New Apparatus of Moiré Iso-hypsigraphy by Parallel Light Projection and Parallel Reflecting Light Recording

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Abstract A new apparatus of moiré iso-hypsigraphy was designed and produced to examine relatively small materials such as human skulls, innominate bones and scapulae. The parallel light source method producing moiré fringes was adopted, which is much appropriate for the small objects. The reflected light, furthermore, was considered, because moiré fringes produced by the parallel light needed to be recorded by the camera system in condition of nearly parallel reflected light. For recording system a 35mm camera with a 800 mm focal length lens was selected. In this system one can measure the photographs with moiré fringes under the permissible error, i.e. 1%. Moiré producing parts of an apparatus has many improvements for the small objects: condenser lens, field lens, reflecting mirror and threads in grating. In the apparatus the skull fixer and co-ordinates indicator, in particular, were specially designed. By them the skulls on which the moiré fringes are produced can be fixed in the Frankfort horizontal plane. In the photographs of them the moiré fringes on the skull will indicate coronal sections as exact equal contours.

Keywords Moiré iso-hypsigraphy, Parallel light projection method, Parallel light recording system, Craniology, Photogrammetry

Introduction

Moiré fringes or moiré methods are widely used in the clothing industry and in engineering. In the former they provide a means of examining the texture pattern of cloth. In the latter they can measure two-dimensional transformation of the small materials in the mechanical or machine engineering and also can test the minute surface waviness of industrial materials in the precision engineering. This method, when used in the anthropological measurement, allows us to understand and measure three-dimensional data as visible contour fringes on the subject without difficult complicated processing. TAKASAKI (1970) and MEADOWS et al. (1970) were the first researchers to introduce the moiré method for use on larger materials such as the human body. TAKASAKI sug-
gested to use the actual grating, one point light source and to move the grating. The moiré fringes produced by this method have unequal contours. Many research workers in medical and anthropological studies have adopted Takasaki's method (Terada and Kanazawa 1974b, Suzuki et al. 1975, Hat- tori et al. 1980). These studies have, in general, treated the living human bodies. In osteology, however, moiré methods have only been used infrequently. Terada and Kanazawa (1974a), for instance, fixed skulls in norma lateralis to make clear the three-dimensional position of the landmark Euryon. Endo (1971) built a small moiré apparatus and compared the tuberosity of neanderthal humeri and recent human specimens. Kanazawa (1980) studied three-dimensional variations of the landmark positions defined by Martin's textbook (1928). And Ikeda (1980) studied cartilaginous articular surfaces of the patellae by the parallel light source moiré apparatus, which Ikeda (1976) formerly reported as an application for the small materials.

There are three reasons why moiré methods have been used by so few anthropological or osteological workers. First, the materials analysed by the moiré methods cannot be fixed within the standard and defined co-ordinate system. Second, the measurement errors caused by the recording system of reflected light contaminate photographs of moiré fringes. Third, the information produced by moiré fringes cannot be used effectively, since it is not three-dimensional data. This report will describe one solution to these problems; a new apparatus which is specifically designed to facilitate the application of the moiré method to the human skull, which I will describe differs from that of Ikeda (1979) in that it creates contour fringes by using a parallel beam of light and then records these contours with nearly parallel reflected light. The recording system, therefore, is located almost in the infinite distance. Takasaki (1970) and Meadows et al. (1970) also described the parallel light method by the telecentric observation. They, however, did not consider that this method would be useful for the actual measurement of materials such as the human skull.

**Explanation of the Moiré Contour Fringe**

The theoretical basis and production of moiré fringes are described in detail in optics and precision engineering textbooks (e.g. Inoue and Sayanagi 1970, Watanabe 1976). The moiré apparatus described in this report is designed and produced to analyse smaller anthropological materials such as the human skull. I have also reconsidered the degree of error possible for the measurement of both moiré fringes and materials analysed in anthropological craniology. I am using theoretical and practical assumption, derived from both moiré theory and the apparatus used in geometrical optics.

Fig. 1 depicts moiré fringes schematically from both a superficial and cross-sectional view. Fig. 1(A) shows groups of parallel lines, A and B, which cross each other. Note that dark shadows can be seen at the points where the two lines cross and that these points continue in one direction as belt C. This dark belt is called a moiré fringe. These moiré fringes produced by the almost identical parallel lines are used in measuring the small angles or small differences of industrial materials. Fig. 1(B) shows the schematic cross-sectional view when the moiré fringes are produced on the subject's
Fig. 1. Theoretical explanation of producing moiré fringes.
(A) Moiré fringes in their superficial view.
(B) Moiré fringes in their cross-sectional view.
Fig. 2. Two different methods produce the moiré fringes.  

(A) The one point light source method: this cannot make an equal depth between contour fringes, so it is too much complex to calculate the contour depth.

(B) The parallel light source method: this can make an equal depth between contour fringes, so it is easy to calculate the contour depth.
surface. G is a cross-section of the grating and M is the surface of the subject. Parallel lines A and B are project light and reflected light beams, respectively. When two parallel lines cross on the subject surface, we see bright contour lines, C, as moiré fringes.

**Selection of Source Light and Reflected Light**

To study anthropological materials using the moiré method, we must choose a technique which, on one hand, produces moiré fringes on the subject material and, on the other hand, records them. The key factor here is the selection of an appropriate light source.

Fig. 2 schematically shows two different methods of producing moiré fringes; one using a single point light source and the other a parallel light source. These two methods are compared in Table 1. The depth of moiré fringe contours for (A) and (B) are calculated using the following formulae.

(A) The one point light source method:

\[
\frac{PS}{BC} = \frac{SA}{BA} = \frac{SA}{BA} = \frac{(l+h_1)}{h_1} \]

\[
d:s=(l+h_1):h_1 \]

\[
h_1 = \frac{s*l}{d-1*s} \]

\[
h_N = N*s*l/(d-N*s) \]

N is the number of the fringe order counting from the grating.

(B) The parallel light source method:

\[
h_0 = s*cot\theta \]

Abbreviations are indicated in Fig. 2. To calculate the depth of moiré fringes using method (A), four parameters, \(N\), \(l\), \(d\), and \(s\) are needed. The depths, furthermore, increase relative to the number of fringes. Method (B), in contrast, requires only two parameters, \(s\) and \(\theta\). The depth of every contour is equal. TAKASAKI (1970, 1973) and TERADA (1973) described moiré fringes produced with non-collimated light when they described the application of the method to large materials such as living human body. THEOCARIS (1966) and TERADA & IKEDA (1979) produced moiré fringes using parallel beams of light. They applied their method only to small materials. OKAZAKI et al. (1978) produced moiré fringes on a television display screen by using electrical interference. The method appropriate for each individual case must be decided by the each researcher.

Anthropological research, in general, deals with relatively small objects. The parallel light source method is more appropriate for

<table>
<thead>
<tr>
<th>Method</th>
<th>Projecting light</th>
<th>Position of recording system</th>
<th>Reflected light</th>
<th>Fringe contour</th>
<th>Subject size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel light</td>
<td>Parallel</td>
<td>Not limited (as far as possible)</td>
<td>Nearly parallel</td>
<td>Nearly constant</td>
<td>Limited by the field lens</td>
</tr>
<tr>
<td>One point light</td>
<td>Divergent</td>
<td>Limited (same distance as the light to the grating)</td>
<td>Convergent only</td>
<td>Not constant</td>
<td>Limited by the grating size</td>
</tr>
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</table>

Table 1. Comparisons of two different light source methods of producing the moiré fringes; one point light source and parallel light source. For small subject materials parallel light source method is much appropriate.
Fig. 3. Two recording systems of parallel light source moiré fringes.

(A) The recording system consists of the short focal length lens, i.e. normal lens. The measurement on obtained moiré pictures are greatly effected by their depths from the focusing plane.

(B) The recording system consists of the long focal length lens. The measurement on obtained moiré pictures are not so much effected by their depths. The apparatus explained in this report uses this long focal lens system.
studying such small objects as skulls, innominate bones and scapulae. Moiré fringes produced by this method have contours with constant depth and relatively darker shadow. The apparatus, furthermore, is simple and small. It can, therefore, be easily transported. The moiré pictures obtained by the one point light source method could have constant depth contours by post-processing in experimental studies (SUZUKI & SUZUKI 1976, MURAKAMI & TERADA 1981, FUJISAKI et al. 1982). Their original pictures, however, cannot have real information of the subject materials, i.e. the each moiré fringe does not have same linear distances. The recording system with a short focal length lens heavily influenced the measurement on their pictures (TAKAYAMA 1980). And it takes too much processing time when micro-computers are used to analyse their moiré fringes. Thus, there are almost none of anthropological or osteological analyses using the processed moiré data in my available references.

A second important consideration in using the moiré method is the selection of the reflected light, i.e. the recording system. If we select an appropriate parallel light source but give no thought to the reflected light caught by recording system, there will be no marked improvement in anthropological measurement even when the moiré method is used. Fig. 3(A) and 3(B) illustrate variations in results when two different recording systems were used with the same parallel light source moiré method. Fig. 3(A) illustrates results obtained using a recording system comprised of a short focal, (i.e. normal) lens, and a 35mm camera. This recording system cannot give the identical depth of the moiré fringes so that they appear irregular: the upper portion of fringes become smaller than the actual and the lower of them become larger. The long focal lens system of Fig. 3(B), on the other hand, can approximately record moiré fringes at identical depths. The anthropological researcher who wants to study small materials precisely, therefore, will prefer a recording system with a long focal lens.

**Design of Apparatus**

The purpose of my research was to examine the human skull, therefore, the objects studied were all relatively small. The method using a parallel light source seemed most appropriate. This method has several advantages over other moiré methods such as, for example, the one point light source method described above. There remain, nevertheless, many problems in the anthropological application of the moiré apparatus. Table 2 outlines possible problems which may be encountered when using the moiré method and describes adaptations and improvements that have been made on the parallel light source moiré method to make it more suited to analysing human skulls. The first problem encountered when using the moiré method to measure human skulls is to obtain a photograph with measurement within the permissible error limits (the permissible error limits of manual measurements in craniology is usually less than 1%). A second problem is that photographs of the moiré fringes and the skull must have complete optical information and must, at the same time, produce clear and bright moiré fringes. A third difficulty is that skulls must be fixed in the same standard and determined co-ordinates systems so that the moiré fringes can easily be analysed on photographs. Finally, the apparatus must be small enough to allow easy transport and
Table 2. Possible problems and necessary conditions and adaptations and improvements in designing and producing parallel light source moiré apparatus

<table>
<thead>
<tr>
<th>Parts</th>
<th>Possible problems and conditions</th>
<th>Adaptations and improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producing of moiré fringes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light source</td>
<td>Smallest as a pin-hole Brightest and most luminent as sunlight</td>
<td>Carbon short arc light</td>
</tr>
<tr>
<td>Producing parallel light</td>
<td>Optical linearity of field lens—light source Abbreviation of field lens</td>
<td>Standard rail for photo-elasticity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Riken rail)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Produced specially</td>
</tr>
<tr>
<td>Direction of projecting light</td>
<td>Reflecting mirror Measurement of projecting light angle</td>
<td>Normal glass mirror Protractor</td>
</tr>
<tr>
<td>Grating</td>
<td>Parallellity and plane stability of the surface of the gratings</td>
<td>Produced specially</td>
</tr>
<tr>
<td></td>
<td>Obstruction of the grating threads</td>
<td>Non-glared black cotton threads</td>
</tr>
<tr>
<td>Recording of moiré fringes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skull fixer</td>
<td>Many mobile parts to fix the skull to the co-ordinates axes</td>
<td>Produced specially</td>
</tr>
<tr>
<td>Co-ordinates indicator</td>
<td>Always indicates spatial three-dimensional co-ordinates axes</td>
<td>Produced specially</td>
</tr>
<tr>
<td>Recording system</td>
<td>Perspective errors caused by the field angle (focal length) of the lens</td>
<td>800 mm focal length lens and 35 mm camera (the field angle of the lens is 1.2&quot;)</td>
</tr>
</tbody>
</table>

ree-construction, since the institutes and museums which contain fossil specimens are scattered in relatively inaccessible areas around the world.

When making improvements on the moiré apparatus so that a parallel light source can be used, I took all of these problems into consideration. Fig. 4 shows the design chart of the moiré apparatus and its recording (photographing) system. The whole apparatus occupies a space which is 250 cm in length (L) × 150 cm in width (B) × 200 cm in height (H). The 35 mm camera used for recording must be located at least 1200 cm from the main apparatus. The actual working space for the apparatus, therefore, is 350 cm in length (L), 250 cm in width (B), 300 cm in height (H), plus a 1200 cm corridor. The moiré apparatus is composed of five working parts; A) the light source, B) the parallel light producing unit, C) the reflecting mirror, D) the grating, and E) the skull fixer and the standard co-ordinates indicator. The features of these working parts which were specially designed for my research are described below.

A) The light source: The light source must be as small and bright as possible. Readily, available standard lamps are filamental and are not bright or intense enough to make a pin-hole point. I, therefore, used a carbon shoot arc lamp as a light source. Two carbon rods provide luminescence by electric shots. Light from this source resembles sunlight, in both brightness and luminescence.

B) The parallel light producing unit: The purpose of the condenser lens is to force the convergence of light. When the lens is used the light remains stable despite any expansion or vibration of the light source resulting from the shrinking of the carbon rods. The condenser lens is 150 mm in diameter and has a focal length of 150 mm.
Fig. 4. Fundamental design chart of the moiré apparatus and recording system produced in this report. Abbreviations in the chart are SX: skull fixer, L: light source, C: condenser lens, F: field lens, M: reflecting mirror, G: grating for moiré producing and R: the recording system with long focal length lens.
Fig. 5. Design charts of the skull fixer (FX) and the co-ordinates indicator (CD). (A) is in the horizontal view and (B) is in the vertical view. Numbers in the charts show the movable parts of the instruments: (1) shows the two plates move obliquely in the rectangular direction, (2) shows that the main shaft moves vertically in straight, (3) shows that the main discoid plate moves horizontally in round, and (4) shows that the upper parts of the fixer move horizontally to each rectangular directions.
The field lens has the important function of determining the moiré fringe boundary and the object’s size. The field lens is 275 mm in diameter and has a focal length of 800 mm.

C) The reflecting mirror: The mirror I used was a standard optically flat polished glass mirror; the kind normally used as household furniture. I also considered special use mirrors, for example, silver coated surface mirrors and metallic surface mirrors. Surface mirrors, however, are affected by moisture, temperature changes, and physical shocks. Normal polished glass mirrors are quite satisfactory when using a parallel light source.

D) The grating: The grating is one of the most important parts of the apparatus. The period of the grating is 1 mm. Measurement was made using a stainless steel (JIS 1st standard) serrated edge measure. The threads of the grating are made of black non-glare cotton. I did consider using black coated threads made of synthetic resin. But since they can neither be fixed on a flat plane nor make the grating constant equal, I rejected them.

E) The skull fixer and standard co-ordinates indicator: This part is characteristic of and essential to this particular moiré apparatus. The moiré apparatus usually used for anthropological analysis is designed to make moiré fringes appear clearly and brightly on the materials. Unfortunately, when this is done the detailed analysis of the moiré fringes themselves and the materials upon which they are produced tends to be ignored. My plans when designing the apparatus were to study moiré fringes on human skulls. In my research, therefore, a skull upon which moiré fringes are produced is first fixed in the standard co-ordinates system and then photographed with the visible co-ordinates axes.

Fig. 5 shows the design chart of the skull fixer. CD in Fig. 5 is an apparatus determining the standard co-ordinates system. This apparatus is composed of a large and a small square scale which intersect each other making two perpendicular planes. FX in Fig. 5 is the skull fixer which positions the skull in the co-ordinates system. The fixer has many mobile portions. This allows the flexibility necessary to fix the skull in the co-ordinates. These two apparatus, the co-ordinates indicator and the skull fixer, are used together to set the moiré fringes and skull in the standard co-ordinates system.

All of these parts function independently. When setting in the iron frames they comprise the moiré apparatus. The frames can be dismantled and reconstructed easily in about 1-2 hours.

Recording System

I already discussed and explained the photographic recording system and its problems (TAKAYAMA 1980). In this report I concluded that acceptable craniological data can be obtained from photographs taken with a 35 mm camera using a field angle of under 2 degrees, and focal length of over 800 mm. Notice that I use an 800 mm focal length lens on a 35 mm camera positioned in a stand with both horizontal and vertical fine adjusters. This system is schematically shown in Fig. 4.

The resulting negatives are enlarged using poly-ester-thick base lith films and copy films. These kinds of films are normally used by design artists in graphic art, or by architects for their design charts. The use of these special films decreases the number of errors resulting from temperature, moisture and chemical stress. This is because they are
more stable than the plastic coated paper, or the normal plastic base films ordinarily used to develop positive photographs.

**Examples Recorded by This Apparatus**

Moiré photographs taken by this apparatus are shown in Fig. 6. Skulls in these photographs were positioned on the Frankfort horizontal plane which coincides with optical axis of the recording system. These pictures of moiré fringes are not so clear and distinct, because it is so long a distance that a long focal length lens needed and the floating and dispersing dust in the air caused the reflected light obscure. I also consider to move the grating as suggested by TAKASAKI (1970), but I cannot design the portable apparatus which can move the grating constantly and kill the vibration of threads. The moiré fringes of these pictures, however, are exact contours on the skull which have approximately identical depths.

**Summary**

In this report I discussed potential applications of the moiré method to anthropological craniology, and described the construction of the parallel light source moiré apparatus and the function and special characteristics of its parts. My discussion can be summarized as follows.

1) A moiré method which uses a parallel light source is best suited to analysing small objects, particularly the human skull. (Fig. 1, Fig. 2, Table 1) Also the system which catches the reflected light of moiré fringes is very important for the anthropological measurement. (Fig. 3) The record system

**Fig. 6.** This photograph shows that the subject skull completely fixed in the skull fixer and that we can read the co-ordinates axes including the Frankfort plane by the right and left vertical indicators. Sample skulls are (A); Japanese neolithic Jomon female (Tsukumo No. 19), (B); the plastic cast of male chimpanzee.
of the reflected light is described in 4).

2) The apparatus I designed was specifically aimed at studying the human skulls. The specially designed working parts of the apparatus are the parallel light source, the grating, and the skull fixer and co-ordinate indicator. (Fig. 4, Table 2) The light source, the reflecting mirror, and the iron frame which comprise the apparatus are particularly important when examining skulls. The iron frame is easily dismantled and reassembled.

3) The skull fixer and the co-ordinates indicator are specially designed parts which were carefully planned and produced. (Fig. 5) Using these parts we can take a photograph of the skull covered with moiré fringes. For photographing, the skull was fixed on the Frankfort horizontal plane which coincides with the optical axis of the recording system. Of the axes which comprise the spatial co-ordinates, the horizontal is clearly shown in the photographs. Thus, the moiré fringes on the skull surface are the same as the anthropologically defined coronal sections of the skull.

4) The recording (photographing) system is composed of a 35 mm camera fitted with an 800 mm focal length lens with field angles of under 2 degrees. (Fig. 4) I used non-elastic films such as poly-ester-thick base lith films and copy films. In my experience these film bases neither expand nor contract when exposed to various physical and chemical conditions.

5) Using this specially designed apparatus and the recording system, it is possible to take a photograph of the moiré fringes on a human skull with a data of accuracy under 1%. This accuracy is same as that of manual measurement normally used for anthropological research. (Fig. 6)

Acknowledgments

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モアレ線は干涉線の一種で、平面におけるモアレ線を2つの同一直線の重なりあいとして示した図がFig. 1(A)である。これは微小な角度差の検証などに利用されている。同じくFig. 1(B)は、平行に並ぶ格子によってできた物体表面の等高線としてのモアレ線を、模式的に示している。このような光学的なモアレ線を実物の格子を用いて発生させる方法は、大きく分けて2つある。それぞれ用いる光学によって、点光源法（一点照射法）、平行光線法（平行光照明法）と呼ばれている。両者の理論図は、Fig. 2の(A)、(B)に示した。また、両者の判点・欠点については、Table 1に表として比較した。視野レンズを拘束されることを除けば、平行光線法の方が、小標本に対して有利な点が多いことがわかる。従って、本研究では、平行光線を光源として用いることにした。さて、光源を平行にしても、撮像系（記録系）が、平行光を捕らえ得なければ、平行光線によるモアレ線は意味を失う。これを、模式的に示したのが、Fig. 3(A)、(B)である。3(A)のように短焦点レンズ（標準レンズ）を用いると、得られるモアレ線は平行光を記録していないことにならない。3(B)のように長焦点レンズを用いると、平行光に近い形でモアレ線の記録写真が得られる。本研究では、撮像系（記録系）として、800 mm レンズを装着した35 mm判カメラを用いた（TAKAYAMA, 1980）よれば、このような超遠望レンズによる標本写真は、人類学の計測に影響するようなパースペクティブの誤差はほとんどふくまれない。

これらモアレ線発生・記録に伴う問題点、必要とされる条件、それに対する理論、装置の改善点、考慮した点をTable 2に、装置の各部分別に比較して示した。これらを全て組み合わせた状態の図が、Fig. 4である。このうちで、対象物体の固定に伴う。本研究では特に頭骨のための頭骨架台を座標軸決定装置を新たに設計・作製した。座標軸決定装置は、2台のスコヤ（直角検定器）を直角に組んで作られている。頭骨架台は、種々の方向に細かく動かすことが可能で、平面決定装置が指示する平面に頭骨を移動し固定することが容易に行なえるようになっている。この2つの装置を組み合わせた図が、Fig. 5である。

今回開発したモアレ線発生・記録装置によって得られる頭骨のモアレ線写真の実例を、Fig. 6に示した。頭骨上に表れたモアレ線は、間隔2 mmの等方線としてある。これらのモアレ線写真は、実物大に引き伸ばした写真上で計測を行なっても、その誤差は実際の標本上で行なう計測の誤差とほとんど差が無い。

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