals of Light and Lasers*

Module 1-1: *Nature and Properties of Light*
Module 1-2: *Optical Handling and Positioning*
Module 1-3: *Light Sources and Laser Safety*
Module 1-4: *Basic Geometrical Optics*
Module 1-5: *Basic Physical Optics*
Module 1-6: *Principles of Lasers*

Course 2: *Elements of Photonics*

Module 2-1: *Operational Characteristics of Lasers*
Module 2-2: *Specific Laser Types*
Module 2-3: *Optical Detectors and Human Visions*

Photonics-Enabled Technologies: Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment, Profiling, and Position Sensing

OBJECTIVES

- Given the relevant parameters for an interferometric distance-measuring system, calculate the amount of movement and the maximum measurable distance.
- Given the necessary information about how a time-average hologram of a diaphragm is produced and reconstructed, and information about the fringes in the pattern, correctly calculate the maximum displacement of the diaphragm.
- Describe holographic interferometry, in terms similar to those in the text. Include three types of holographic interferometry, a statement about how each type is produced and the relative advantages and typical applications of each type.
- Given a laser, a pre-recorded double-exposure hologram of a diaphragm and other necessary equipment, reconstruct the hologram, photograph the reconstruction, and measure the profile of the diaphragm. The result will be a graph of the diaphragm as a function of position. Identify at which areas, if any, the diaphragm might be expected to fail in use.

SCENARIO

Ming Li is a photonics technician who works for a company that manufactures disk drives. Her job is to test the drives for possible distortion when they are heated. Small amounts of heat from internal components can cause the base plate for the drive to expand or to warp, leading to misalignment of the carriage and spindle of the drive. Ming Li uses holographic interferometry to measure the amount of distortion. She first makes a hologram of the base plate. She applies thermal stress by heating the base plate. She then records a second hologram and superimposes it over the first pattern. The two superimposed holograms produce black and white fringes that are interference patterns resulting from changes in the base plate. Ming Li reads the fringes like a topographical map and determines the amount of distortion in the base plate. Then she can make a decision on whether to accept or reject the disk drive.

BASIC CONCEPTS

Lasers for Industrial Measurement

The laser most often used for measurements in interferometry and nondestructive testing to be described in this module has been the HeNe laser operating at a wavelength of 632.8 nm. Because of the poorer coherence of diode lasers, they have not been used so much for applications that require good coherence.

HeNe lasers are available in stable, long-lived commercial models and are relatively inexpensive. Typical properties of HeNe lasers used in industrial settings are presented in Table 1.

Table 1. Characteristics of a HeNe laser for alignment applications

Power output	2 mW
Mode	TEM_{00}
Beam divergence angle	1.6 milliradian
Beam diameter	0.5 mm
Beam wander	<30 microradian
Long-term power drift	<5%

For many of the applications involving interference, it is desirable to have very narrow linewidth and frequency-stabilized HeNe lasers. The lasers are constrained to operate in a single longitudinal mode by making them short so that only one mode will fall within the fluorescent linewidth. (Remember that the spacing between longitudinal modes in a laser of length L is $c/2\ell$, with c the velocity of light and ℓ the distance between the two mirrors.) The lasers are mounted on a single piece of material with a low coefficient of thermal expansion. They are in temperature-controlled enclosures. The length of the laser cavity may be servo-controlled at the position of a small dip in power that occurs when the laser frequency lies at the center of the neon fluorescent line. With these precautions, the linewidth of the frequency-controlled HeNe laser may be around 10^6 Hz.

In some holographic applications, argon lasers are used. With their higher values of power, as compared to HeNe lasers, brighter holograms may be obtained.

Interferometric Principles

Laser-based measurements of the motion of manufacturing tools are usually performed with interferometric techniques.

Measurements of length using optical interferometry have been performed since the 19th century. But the limited radiance and coherence of conventional light sources restricted the measurements, which were difficult and suitable for use only over distances of a few centimeters. The development of lasers with high coherence removed these restrictions. Lasers allow interferometry to be performed as a fast, highly accurate technique for measuring longer distances. Laser measurement of distances is best suited to measurement made in a controlled atmosphere (for example, indoors) over distances up to a few tens of meters.

Most laser-based interferometric systems use a frequency-stabilized HeNe laser. An unstabilized laser, operating in a number of longitudinal modes, will have a total linewidth around 10^9 Hz. This spread in linewidth will cause the interference fringes to become blurred and to lose visibility as the distance increases. An unstabilized laser is suitable for measurements only over distances of a few centimeters. Stabilized lasers, usually in a temperature-controlled environment and operating in a single longitudinal mode, as mentioned earlier, are used for longer distances.

As mentioned, diode lasers, with poorer coherence, are not often used for interferometry.

We describe first the operation of a system based on the Michelson interferometer, because it is easy to understand the basic principles of distance measurement with this interferometer. Later we will describe variations that provide better performance under conditions of atmospheric turbulence.

Figure 1 shows the basic configuration of a Michelson interferometer. The beam from the laser falls on a beamsplitter that reflects half the beam in one direction (the reference arm) and transmits the other half (the measurement arm). The two beams are each reflected back by mirrors, a stationary mirror in the reference arm and a movable mirror in the measurement arm. In practice, the two mirrors are often cube corner reflectors (retroreflectors), which offer better stability against vibrations than do conventional flat mirrors.

The two beams are recombined by the beamsplitter to form an interference pattern that is viewed by an observer or measured by a photodetector. The character of the interference fringes is related to the different optical path lengths that the two beams have traveled before being recombined.

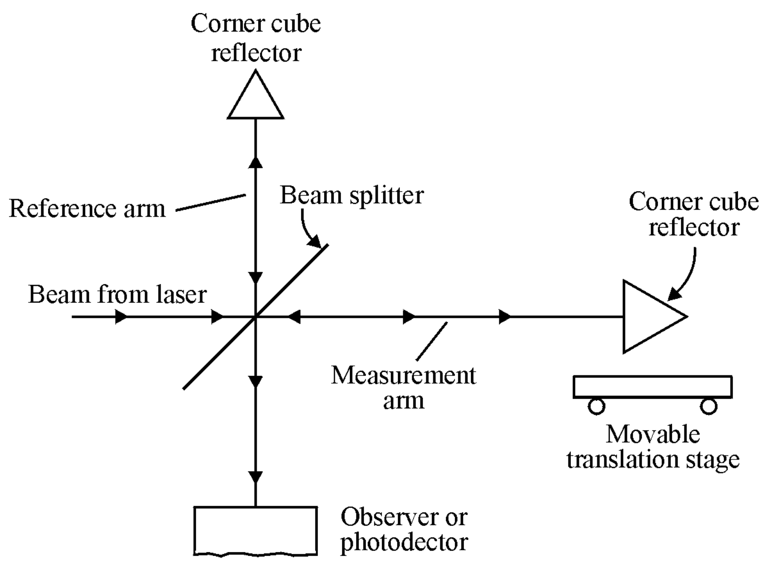


Figure 1 *Diagram of the application of a Michelson interferometer to measurement of distance*

Suppose, for example, that the detector "sees" a bright fringe in the interference pattern when the movable mirror is at a certain position. If the movable mirror then moves a distance equal to 1/4 of the wavelength of the light, the round-trip distance traveled by the light in the measurement arm will change by 1/2 wavelength and the fringe pattern will change so that the detector now views a dark fringe. The distance measurement thus consists of counting the number of fringe variations as the mirror moves. Each complete fringe (bright to dark to bright) corresponds to a *phase variation* equal to 2π radians. The total variation in phase δ_{tot} is determined by Equation 1.

$$\delta_{tot} = \frac{4\pi\Delta x}{\lambda} \qquad (1)$$

where λ is the wavelength and Δx is the distance the movable mirror has moved. It is apparent that this method offers high precision, allowing a measurement of Δx to be made with an accuracy of the order of a fraction of the wavelength of light.

We note that the measurement of the distance that the movable mirror has moved is the distance relative to its starting position, not an absolute position measurement in space.

The maximum distance that can be measured in this way is given by Equation 2.

$$\Delta x_{\text{max}} = \frac{c}{\Delta v} \tag{2}$$

where c = the velocity of light and Δv = linewidth (spread in frequency) of the laser. This equation shows that to obtain measurements over long distances, one must use a frequency-stabilized laser with a small linewidth.

Example 1: Distance measurement in a Michelson interferometer

Given: A frequency-stabilized HeNe laser, 50-cm long, is used to measure distance with a Michelson interferometer. One observes 2200 fringe changes (bright-to-dark-to-bright) as the movable mirror is moved a distance Δx.

Find: The distance that the mirror moved and the maximum distance that could have been measured

Solution

Each fringe change (bright-to-dark-to-bright) corresponds to a change of 2π radians in phase. The total change in phase δ_{tot} is $2200 \times 2\pi$. Using Equation 1,

$$\delta_{\text{tot}} = \frac{4\pi\Delta x_{\text{tot}}}{\lambda}$$

$$\therefore \Delta x_{\text{tot}} = \frac{\lambda\delta_{\text{tot}}}{4\pi} = \frac{(0.6328\times10^{-6}\text{ m})(2200\times2\pi)}{4\pi}$$

$$\text{So } \Delta x_{\text{tot}} = 6.96 \times 10^{-4}\text{ m} = 0.0696\text{ cm} = 0.696\text{ mm}$$

Suppose that the laser in Example 1 is a *two-mode* laser. That is, two—and only two—longitudinal modes fit underneath the fluorescence line shape. In a laser, the spacing between longitudinal modes is $\frac{c}{2\ell}$, where c is the velocity of light and ℓ is the mirror separation in the laser. Thus the *two-mode* HeNe laser will have a linewidth Δv equal to

$$\Delta v = \frac{c}{2\ell} = \frac{3\times10^{10}\text{ cm/sec}}{2\times 50\text{ cm}} = 3 \times 10^8/\text{sec} = 3 \times 10^8\text{ Hz}$$

Using Equation 2, we then have for the maximum distance Δx_{max} that could have been measured:

$$\Delta x_{max} = \frac{c}{\Delta v} = \frac{3 \times 10^{10}\ \text{cm}/\text{sec}}{3 \times 10^{8}/\text{sec}} = 100\ \text{cm}$$

The distance measured is an optical measurement of the optical path, which is the physical path multiplied by the index of refraction of the air through which the measurement is made. In measurements requiring high precision, one must correct for changes in the index of refraction that occur as a result of temperature, pressure, etc. The index of refraction of dry air at a pressure of 760 Torr and a temperature of 15° C is 1.0002765 at the HeNe laser wavelength. As conditions in the air change, the index of refraction changes. For example, the change in refractive index is:

- 0.36 parts per million for an increase of 1 Torr in atmospheric pressure.
- 0.96 parts per million for an increase of l° C in temperature.
- 0.06 parts per million for an increase of 1 Torr in the partial pressure of water vapor.

So a measurement system that requires high precision must include sensors for measurement of air temperature and pressure (and perhaps relative humidity) and a means (usually an automated computer-based means) for correcting for the variable atmospheric parameters.

System configurations

Now we turn to the use of interferometric methods for measurement of motion of machine tools and the control of the dimensions of manufactured parts. Figure 2 shows a diagram of a system used to control the motion of a machine tool carriage. The system uses two photodetectors to determine the direction of the motion. The two detectors collect light from different portions of the fringe pattern. The relative phase of the modulation of the fringes will be different depending on whether the carriage is moving away from the laser or toward it.

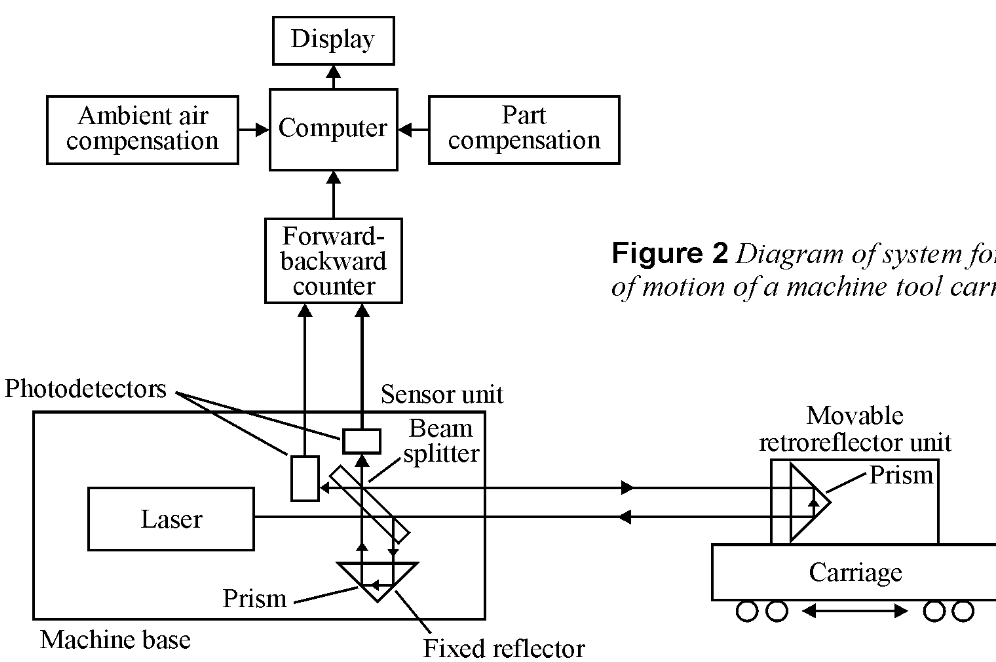


Figure 2 *Diagram of system for measurement of motion of a machine tool carriage*

The interferometric technique described above was developed soon after the invention of the laser and was the basis of early industrial control systems. It suffers the drawback of being sensitive to turbulence in the air, which can wipe out the interferometric fringe pattern. This problem has been reduced with the use of a two-frequency laser system that mixes beams of the different frequencies and measures the Doppler shift of the beam reflected from the moving mirror. This system, developed in the 1970s, forms the basis for many modern interferometric distance-measuring applications.

The operation of such a system is shown in Figure 3. In this figure, f_1 and f_2 are the two laser frequencies and Δf is the Doppler shift produced by the motion of the retroreflector.

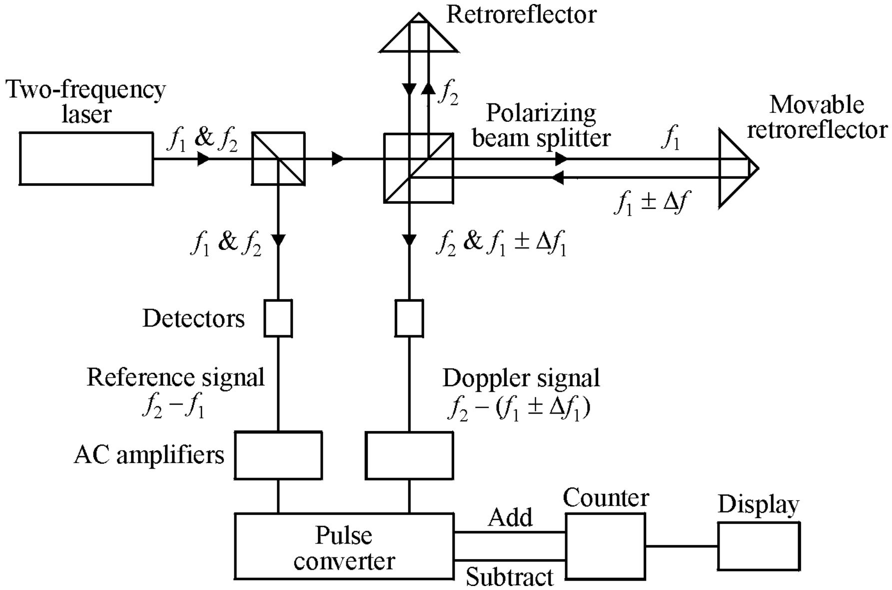


Figure 3 *Two-frequency distance-measuring system*

The HeNe laser emits light at two slightly different frequencies, f_1 and f_2, with different polarizations. The laser has an axial magnetic field that splits the fluorescent line of neon into two differently polarized components separated by a frequency around 2 MHz.

A polarization-sensitive beamsplitter separates the two frequencies so that they follow different paths. Frequency f_2 is sent to a fixed reflector. Frequency f_1 goes to the movable reflector attached to the part whose distance is to be measured. If the part moves with velocity v, the frequency f_1 upon reflection changes by Δf_1, given Equation 3.

$$\frac{\Delta f_1}{f_1} = \frac{2\mathrm{v}}{c} \tag{3}$$

where c is the velocity of light.

This shift is due to the Doppler effect and is analogous to the familiar Doppler effect in acoustics. The two beams with frequencies $(f_1 + \Delta f_1)$ and f_2 are recombined by the beamsplitter and sent to a detector. The output of the detector will contain an oscillating component at frequency $(f_1 + \Delta f_1) - f_2$, which can be compared to the original difference frequency $(f_1 - f_2)$

generated at a second detector. This gives a measure of Δf_1 and hence of v, according to Equation 3. The value of v can then be integrated over time to give the total displacement.

This type of system is not highly sensitive to degradation produced by air turbulence, air motion, etc. It can provide measurements of motion in the *one-millionth-inch* range in an industrial environment.

Accurate laser-based interferometric measurements have been applied in a wide variety of practical cases in industry, such as checking the accuracy of the runout of machine tools and automatic compensation of the errors, leading to improved dimensional control for manufactured parts.

A specific example of the use of laser-based distance measurement for dimensional control in manufacturing involves pattern generation in the semiconductor industry. The patterns are made up of the tiny circuit elements in integrated circuit manufacturing. The workpiece, often a semiconductor wafer, is covered with photosensitive material that is exposed by a conventional light source to form a pattern that is then chemically etched into the workpiece. This is the process for forming the circuit elements on the semiconductor. The exposure takes place through apertures that are positioned to form a rectangular area that is to be exposed. A laser control system, similar to that in Figure 3; controls the positioning of the apertures. The position control involves five degrees of freedom, two for the coordinates of the center of the rectangle, one each for the length and width of the rectangle and one for the angular orientation of the rectangle.

The laser is a two-frequency HeNe laser with output power around 1 mW. The system provides an accuracy of plus or minus 0.25 micrometers in the positional coordinates and 0.1 arc sec in the angular coordinate. The system is located in a controlled environment, where changes in temperature and relative humidity are controlled and changes in air temperature are compensated for. This control system provides greater accuracy for the pattern generation than conventional techniques, like stepping motors or mechanical indexing.

Holographic Nondestructive Testing

Holographic interferometry is useful for a number of important nondestructive testing applications on manufactured parts, including defect detection, strain analysis and vibration analysis. The student should review Module 2-6, *Basic Principles and Applications of Holography*. A hologram may be regarded as a storage device. It stores information that is related to the image of some object. At any time, the hologram may be "interrogated" and the image of the object may be "recalled" and used. In *holographic nondestructive testing,* the image of the object is used to interfere with a reference wavefront. In the process of interference, fringes will be formed. If the two wavefronts represent the object at different times, the fringe pattern can yield information about changes that have taken place on the surface of the object over some time interval. These measurements can be carried out with high sensitivity.

Real-time holographic interferometry

In this technique, sometimes called live-fringe holographic interferometry, a hologram is made of some object. The hologram is developed and placed back in the position it occupied when it was made. (Alternatively, the hologram may be developed in place, without moving it.) Then it is re-illuminated with the reference beam that was used to make the original hologram. When you view the hologram, you see an image of the original object.

Now suppose the object has remained in place and continues to be illuminated with reference beam laser light. In this case, the original object is the source of the comparison wavefront. There will be two views of the object, one coming from the real object and one from its holographic image. There will be interference between the light waves coming from the object and from its holographic image. If the object has changed, the light waves forming the two images will travel different distances. Wherever the path difference traversed by the two waves changes by one wavelength of the light, an interference fringe will appear. The fringes can be regarded as a contour map of changes in the physical profile of the object.

Figure 4 shows this process schematically. In Figure 4a, a hologram is made of the object, which is represented as a small can. Light is reflected from the end face of the can (*object beam*) and reaches the photographic film. The *reference beam* is reflected directly from a mirror to the film. The two beams interfere at the position of the film that records the interference pattern. Then the film is developed and *replaced in its original position*.

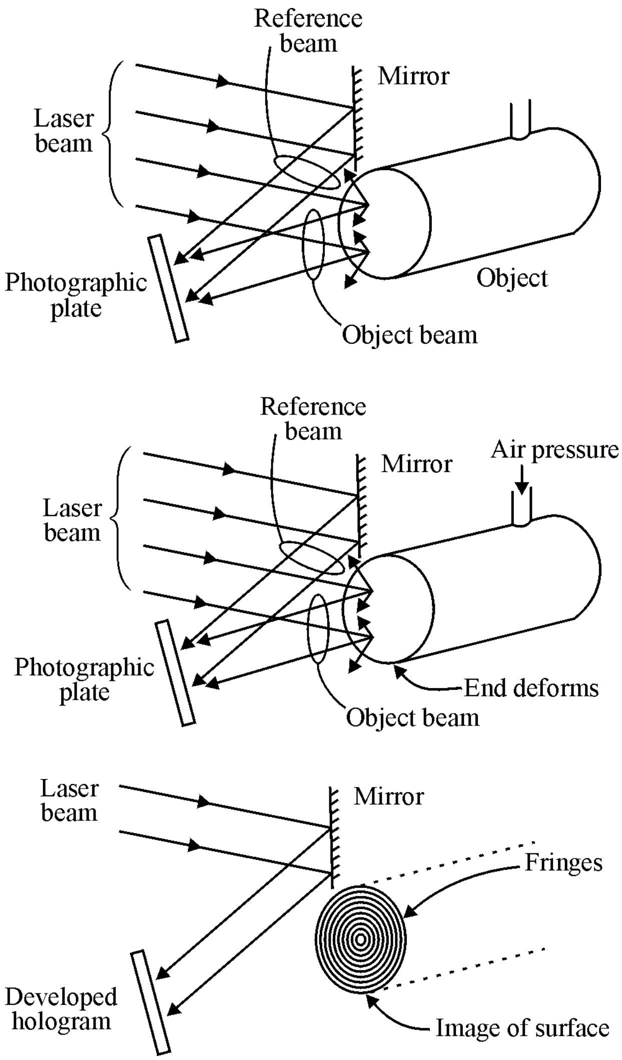
In Figure 4b, the film has been repositioned and there are now two views of the object. The original object is still present and can be seen, as can its holographic image. If the object has not changed in any way from the time that the hologram was made, the result is not very interesting. The two views of the object are the same. They simply overlap.

But now we consider what happens if the object has been changed, for example, by stressing it. Figure 4b shows the can being deformed by increasing the air pressure inside it, so that the end face bulges. Now the two views of the can are slightly different and the images will interfere. One can see fringes spreading across the surface as the air pressure increases. Each fringe represents a surface displacement of one-half the wavelength of the light. The form of the fringe pattern is illustrated in Figure 4c.

The fringes can be seen to move in real time as the object changes. The spreading and change of the fringe pattern in accordance with the deformation of the object can be followed as it occurs. Hence the name *real-time holographic interferometry* has been adopted.

In principle, the spacing and motion of the fringes can be measured and quantitatively related to the deformation of the surface. In practice, this procedure has difficulties. One is the difficulty of replacing the developed hologram in exactly the same position it occupied during exposure to within a fraction of the wavelength of light. To minimize this difficulty, sometimes the photographic film is contained in a specially designed holder that allows the hologram to be developed *in place*.

Another problem is that there is always some distortion of the photographic emulsion during development. Careful control of the processing can minimize this distortion, but in practice, some distortion will always remain. This will give a background shift of a small number of fringes across the object.



a. Hologram formed by usual method of making holograms

b. After hologram is developed and replaced in its original position, the object is strained.

c. Interference fringes are observed.

Figure 4 *Schematic diagram of real-time holographic interferometry*

A third and very serious problem is that of interpretation of the fringe pattern to obtain quantitative measurements of the distortion. The problem arises because of considerations of fringe localization. The fringes will appear to be localized on some surface in space. This will not always be the surface of the original object. The surface on which the fringes appear to be localized depends on the illumination, the direction of observation and the nature of the deformation.

Because of these factors, one usually does not try to extract absolute quantitative information about the deformation. But real-time holographic interferometry still is very useful for *determining strain* in objects as they are deformed under pressure. If there is a weak area in the surface, it will deform more and the fringes will crowd closer together. Thus, one can use holographic interferometry *to detect defects or weak areas* in manufactured parts developed during the manufacturing process.

Double-exposure holographic interferometry

In *double-exposure holographic interferometry,* also called *frozen-fringe* holographic interferometry, the hologram is exposed twice at different times. Between the two exposures, the object will have been changed, for example, by stressing it or heating it. As a result, in the two exposures, the object will be slightly different. The double-exposure method is a comparison between two different conditions of the object, just as in the single-exposure method. However, the two conditions are both stored in the film. The double-exposure method avoids the problems of realignment of the hologram.

After the two exposures of the hologram are completed, the original object and the optical components used to illuminate the object can be removed. The comparison wave, which is characteristic of the object in its original condition, is stored in the hologram, along with the wave representing the altered state of the object. Therefore, this method of holographic interferometry is easier to carry out. The hologram may be viewed in the same way as an ordinary display hologram, without the need for exact positioning or alignment. The emulsion shrinkage is identical for both exposures, so possible distortion due to shrinkage is not important. However, the same cautions about fringe localization and the difficulties in interpreting the exact quantitative deformation of the surface from measurements of the fringe structure still apply.

A disadvantage of the double-exposure method is that it compares the original object with only one (later) perturbed state of the object. Thus the double-exposure method is somewhat less versatile than the real-time method and provides less information. But in many cases continuous examination of the surface deformation is not necessary. Recording the relative surface deformation over a fixed interval of time may be all that is required.

Now consider the analysis of the fringe pattern to obtain the deformation of a surface. As was discussed earlier, the analysis is very difficult in the general case. We describe one case that can be analyzed simply. This is the case of a deformed diaphragm. An example would be the end face of a small metal can. A double-exposure hologram is made of the diaphragm. In the first exposure, the can is not deformed. In the second exposure, the diaphragm is deformed, for example, by air pressure. The diaphragm is deformed as shown in Figure 5.

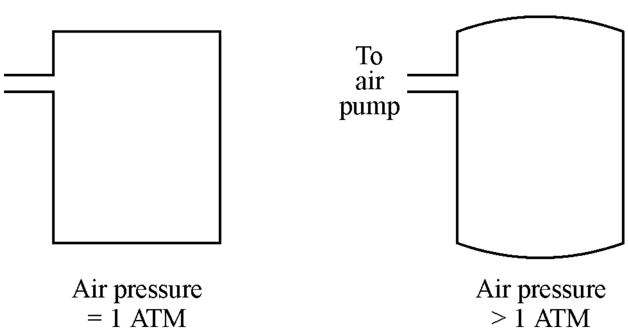


Figure 5 *Diagram of deformation of a small can in which air pressure is increased*

If the diaphragm has no defects and is reasonably homogeneous, the fringe pattern will consist of a series of concentric circular fringes. In this case, the fringes will be localized near the surface of the diaphragm for a viewing direction normal to the unperturbed surface of the diaphragm and with the reconstructing light incident in the same direction. The fringes can be formed by a lens placed relatively distant from the diaphragm as shown in Figure 6. The fringes will be formed in the image plane of the lens where they can be photographed. As one moves in the x-direction image, the intensity I of the fringes will vary as given by Equation 4.

$$I = K(1 + \cos \delta) \tag{4}$$

where δ is the phase shift between light coming from the two different waves stored in the hologram and K is a value that is approximately constant. The phase shift δ for a point P_1 that has moved to a position P_2 (as shown in Figure 6) during the deformation is shown in Equation 5.

$$\delta = \frac{4\pi z}{\lambda \cos \alpha} \tag{5}$$

where the angle α is defined in Figure 6, λ is the wavelength, and z is the displacement in the direction perpendicular to the original diaphragm. The value of z will be a function of distance across the fringe pattern. In practice, the angle α is always small, so that $\cos \alpha$ is approximately equal to unity.

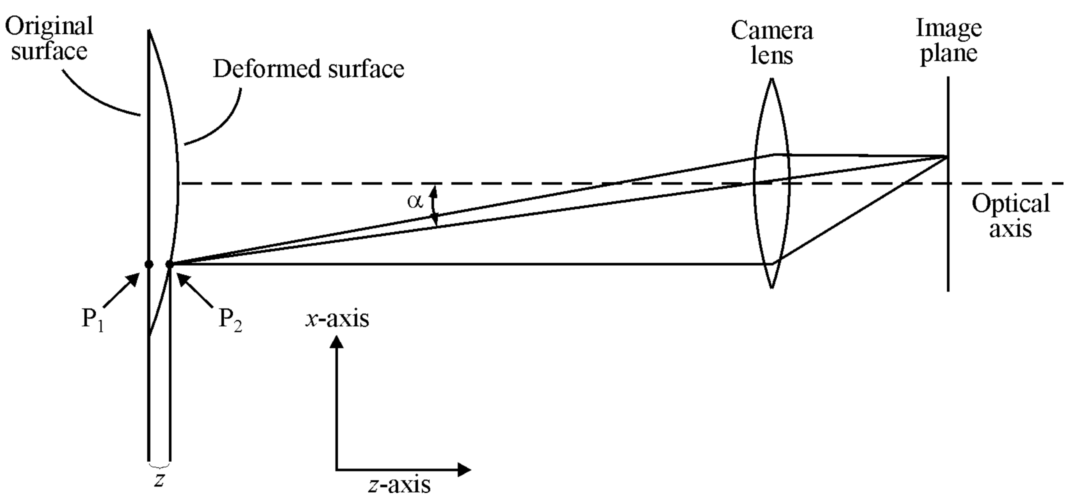


Figure 6 *Geometrical arrangement for viewing the interference fringes from deformation of a diaphragm*

A fringe will occur every time that δ changes by 2π. One full fringe change (bright-to-dark-to-bright) represents the motion of the surface of the diaphragm by one-half the wavelength of the light that was used to make the hologram.

These results, represented by Equations 4 and 5, will be used in the laboratory procedures to determine the deformation of a diaphragm.

Example 2: Deformation of a diaphragm

Given: In a holographic measurement of the deformation of a diaphragm as described in the text, eight concentric fringes (bright-to-dark-to-bright) are observed. A HeNe laser ($\lambda = 0.6328\ \mu$m) was used for the measurement.

Find: Displacement of the center of the diaphragm from its original position

Solution

The presence of eight fringes means a total phase shift of $8 \times 2\pi$ at the center of the diaphragm. Using Equation 5, $z = \frac{\lambda\delta\cos\alpha}{4\pi}$, where $\delta = 8 \times 2\pi$, $\cos\alpha \simeq 1$, and $\lambda = 0.6328\ \mu$m, the displacement z is given by:

$$z = \frac{(8 \times 2\pi)(0.6328 \times 10^{-6}\ \text{m})}{4\pi} = 2.53 \times 10^{-6}\ \text{m}$$

$$\text{or } z = 2.53 \times 10^{-4}\ \text{cm} = 0.00253\ \text{mm}$$

This example shows the use of holographic interferometry for detecting *small amounts* of deformation.

Time-average holographic interferometry

Time-average holographic interferometry is used to study vibrating surfaces. During the exposure, the object is moving continuously. The resulting hologram can be considered as the limiting case of a very large number of exposures over many positions of the vibrating surface.

The time-average hologram may be regarded as similar to a double-exposure hologram in which the two exposures represent the positions where the surface spends the most time—that is, at positions where the speed of vibration is low. These two positions correspond to the positions of extreme displacement of the surface. In this simplified view, the wave being measured may be considered to come from the surface when it is at one extreme position while the other comparison wave is considered to come from the other extreme position. The geometry is sketched in Figure 7.

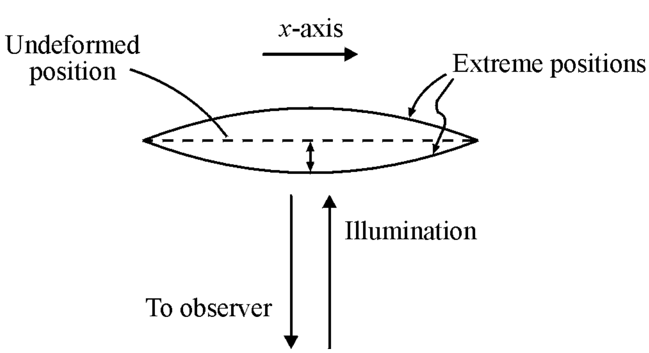


Figure 7 *Geometry for interpretation of time-average holographic interferometry of a vibrating surface*

This method allows the vibrational amplitudes of diffusely reflecting surfaces to be measured with high precision. It is simple to employ. It involves making a single hologram while the surface is vibrating. We note that the restriction, which is usual in holography, of no motion during the exposure, has been removed. The hologram is simply made as if the subject were motionless, when in fact it is motionless only at the extreme positions of the vibration.

After exposure, the hologram is developed and re-illuminated. The resulting fringe pattern is monitored t o provide information on the relative vibrational amplitude as a function of position on the surface. Such measurements have been extremely useful in determining the modes of vibration of complex structures, which would be difficult to measure by other techniques.

As compared to other types of holographic interferometry, time-average holographic interferometry is useful in one particular case, namely, where vibration analysis is desired.

To obtain a quantitative measurement of the amplitude of surface vibration from the fringe pattern, consider the geometry in Figure 7. The surface is vibrating symmetrically between the two extreme positions, both of which form a holographic image on the film. When the two images are viewed, they will interfere and form an interference pattern just as the two surfaces of a thin film create interference fringes. The intensity of the fringes depends on the phase difference between the waves coming from the two surfaces. If the waves are in phase, the interference will be constructive and the intensity will be maximum. If they are out of phase, the intensity will be zero. The intensity I of the fringes may be calculated using Equation 6.

$$I = I_0 \cos^2\left[\frac{4\pi D(x)}{\lambda}\right] \tag{6}$$

where $D(x)$ is the displacement of either surface from the original undeformed surface position. This equation is valid when $4\pi D(x)/\lambda$ is greater than unity. It allows analysis of a fringe pattern to obtain the displacement as a function of position across the surface. Each new bright fringe forms when the optical path difference changes by one wavelength. Since the path difference between the surfaces is $4D(x)$, a fringe will form whenever $D(x)$ changes by $\lambda/4$. Counting the fringes across the pattern allows one to calculate the displacement of the surface.

The amplitude of the fringes decreases as the displacement increases, because the surface must move more rapidly as its amplitude increases. The surfaces spend less time at their extreme positions and the image becomes fainter. Thus, this method is useful only for small displacements of the surface from its equilibrium position.

Time-average holographic interferometry has proved valuable for analysis of vibration of many types of surfaces, for example, musical instruments. Such holography offers a valuable tool for analyzing surface motion in cases that would be very difficult if conventional techniques were used.

Summary of holographic interferometry

We summarize the three types of holographic interferometry by comparing their advantages, limitations, and typical uses in Table 2.

Table 2. Summary of methods for holographic interferometry

Method	Advantages	Limitations	Typical use
Real-time	Complete information about changes in object	Problems in quantitative interpretation, repositioning, and film shrinkage	Strain analysis, defect detection
Double-exposure	East to make, no repositioning or film shrinkage problems	Less complete information than real-time, problems in quantitative interpretation	Strain analysis, defect detection, analysis of transient events
Time-average	Easy to make, relatively easy to interpret	Not usable for static surfaces	Vibration analysis

Use for defect detection

Holographic interferometry is used in industry to measure deformations and to identify defects in manufactured parts. Double-exposure holographic interferometry is perhaps used more than the other two techniques. It offers a simple method for locating defects.

In one classic example, *double-exposure holography* has been used in the testing of tires. A double-exposure hologram is made of the tire, one exposure with low air pressure in the tire and the second with high air pressure. When one views the fringe pattern obtained when the hologram is reconstructed, there may be regions where the fringes crowd relatively close together. These areas indicate relatively large distortion of the tire when the air pressure is increased. The areas with high fringe density thus represent areas of low strength and usually indicate defects in the tire.

Testing of composite materials and structures for defects has become common. Such materials can be stressed by heating. One makes a hologram of the material at ambient temperature and then views the interference pattern in real time as it is heated above ambient temperature. The interference fringes will be distorted as they move over voids, disbonded areas, or other defects.

Many laminated or composite structures have been tested in this way, including honeycomb panels, multilayer circuit boards, automotive clutch plates, composite compressor blades, and graphite-epoxy jet engine fan blades.

In the electronics industry, holographic interferometry is used to analyze heating that occurs when a circuit is turned on. If a particular area heats excessively, the structure is deformed more in that area. Closely spaced fringes identify where these areas are located. The large deformation can cause stress on contacts and component leads. These are areas of possible circuit failure.

The holocamera

We have discussed holography so far in terms of the use of photographic film for the recording of holograms. Probably all of the original uses of holographic interferometry for nondestructive testing were developed using photographic film. But now in industry, probably most applications are carried out using so-called *holocameras* that do not involve photographic film. Holocameras use materials like thermoplastics to record the images. The development is by electrical and thermal means, and can be accomplished in a few seconds without having to move or reposition the recording medium, and without the need for wet chemical processing.

In one commercially available device, the thermoplastic recording medium has four layers. There is a transparent glass substrate. This is coated with a thin transparent conductor, like indium tin oxide. Then there is a layer of a photoconductive organic polymer, polyvinyl carbazole. The final layer is a thermoplastic, which is a material that will repeatedly soften when heated and harden when cooled. The structure is shown in Figure 8.

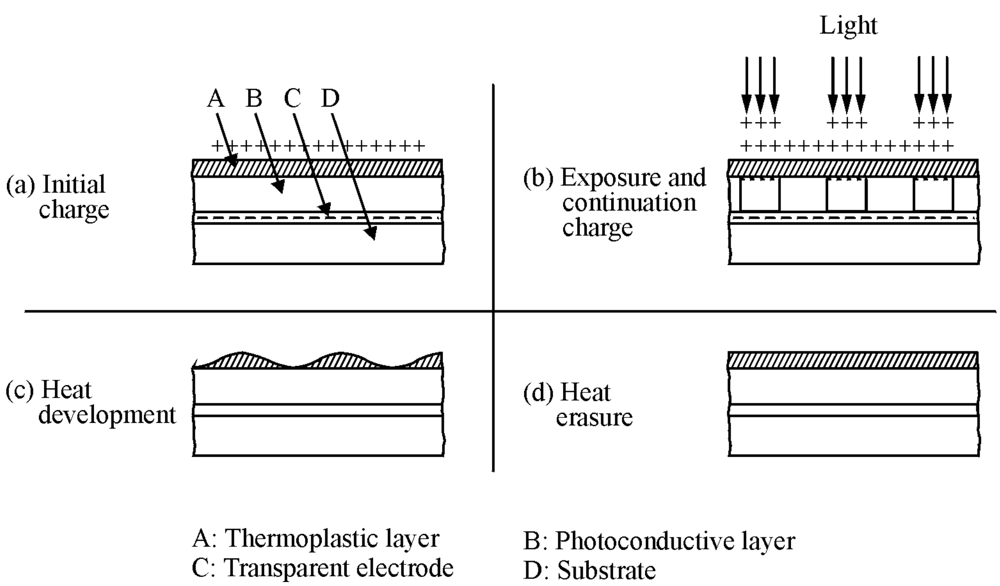


Figure 8 *Recording and erasing in a thermoplastic device*

The surface initially receives a positive electrical charge, for example, from a corona discharge, as shown in Figure 8a. Then the surface is illuminated with the fringe pattern that is to be recorded. The fringes are reproduced in the photoconductive layer as a conductive pattern. The material is then charged again with the corona discharge. Charge flows through the photoconductor in those areas where light has 'made it conductive and the interference fringes are reproduced by conduction as electrical charge on the bottom surface of the thermoplastic. These steps are illustrated in Figure 8b. Then a heat pulse is applied and the thermoplastic softens. The soft thermoplastic deforms in response to the electrical attraction of the positive and negative charges on its opposite sides. The pattern of interference fringes is transferred to a pattern of surface relief, as shown in Figure 8c. The thermoplastic has thus recorded a hologram.

The hologram can be viewed and the desired information on strain or defects can be obtained. Because development is done without moving the hologram from its original position, there is no problem with repositioning. The development is done with heat and electrical charge, not with wet chemical processing. Thus, the hologram can be developed and viewed rapidly, in a matter of seconds. This makes holographic interferometry compatible with rapid inspection and analysis in an industrial environment.

When the operator has finished with the hologram, it can be erased. The thermoplastic is heated again to its softening point and the surface returns to its original flat profile, as shown in Figure 8d. The material is then ready to be reused to make another hologram. A particular sample of thermoplastic can be erased and reused hundreds of times.

The holocamera, based on the thermoplastic recording medium, has become a practical tool suitable for use in an industrial setting. Commercial models are available. The holocamera has removed drawbacks and limitations associated with the processing of photographic film. The holocamera has considerably enhanced the usefulness of holographic nondestructive testing for industry and manufacturing.

EXERCISES

1. A HeNe laser operating in a single longitudinal mode and with a linewidth of 1.2×10^7 Hz is used to measure distance in a Michelson interferometer arrangement. The detector measures a shift of one-half fringe (that is, a change from maximum intensity to minimum intensity) as the movable mirror is displaced slightly. How far did the mirror move? What is the maximum distance that one could measure with this apparatus?
2. Measurements are made on a time-average hologram of a vibrating diaphragm, which is made and reconstructed with a HeNe laser operating at 632.8 nm. The hologram is illuminated and viewed perpendicular to the plane of the undeformed diaphragm. A bright fringe appears at the edge of the pattern where the diaphragm is held motionless, and another bright fringe appears at the center of the pattern. In going from the edge to the center you pass through 20 complete fringes (bright-to-dark-to-bright). What is the maximum displacement of the diaphragm from its undeformed position? Remember that one fringe corresponds to a phase shift of 2π.
3. Describe, in terms similar to those in the text, real-time holographic interferometry, double-exposure holographic interferometry, and time-average holographic interferometry. Include a statement about how each type is produced and the relative advantages and typical applications of each type.
4. Describe how a holocamera works and its advantages over holographic techniques involving film.

LABORATORY

Materials

HeNe laser

Optical rail and mounts

Beam expander

Double-exposure hologram in holder. The hologram is a prerecorded hologram of a thin metal diaphragm that has been stressed between exposures.

Micrometer

Meterstick

Polaroid film pack holder

Polaroid camera

Polaroid film

Procedure

Deformation of thin metal diaphragm—In these procedures, you will obtain a profile of the deformation of a thin metal diaphragm under pressure loading and detect potentially defective areas on the diaphragm.

1. Mount the HeNe laser and beam expander on the optical rail. Adjust the beam expander so that the expanded beam has a diameter slightly larger than the pre-recorded hologram.
2. Mount the pre-recorded double-exposure hologram of a stressed diaphragm on the rail and rotate it, relative to the laser beam, until the brightness of the reconstructed image is maximum.
3. Set up the camera and photograph the reconstructed image. It is preferable to photograph the real image because the virtual image may be located far enough behind the hologram that the photograph would require enlargement for accurate measurement. It is important that the fringes and the object be simultaneously focused on the film so that a one-to-one correspondence can be established between the deformation represented by the fringes and their position relative to the object. This simultaneous focusing may occur only at high values of the f-number setting of the camera. The exact focusing will depend on the method used to make the hologram. The procedure used to make the photograph should be:
   a. Open the field stop on the camera lens and focus on the object.
   b. Reduce the aperture stop (f-number) until the fringes are sharp.
   c. If *speckle noise* becomes severe in step b above, strike the best compromise between sharp fringes and minimum speckle noise.
4. The photograph should have a set of circular fringes with some small circular fringes superimposed on the overall circular pattern. Draw a straight line across the fringes passing through the center of the main circular fringe pattern. Choose a line that passes through the center of the pattern and avoids any of the small circular fringe patterns, if

possible. Use the meterstick to measure the positions where the bright fringes cross the line and record them in a data table.

5. Plot the deformation of the diaphragm as a function of position along the line across the diaphragm. Do this by calculating the displacement of the diaphragm at each fringe. Assume that the center of the fringe pattern is the highest point and that each bright fringe represents a one-fourth wavelength displacement of the diaphragm. Note that each completely closed fringe represents a contour of equal height. Therefore, small circular fringes that do not have their center at the center of the pattern do not contribute to the overall displacement of the diaphragm. They represent local deviations of the surface where the shape changes rapidly as a result of material inhomogeneity.
6. Examine the photograph. Locate and mark all the small circular fringes that are superimposed on the main fringe pattern. These represent areas that are weaker and deform more under stress. These areas are possible positions where failure could occur. The assumption is that the closer the fringes are spaced, the larger the irregularity and the greater the chance of failure. List the areas that you have identified.

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