Optical fabrication and testing: a historical review

By Daniel Malacara

Optical fabrication and testing techniques are more than two thousand years old. It was discovered in 1927 that as far back as 1600 B.C., crystal magnifier lenses were made in Crete. Spectacles were invented around the year 1260. The next great advance came when the Dutch microscopist Anthony von Leewenhoek in 1719 made his own small magnifying lenses to examine microscopic objects. He discovered microorganisms with his small lenses. The manufacturing details until this time are not well known, and probably no attempt was made to test the quality of the surfaces.

The traditional method of polishing with pitch was already known to Newton. He used pitch to polish his reflecting telescope, but very likely he was not the first. For many years, the testing and fabricating methods remained the same, with small variations. These have been described in many books, like the classical book by Twyman,[1] and the books by Charles Deve,[2] Kumanin,[3] and Horne.[4]

In parallel with the progress in fabrication techniques, testing procedures were also generated to determine the quality of the lenses. Probably the greatest testing development was that of Foucault[5] in France, when he invented the knife edge test and the quality of an optical surface was evaluated for the first time.

Foucault's test may be considered a method for detecting the presence of transverse aberrations. This is accomplished by intercepting with a knife the rays deviated from their ideal trajectory. This test is extremely sensitive. If the wavefront is nearly spherical, irregularities as small as a fraction of the wavelength of the light may be easily detected. This is one of the simplest and most powerful qualitative tests for observing small irregularities and evaluating the general smoothness of a concave spherical surface.

Another early important development in the testing field was the Ronchi test, invented by Vasco Ronchi[6] in Italy in 1923. A coarse ruling is placed in the convergent light beam coming out from the surface under test, near its focus. The observer places its eye behind the ruling. The dark bands in the ruling are then projected back to the surface being tested as shadows. These shadows will be straight and parallel only if the wavefront is perfectly spherical. Otherwise, the fringes will be curves whose shape and separation will depend on the wavefront deformations. The main virtue of this test is that each type of aberration wavefront produces a characteristic Ronchi pattern. Thus, the aberrations in the optical system may be easily identified, and their magnitude estimated.

The importance of testing

Most of the time, comtemporary optical surfaces have a flat or a spherical shape, but they may also be toroidal or rotationally symmetric aspheric. It is easy to understand that an aspherical surface is more difficult to manufacture. In this process, the most difficult step is its testing. An aspherical surface can only be made as good as it can be tested. Hence, it is important to develop good testing methods. This subject has been covered in many articles and books, for example in the book edited by Malacara.[7]

Probably the first quantitative test useful for aspherical surfaces was invented in Germany by Hartmann.[8] It is a method for determining the figure of a concave aspherical mirror. In this test, a point light source illuminates the optical surface, covered with a screen with a rectangular array of holes in front of it. Then, the position of the beams reflected through each hole on the screen is measured in a plane near the center of curvature to determine the value of the transverse aberration at each point.

The next step was the invention of the interferometric tests, mainly the Fizeau and Twyman-Green interferometers. Later, several other types of interferometers—such as the lateral shear, radial shear, and common path interferometers—were developed. Since about 1969, the use of the laser as a light source in interferometry has greatly simplified interferometric optical systems. Unfortunately, for many years these tests remained primarily qualitative, since quantitative evaluation required taking a photographic image performing extensive manual calculations.

A null interferometric test is one that produces either straight or no fringes when the optical surface is perfect. Thus a null test is simple to interpret. Frequently, a null test can not be obtained without some additional optical elements that compensate the spherical aberration of the optical element under test if it is aspheric. Many different types of compensators have been invented. Some are reflective elements, or lenses like the Offner compensator.[9] Others are diffractive elements like real or computer generated holograms.[10]

Enter the computer

The advent of computers and electro-optical detectors in the early '60s allowed faster and simpler quantitative interferometric evaluations. The common method for

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evaluating an interferogram consists of two main steps. The first is the measuring of some samples for the fringe positions. These measurements are made in many ways, for example, by means of a measuring microscope, a digitizing tablet, or a video camera connected to a computer. If the wavefront is very irregular or the test is not null, the data points will not be uniformly distributed over the wavefront. Thus, information about many large zones is lost.

The second step is the evaluation of the entire wavefront, interpolating intermediate values by any of several existing methods. One method is to fit the wavefront data to a two-dimensional polynomial by means of a least squares fitting, or by the use of splines, typically by means of a polynomial fitting to the measured data.

Phase shifting

The problems of traditional interferometric methods have been overcome by the phase shifting interferometric techniques, where the density of sampled data points as well as the sensitivity and accuracy of the test is constant over the wavefront.

In addition, phase shifting interferometry is simple and fast, thanks to modern tools like the array detectors (CAD) and the microprocessors. Most of the conventional interferometers—Fizeau, Twyman-Green, etc.—have been adapted to perform the phase shifting techniques, the current trend in interferometry. These techniques are described below and additional details may be found in the review article by Creath.[11]

Phase shifting interferometric techniques began less than 20 years ago, with Crane,[12] Moore,[13] Bruning et al.,[14] and many others. In phase shifting interferometers, the reference wavefront is moved along the direction of propagation, with respect to the wavefront under test, changing in this manner their phase difference. The interference fringes then change their position, hence the initial name "fringe scanning" for these techniques.

By measuring the irradiance changes for different phase shifts, it is possible to determine the difference in phase between the wavefront under test and the reference wavefront, for that measured point over the wavefront. By obtaining this phase difference for many points over the wavefront, the complete wavefront shape is thus determined.

The advance in testing techniques would be incomplete without advances in fabrication techniques.

If we consider any fixed point in the interferogram, the phase difference between the two wavefronts has to be changed to make several measurements. This change in the phase may be accomplished only if the frequency of one of the beams is modified to form beats. Of course, as we will see below, this may be done in a continuous fashion using certain devices, but only for a relatively short period of time with some other devices. Since the frequency can be modified in a permanent way, this technique is frequently called "AC interferometry," "heterodyne interferometry," or a "frequency shift interferometer." However, the name "phase shifting interferomtry" is more common.

In phase shifting interferometry, each detector must have a phase difference smaller than π with the closest neighboring detector to avoid 2π phase ambiguities and ensure phase continuity. In other words, there should be at least two detector elements for each fringe. If the slope of the wavefront is very large, the fringes will be too close together and the number of detector elements would be extremely large. A solution to this problem is to use two different wavelengths—λ_1 and λ_2—simultaneously. The group wavelength or equivalent wavelength λ_{eq} is much longer than any of the two components. This clever idea was proposed by Yaou-Yan Chang and J.C. Wyant.[15]

The new electronic phase shifting digital techniques have several distinct advantages, among which we may mention: a) improved accuracy of the interferometric measurements by at least one order of magnitude; b) with the help of the new imaging devices and microcomputers, improved precision and the ability to achieve quantitative results can be made in real time; c) a smaller possibility that the interference pattern might be misinterpreted.

Parallel advances in fabrication

The advance in testing techniques would be incomplete without advances in fabrication techniques. Newer methods were developed, for example, fast polishing with high speed spindles and polyurethane laps. Computer controlled polishing began in the early '70s. Planetary machines for almost automatic polishing of high quality optical flats made it possible to manufacture them in much larger quantities. Teflon polishers have been developed to automatically polish optical flats with high quality, even better than we can measure them. Abrasive water cutting of glass permits us to cut glass like wood, with complicated shapes and quite fast. Ion bombardment polishing is now being used to aspherize surface with high reliability and accuracy. Another important fabrication development is the diamond turning technique.

All these new testing and fabrication techniques have made it possible to fabricate high quality optical components, with aspheric shapes that a few years ago were considered too complicated to even attempt to manufacture. However, it is important to point out that newer techniques are not a substitute for the high skill and training required by those in optics shops. Frequently, a high degree of ingenuity and imagination can produce better results than all automatic machines together. Many examples of this are found in the *Applied Optics* articles by Frank Cooke, compiled into the *Optics Cooke Book*:[16]

This issue of *Optics & Photonics News* offers an overview of many new and exciting developments in the field of optical fabrication and testing.

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International optical standards

By Robert E. Parks

In 1979, the International Standards Organization (ISO) formed a technical committee (TC172) to work on international standards for optics and optical instruments. As part of the committee's work, an optical drawing standard was developed and will be published in draft form before the end of the year. Because all the countries that have large optical industries are participating in writing these standards and the various delegations have reached a general consensus, it can be assumed that the standard will be adopted worldwide shortly after it is published in final form.

During this same period, the U.S. Office of Management and Budget put out a directive to all federal agencies requiring them to use voluntary instead of government standards whenever appropriate voluntary standards existed. But the directive has had little effect, since there are very few voluntary U.S. optical standards.

Once the ISO optical standards are adopted, this situation will change drastically. The United States can either formally adopt the ISO optical standards as national standards, paving the way for a smooth transition to voluntary optical standards, or it can wait for the international standards to become de facto standards because of world market pressures. The U.S. optics industry would be best

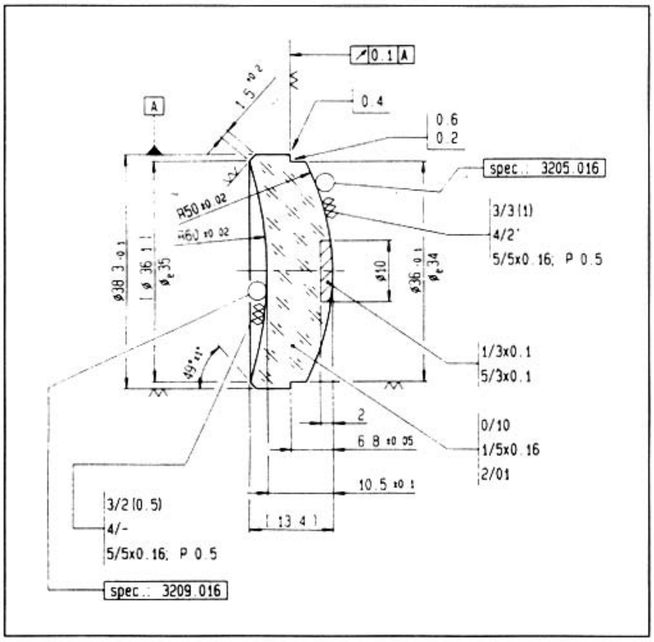

FIGURE 1. Typical optical element drawing following the ISO 10110 Optical Drawing Standard.

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