A New Technique for Deciding Convexity or Concavity on Moiré Fringes in Biostereometrical Analysis of Motion

Toshiko Ikeda, Yasutoshi Shirota* & Harumi Terada

Dept. of Anatomy, Kitasato University Medical School
Sagamihara, Kanagawa-ken, 228 Japan and
*Dept. of Information Science, Sagami Institute of Technology
Tsujido, Fujisawa, Kanagawa-ken, 251 Japan

Commission V/5

For the three-dimensional analysis of the shape of human body surface and its changes during motion, the moiré interferometry has been introduced and proved to be a feasible technique in the field of biostereometrics. It has an advantage that it could be accomplished by inexpensive procedure with ordinary black and white films and photographic papers, and the light used is no harm to the subjects examined. One of the disadvantages, however, was the difficulty in deciding ups and downs at the time of analyzing moiré fringe patterns, especially for the surface with unknown undulations. The purpose of the present presentation is to describe the principles of our new technique of deciding ups and downs in moiré photographs and also to demonstrate some of its applications on the moving part of body surface.

Principles

The original grating is a structure composed of close equi-distant and parallel lines. The grating is placed so that its surface is parallel to the standard plane of the object (Fig.1). The original grating is illuminated by collimated light with an incidence angle θ , and its projected shadow on the object is used for a master grating. Two lines ga and gp of the original grating are arbitrary, and so are points A and P on these lines. The Cartesian coordinate is set up, so that the x-y plane corresponds to the standard surface of the object. The x-axis is perpendicular to the direction of lines of the original grating, which surface is parallel to the x-y plane. The z-axis is perpendicular to the x and y axes, and is along the direction of the view from the camera. The sign of the x-coordinate is plus, when it is directed toward the side of the light source, and that of the z-coordinate is plus, when it is directed toward the camera.

Without any deformation, that is, when the whole x-y surface of the object is smoothly flat, the line ga on the original grating is projected to the standard surface as a line gb and that of gp as gq. The point A is projected as B and the point P is projected as Q on the flat surface. When two deforming structures, a hill and a valley, are built on the standard surface of the object as in Fig.1, the image of ga is deformed as a curve gc on the hill, and that of gp as a curve gr at the bottom of the valley. Also the point A is projected as C on the hill, and the point P is projected as R on the base of the valley.

The object is observed by a camera which is placed in direction of the z-axis, that is, perpendicular to the x-y plane. Now, the point C is seen from the camera as if it is located at the point D on the x-y plane. In other words, the point B is displaced on the standard plane to D and the projected curve gc is transferred to a curve gd due to the existence of the hill. Also the point R is seen from the camera as if it is located at the point S on the x-y plane. Due to the presence of the valley, the point Q is displaced to S and the curve gr is transformed to a curve gs on the standard plane.

The displacement of the point B to D is on the x-axis, and is a component of Ux. It has a plus (+) sign, since it is directing from the line gb toward the side of light source. The displacement of Q to S, on the contrary, has a minus (−) sign, because its direction is opposite. When the displacement on the x-axis is toward the direction of the light source, that is, if the sign of Ux is plus, the displacement along z-axis is always toward the direction of the camera, that is, the sign of Uz is always plus (+).

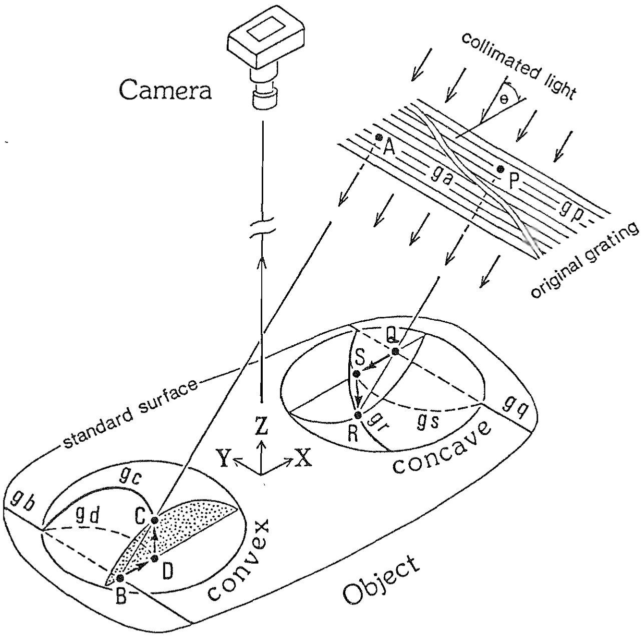


Fig.1. Grating projection system.

As shown in Fig 1, the shape of the deformed surface can be judged as CONVEX with plus z-coordinate, when the sign of displacement on the x-axis is plus. And it is judged as CONCAVE with minus z-coordinate, when the sign of x-displacement is minus. The displacement components on z-axis at points D and S are expressed as U_{zD} and U_{zS}, respectively, and their values are given by

$$U_{zD} = \overrightarrow{DC} = \overrightarrow{BD} \cdot \tan\theta \quad \text{(1 a)}$$

$$U_{zS} = \overrightarrow{SR} = \overrightarrow{QS} \cdot \tan\theta \quad \text{(1 b)}$$

where D and S are the points projected from C and R perpendicular to the x-y plane.

The values of U_x-displacement component $+$BD and $-$QS are obtained directly by measuring the distance from the curved grating lines on the x-y plane using a comparator. However, they may be obtained by superimposing the master grating on the curved grating patterns, and are given by

$$\overrightarrow{BD} = +N_D \cdot P \quad \text{(2 a)}$$

$$\overrightarrow{QS} = -N_S \cdot P \quad \text{(2 b)}$$

where P is the pitch of the master grating, N_D and N_S are fringe orders at points D and S, respectively. If we substitute equations (2 a) and (2 b) into equations (1 a) and (1 b),

$$U_{zD} = +N_D \cdot P \cdot \tan\theta \quad \text{(3 a)}$$
$$U_{zS} = -N_S \cdot P \cdot \tan\theta \quad \text{(3 b)}$$

When the angle θ is 45°, $\tan\theta$ is 1. And it follows,

$$U_{zD} = +N_D \cdot P \quad \text{(4 a)}$$
$$U_{zS} = -N_S \cdot P \quad \text{(4 b)}$$

It should be emphasized that the values of displacement component are obtained simultaneously at the time of judging convex or concave nature of the structure on the artbitrary standard surface.

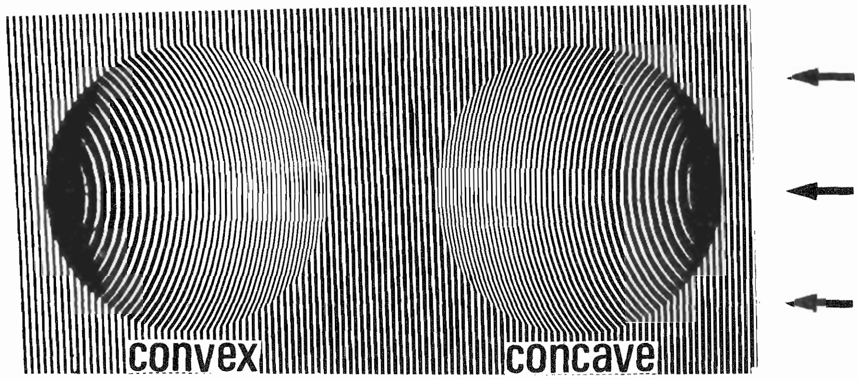


Fig.2. The deformed grating patterns.
Arrows indicate the direction of light from the light source.

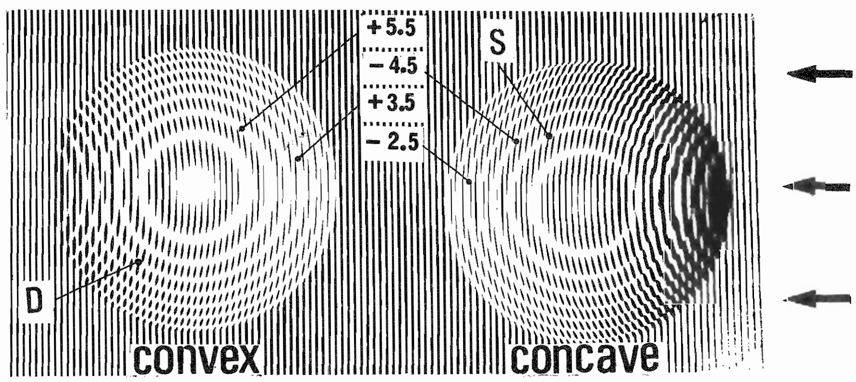


Fig.3. The patterns of deformed grating together with moiré fringes obtained by superimposing the master grating on Fig.2.
Arrows indicate the direction of light from the light source.

Experimental Examples

The master grating was projected on an object with a hill and a valley on its surface, where the deformed surface on the left side is convex and that on the right side is concave, respectively.

The grating lines of the original grating are projected on the up and down surface of the object and their deformed image is shown in Fig.2 as a curved grating. The deformed lines curving toward the side of the light source indicate that the direction of the U_z is away from the standard surface, that is, the area is determined as convex. The reverse is true on the deformed lines at the area on the right side, which is determined as concave.

When the image on Fig.2 is superimposed by the master grating, moiré fringe patterns are obtained as shown in Fig.3. The pitch of the grating is 1.50 mm., and the fringe order at point D is 4.5 and that at point S is 5.5. Accordingly it follows that

$$U_{zD} = + N_D \cdot P = + 4.5 \times 1.5 = + 6.8 \ \text{(mm)}$$

$$U_{zs} = -N_s \cdot P = -5.5 \times 1.5 = -8.3 \text{ (mm)}$$

In applying these equations, the plus or minus sign is determined by the shape of the sinuosity of the deviated grating lines in relation to the position of the light source, that is, the grating lines are curved toward (+) or away from (−) the direction of the light.

The above-mentioned procedure was applied to the moving area of the human body. An experimental region was at the lower half of the face of a young male student, especially around the upper and lower lips. As shown in Fig.4, the projected image of the grating is deforemed according to the movement of the lips at the time of opening the mouth or smiling. The situation in Fig.4-a is supposed to be the standard pose without movement. The pictures were taken at the rate of 5 frames per second with a still camera installed with a motor drive attachment. When these photographs are superimposed by the original grating, the moiré fringes along with the information of + & − signs are visualized as in Fig.5. The displacement component on the z-axis, in other words, the amount of the ups and downs can be easily obtained by counting the number of fringes.

Next, the relief changes made by a motion can be analyzed as follows: When the Fig.4-b is superimposed by Fig.4-a, and Fig.4-c by Fig.4-a or Fig.4-d by Fig.4-b, the amount of displacement component on the z-axis made by opening the mouth widely, is obtained as in Fig.7. Here, the quantity of relief changes as well as information on the ups or downs are obtained. The perspective diagrams are also shown in Fig.6 to facilitate the concept of these changes by motion. The Fig.8 represents the quantitative distributions of dynamic displacement, obtained from Fig.7.

References

1) Benoit, P., Mathieu, E. & Thomas, A.: Sign determination of contour lines. Optics Communications, 15 : 392～395, 1975.
2) Durelli, A. J. & Parks, V. J.: Moiré Analysis of Strain. Prentice-Hall, Inc., N. J., 399 pp., 1970.
3) Honda, T., Kamiya, K. & Tsujiuchi, J.: The determination of hills or valleys in moiré topography using color gratings. Jap. J. Optics, 5 : 87～92, 1976 (Text in Japanese with English summary).
4) Ikeda, T.: Moiré apparatus by use of parallel light projection. Kitasato Med., 6 : 192～199, 1976 (Text in Japanese with English summary).
5) Ikeda, T. & Terada, H.: Development of moiré method with special reference to its application to biostereometrics. Opt. Laser Technol., 13 : 302～306, 1981.
6) Terada, H.: A new apparatus for stereometry: Moiré contourograph. in Nutrition and Malnutrition, Advances in Experimental Medicine and Biology. Plenum Press, p.27～46, 1974.
7) Terada, H. & Ikeda, T.: The photogrammetric application of moiré fringes produced with a parallel beam of light. Opt. Eng., 18 : 399～402, 1979.

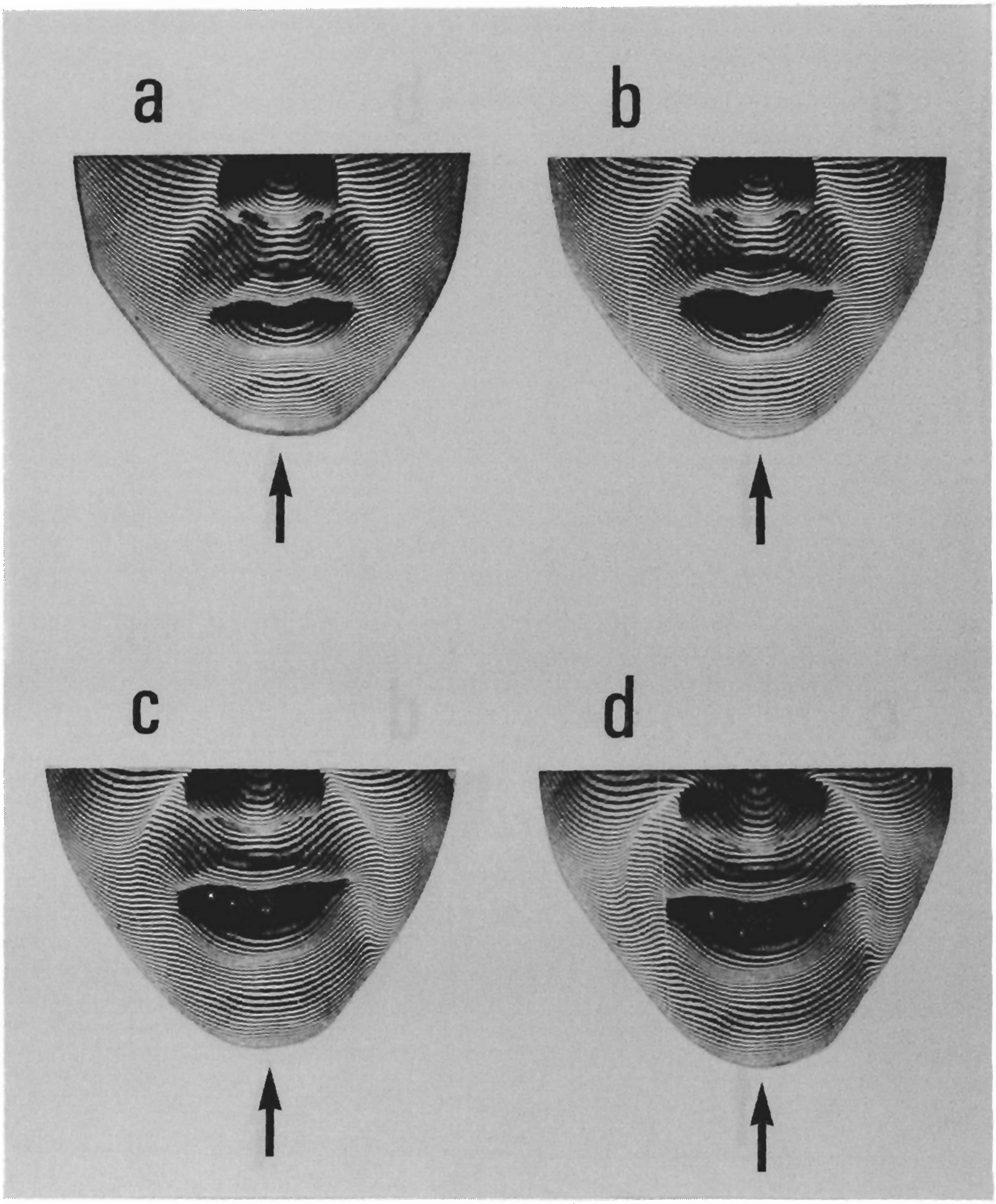


Fig.4. The deformed grating patterns projected onto the face.
$\theta = 45.0°$ (angle of incidence)
P = 2.42 mm. (pitch of the master grating)
Arrows indicate the direction of light from the light source.
Timing of photography: a (0.0~0.2 second), b (0.2~0.4 second)
c (0.4~0.6 second), d (0.6~0.8 second)

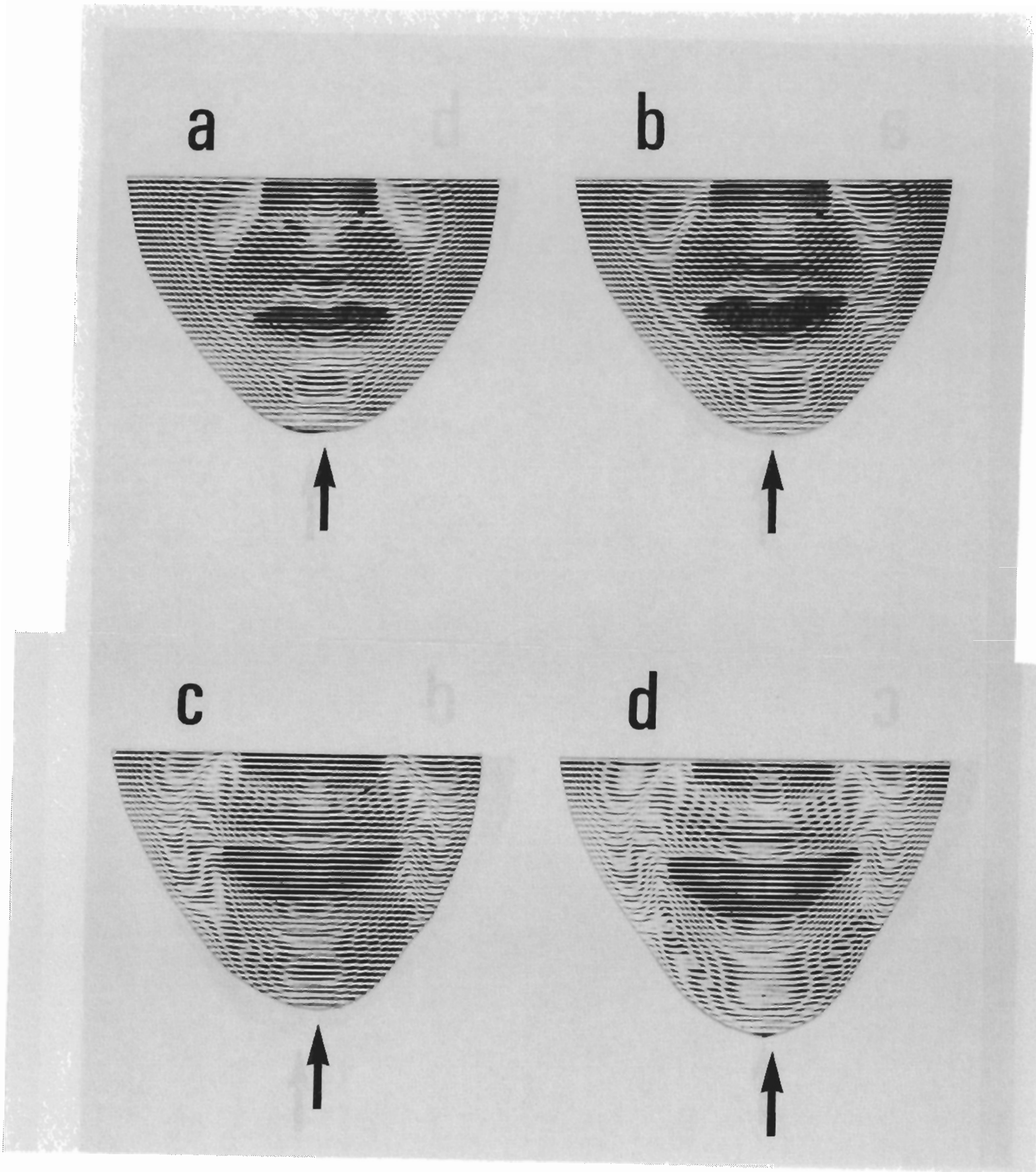


Fig.5. The first moiré fringe patterns obtained by superimposing the master grating on the pictures in Fig.4.
$\theta = 45.0°$, $P = 2.42$ mm.
Arrows indicate the direction of light from the light source.
Timing of photography: a (0.0~0.2 second), b (0.2~0.4 second)
c (0.4~0.6 second), d (0.6~0.8 second)

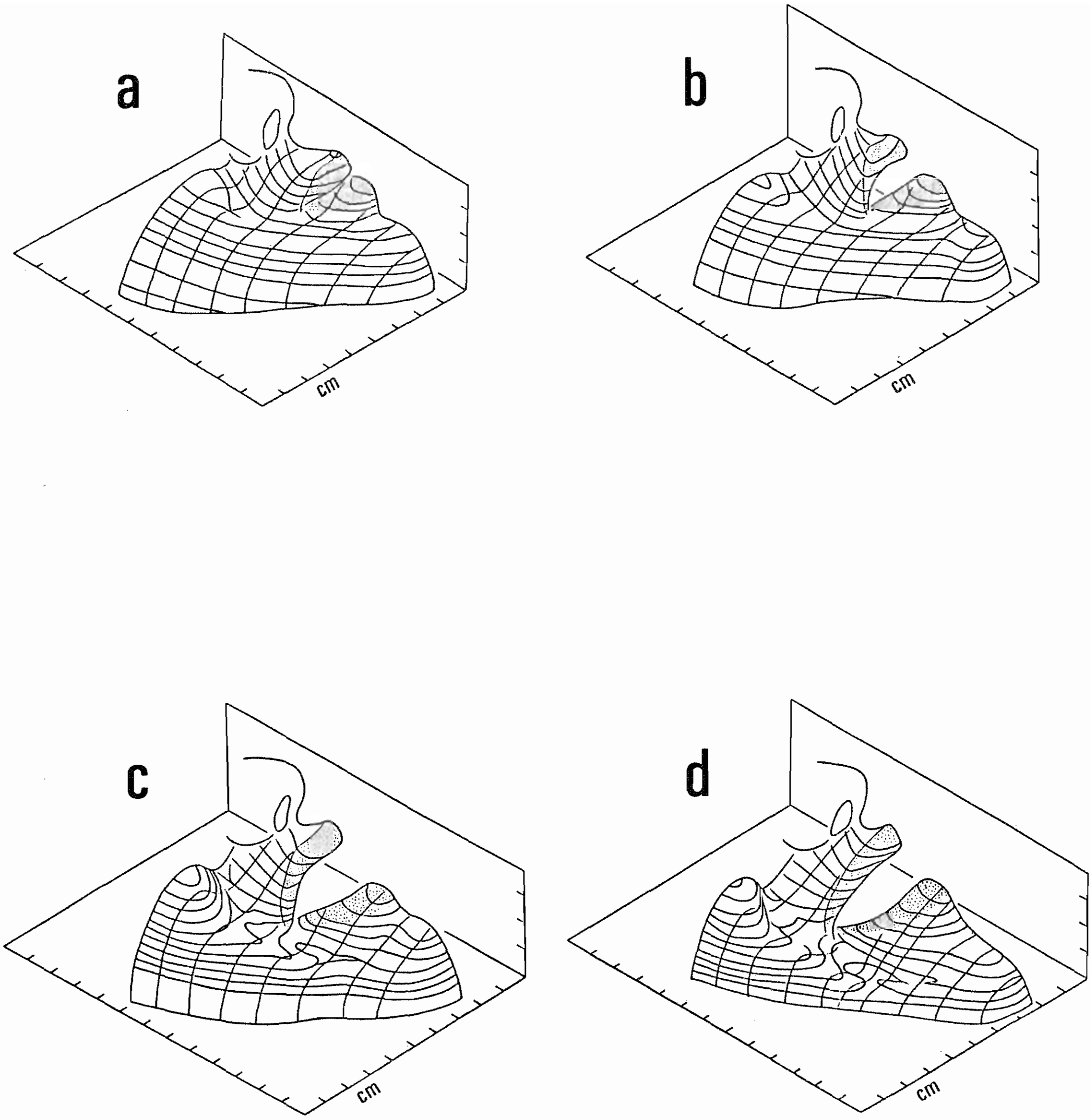


Fig.6. The three-dimensional profiles of the lower-right quadrant of the face obtained from Figg. 4 and 5.

Timing of photography: a (0. 0~0. 2 second), b (0. 2~0. 4 second), c (0. 4~0. 6 second), d (0. 6~0. 8 second)

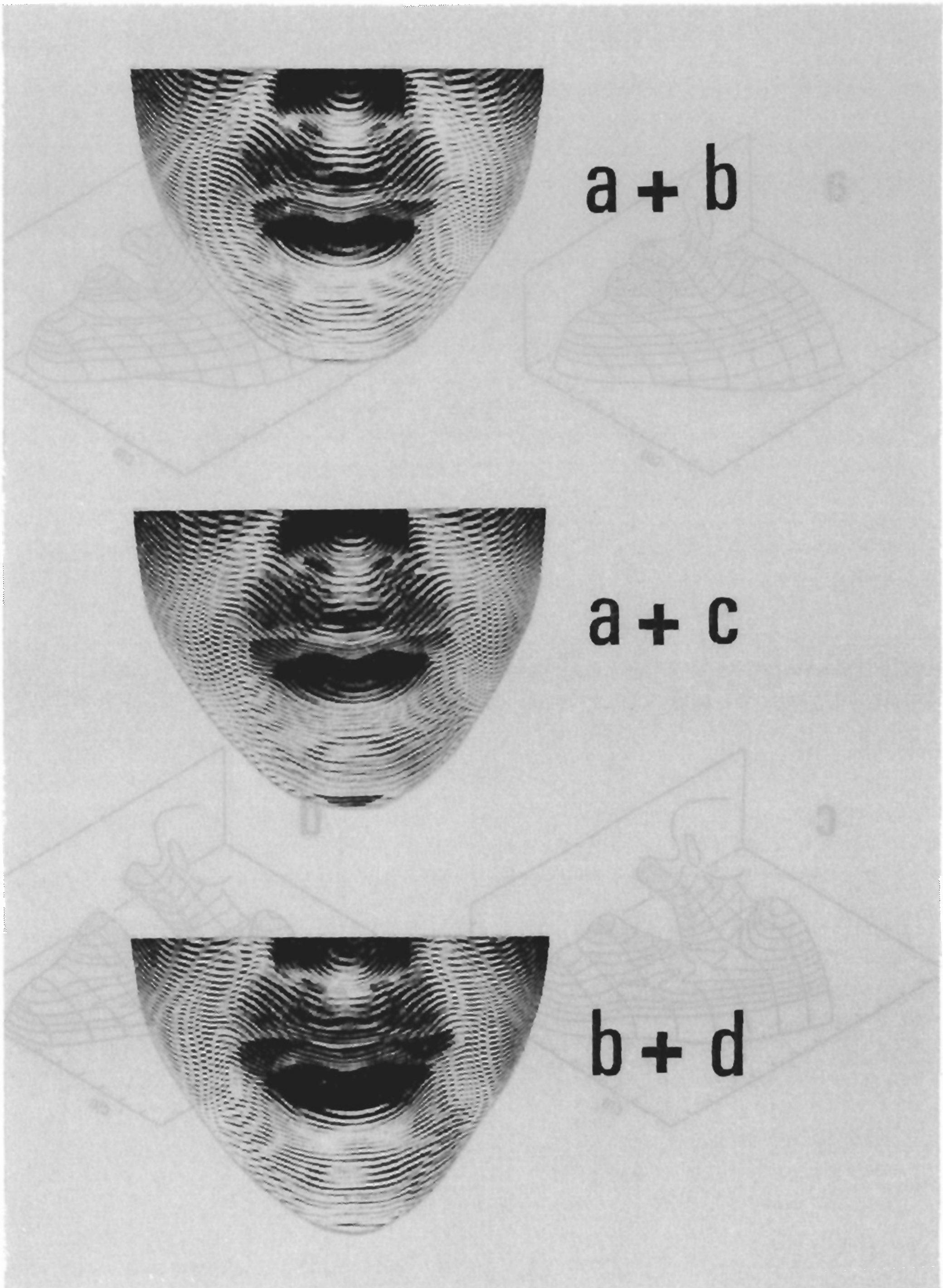
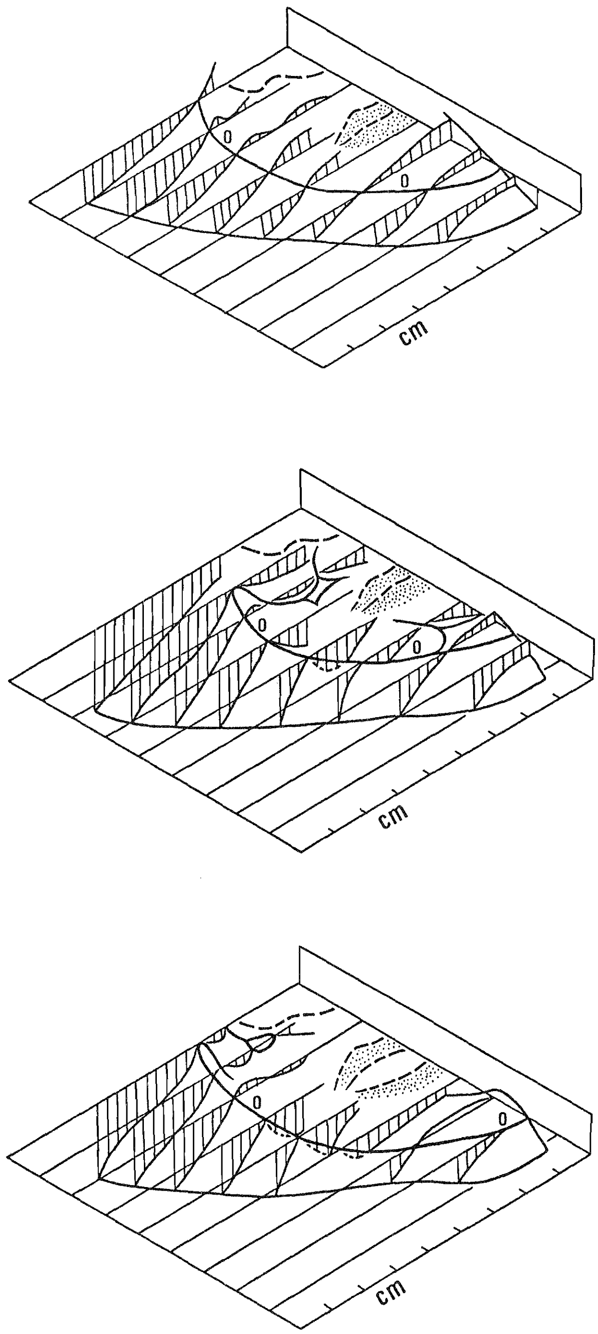


Fig.7. The second moiré fringe patterns representing time derivatives of the out-of-plane displacement, obtained by superimposing two pictures of the deformed grating patterns in Fig.4.



a + b

a + c

b + d

Fig.8. Quantitative distributions
of dynamic displacement, obtained from Fig.7.