W. Fink, W. Schneider *

Optical Testing of Profiles

Optical methods of comparing profiles to master shapes have been investigated. Direct imaging and projection methods have been excluded because of the complicated implementation or low detection capability involved. Two methods based on diffraction (optical Fourier transformation) have been found applicable to routine checks such as part inspection or profile type search. Method 1 utilizes the modulation function of a double slit as a means of detecting differences. Method 2 compares the Fourier transform of the test profile with that of the master.

1. Introduction

Noncontact profile testing is employed as a standard inspection technique in different component manufacturing processes. Optically, the problem is to check the accuracy of the shape of a curve separating regions of high transmission and zero transmission. Conventional methods based on point-by-point measurements of the transmission of the area in question or on projection techniques either involve high expenditure on implementation or suffer from a relatively low detection efficiency.

Coherent-light image subtraction methods based on interferometry are more sensitive to pattern deviations. True image subtraction, however, requires interferometers which are somewhat difficult to adjust [1].

We have investigated two simplified arrangements, based on Fourier transform subtraction for comparing a test profile to a standard, which are suitable for fast and simple automatic monitoring of the quality of mass produced products.

2. Theory

Method 1.

Optical image subtraction, either in the object or Fourier plane, is done by the complex addition of the amplitude distributions of two wave fields due to the patterns to be subtracted, where a relative phase shift of π is introduced between them. In our first method the experimental difficulty of obtaining a phase factor which is constant over the whole pattern area is avoided by abandoning the subtraction of the entire Fourier transforms. Instead, one of the transforms is modulated by a relative phase increasing linearly with one co-ordinate, and the pattern resulting from the complex addition is observed only at points where the phase difference is $(2n+1)\pi$. A linearly increasing phase difference between the transform patterns in the Fourier plane is easily obtained by a relative shift of the object patterns in the object plane.

The profile to be tested, together with the complementary standard profile, forms a pattern described by the transmission function $f(x, y)$. This is compared to a standard pattern $g(x, y)$ formed by the standard profile and its complementary counterpart. These two patterns are placed side by side at a distance a in the front focal plane of a positive lens (fig. 1), thus representing the input function

$$g(x, y)+f(x, y) = g(x, y)+g(x-a, y)+h(x, y)$$

of the optical processor. The function $h(x, y)$ describes the inequality of the two patterns; f, g and h being unit step functions, i.e. with values 0 and 1 only.

With $F(u, v)$, $G(u, v)$ and $H(u, v)$ being the Fourier transforms of $f(x, y)$, $g(x, y)$ and $h(x, y)$, respectively, the Fourier transform of $f+g$ is given [2] by

$$F+G = G+e^{2\pi iua}G+H,$$

and the corresponding intensity distribution by

$$(F+G)(F+G)^* = 2GG^*(1+\cos 2\pi ua)+$$
$$+HG^*(1+e^{-2\pi iua})+H^*G(1+e^{2\pi iua})+HH^*.$$

For identical patterns ($H=0$) the intensity distribution is equal to that of a single pattern modulated by regular parallel fringes, while any difference between the two patterns will cause irregularities of these fringes.

*) Optics and Spectroscopy Division National Physical Research Laboratory Council for Scientific and Industrial Research Pretoria, South Africa.

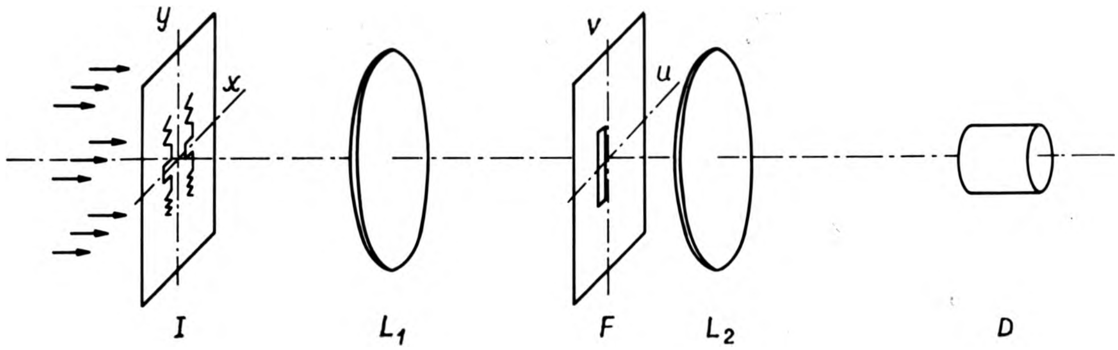


Fig. 1. Double-slit arrangement according to method 1
I — input plane, L_1 — transform lens, F — Fourier plane, L_2 — collecting lens, D — detector

For $u = \frac{2n+1}{2a}$ (in case $H = 0$ this represents dark fringes of relative phase π) the above equation yields

$$(F+G)(F+G)^* \Big|_{u=\frac{2n+1}{2a}} = HH^*.$$

The intensity behind slits representing $u = \frac{2n+1}{2a}$ in the transform plane is therefore given, for infinitesimal slit width, by contributions resulting from pattern inequality only. As it is likely that $h(x, y)$ describing the dissimilarities usually consists of a wide range of spatial frequencies, it will be sufficient in most cases to observe the intensity along the line $u = \frac{1}{2a}$ (first dark fringe) only. A similar method for pattern comparison has been described in the literature [3].

Since any deviation in the position of the test profile yields an intensity increase corresponding to HH^* in the same manner as does any deviation in the profile shape, the relative positional tolerance for the test profile is low.

Method 2.

The second approach comprises a subtraction of the one-dimensional Fourier transforms of the one-dimensional profile functions $f(y)$ and $g(y)$ describing the test profile and the standard sample, respectively, thus again avoiding the previously mentioned difficulties in interferometer adjustment. It has been shown [4] that the one-dimensional Fourier transform $F(v)$ of a function $f(y)$ can be obtained by taking the two-dimensional transform of a slit aperture formed by a profile of the shape $x = f(y)$ and a straight edge representing the abscissa $x = 0$ (transparent for $0 < x < f(y)$, opaque elsewhere). The amplitude distribution along the abscissa $u = 0$ in the Fourier plane displays the required function $F(v)$. Because of the symmetry of the arrangement, a slit aperture which is transparent for $-g(y) < x < 0$ will also yield the Fourier transform $G(v)$ of the function $g(y)$ in the form of an amplitude distribution along the Fourier plane abscissa. Combining the two apertures formed by $f(y)$ and $-g(y)$ and introducing a phase shift of π for one of them (transmission $T = e^{i\pi}$ for $-g(y) < x < 0$, $T = 1$ for $0 < x < f(y)$, $T = 0$ elsewhere) thus yields the intensity distribution $|F(v)-G(v)|^2$ along the Fourier plane abscissa, and provides an indication for the similarity of $f(y)$ and $g(y)$ (fig. 2).

The following positional errors can occur:

1. Translation along the x-axis, i.e. perpendicular to the line of symmetry between $f(y)$ and $-g(y)$: $f(y) \to f(y)+a$.

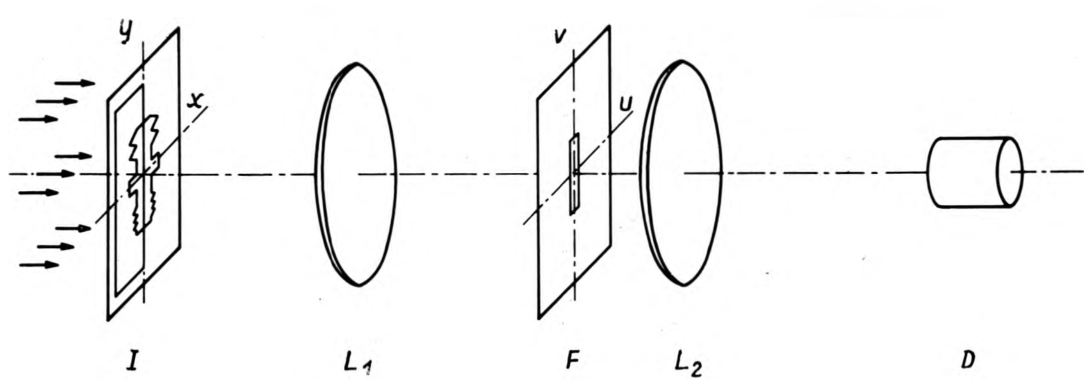


Fig. 2. One-dimensional Fourier transform subtraction arrangement according to method 2
I — input plane, L_1 — transform lens, F — Fourier plane, L_2 — collecting lens, D — detector

2. Translation along the y-axis: $f(y) \to f(y-c)$.

3. Rotation about an axis perpendicular to the x-y-plane.

As the Fourier transform of $f(y)+a$ is $F(v)+a\delta(v)$, it is obvious that error 1 adds only to the zero frequency, or in the practical case to the zero order of the transform. The transform of $f(y-c)$ is given by $F(v)e^{2\pi ivc}$, i.e. the transform is the original one except that every component is subject to a phase shift proportional to its frequency. This gives for the case of error 2 rise to a periodic modulation of the observed intensity along the Fourier plane abscissa.

In order to exclude such a phase modulation, the transforms of $f(y)$ and $g(y)$, being represented by light amplitude distributions, would have to be compared incoherently. This could in principle be done by comparing the energy density spectra of f and g as measured sequentially by means of some sort of scanning device. Another method would be to obtain the cross-correlation of f and g, e.g., by using a matched filter [5], but the positional difficulties involved place this approach beyond the scope of the present aim.

As to error 3, this of course changes in effect the function $f(y)$ as seen in the x-y-coordinate system. Depending on the particular shape of $f(y)$, small rotations can, however, be approximated by $f(y)+ay$; the Fourier transform of the additional term thus being again limited to the centre of the transform pattern.

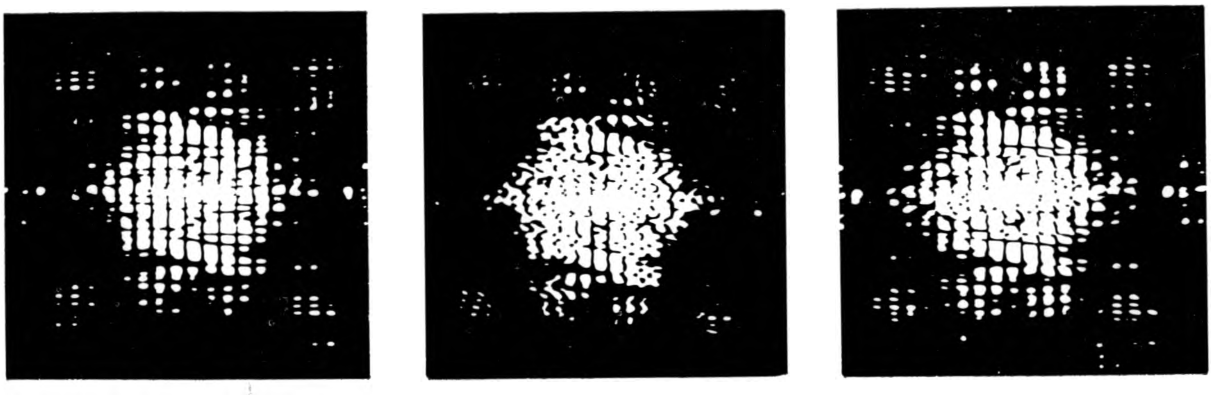
3. Experiments

The experimental setups used were in principle similar to the basic arrangements sketched in fig. 1 and 2. For method 1, examples of the intensity distribution in the Fourier plane for the three cases of identical parallel patterns, identical slightly rotated patterns and for slightly different patterns are shown in fig. 3. With a slit of finite width at the position of the first dark fringe in the Fourier plane it is not possible to obtain zero intensity for identical patterns, but the intensity increase is quite sensitive to profile deviations, as indicated in fig. 4.

Application of method 2 leads to similar results. The advantage of this method with respect to insensitivity against inaccurate position of the test profile has also been verified.

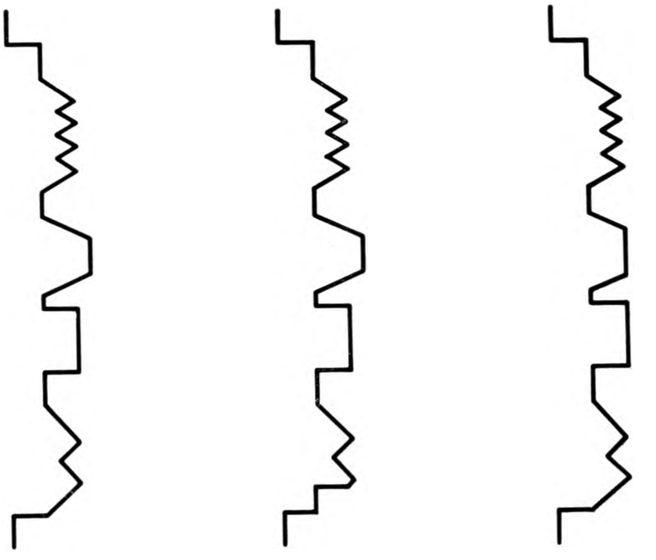
4. Conclusion

Both methods described allow the realization of a simple and rapid device for automatic monitoring



a b c

Fig. 3. Diffraction patterns of (a) standard, correctly adjusted profile, (b) standard, slightly rotated profile, (c) faulty profile



a b c

Fig. 4. (a) Standard profile, (b) faulty profile (intensity increase: method 1 – 65%, method 2 – 60%), (c) faulty profile (intensity increase: method 1 – 50%, method 2 – 60%)

of the profile quality of mass produced products or for recognition of shapes. While offering a comparable sensitivity, method 2 has the advantage of less stringent positional requirements of the profiles to be tested. Measurement accuracy and influence of positional errors are related to particular profile shapes and have therefore to be determined from case to case.

Оптическое тестирование профилей

Исследованы оптические методы сопоставления профилей с формой образца. Методы классического отображения и проекции исключаются по поводу сложного оборудования или низкой способности детектирования. Установлено, что для такого контроля, как проверка частей или исследование профилей подходят два дифракционных метода, основанных на оптической трансформации Фурье. Первый метод использует функцию двойной модуляции щели как средство детектирования разниц. Второй метод заключается в сравнении функций Фурье исследованного профиля и образца.

References

[1] Felstead E. B., *Appl. Opt.* 10, 1185 (1971).
[2] Bracewell R. M., *The Fourier Transform and its Applications*, McGraw-Hill 1965.
[3] Weinberger H., Almi, U., *Appl. Opt.* 10, 2482 (1971).
[4] Lanzl F., Mager H. J., Waidelich W., *J. Opt. Soc Am.* 61, 1355 (1971).
[5] Van Der Lugt A., *Appl. Opt.* 5, 1760 (1966).

Received, May 31, 1972.