History of Moiré
~ Applications to Shape, Deformation and Strain Measurement ~

Yoshiharu MORIMOTO (Harry Moiré)
Professor Emeritus at Wakayama University
Moiré Institute Inc., Osaka, JAPAN
4D Sensor Inc., Wakayama, JAPAN
morimoto@4d-sensor.com

Motoharu FUJIGAKI *(University of Fukui, Japan)*
Shien RI *(AIST, Japan)*

American Indian (Hopi) Pottery

His story of Harry Moiré
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Harry Moiré

History of Moiré Method ~ Applications to Shape, Deformation and Strain Measurement ~

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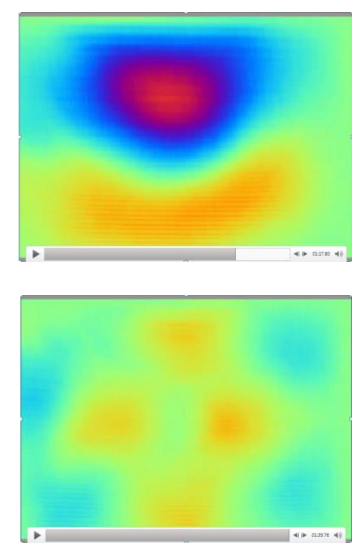

Vibration mode

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Harry Moiré

My dream in my childhood

- Same birthday as Thomas Edison
  →Inventor
- Same handicap as Hideyo Noguchi

→Scientist

Big inventor or
Scientist

His story of Harry Moiré

1944 Born in **Osaka, Japan**
1968 Graduated Master Course of **Osaka University**
1968 **Komatsu MFG**, Researcher
1974 Faculty of Engineering Science, **Osaka University**
1989-1990 Visiting Professor of **Virginia Tech** (VPISU)
1993 Faculty of Economics, **Wakayama University**
1995 Faculty of Systems Engineering, WU
2004 Executive Board (Vice-president) , WU
2009 Established **Moiré Institute Inc.** (Representative director)
2012 Established **4D Sensor Inc.** (Chairman)

Research by Harry Moiré

1965 Photoelasticity, Moiré method
1966 Stress wave propagation analysis by
photoelasticity and high-speed camera
1968 Finite element method
1974 Powder compaction & impact phenomena
1980 Image processing
1984 Scanning moiré by TV

:

:

:

Accomplished research

Optical methods and image processing for shape, deformation, and stress and strain measurement.

1) **Scanning moiré method**, phase-shifting scanning moiré method
2) Phase analysis methods using **Fourier, wavelet and Gabor** transforms
3) **Strain rate distribution** measurement by original **high-speed video** camera
4) Real-time phase analysis by **Integrated phase-shifting method**
5) Shape measurement by **frequency modulated grating** projection
6) Real-time analysis of **photoelasticity** and **moiré interferometry**
7) Shape measurement by **multi-reference planes**
8) Subnanometer displacement measurement by windowed phase-shifting digital **holographic interferometry**

Current research

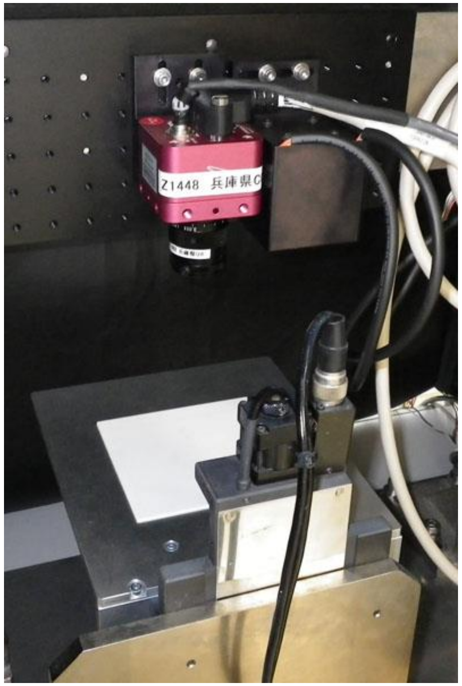
Development of high-speed, highly-accurate and low cost measurement systems using some optical methods and image processing for shape, deformation, and stress and strain measurement

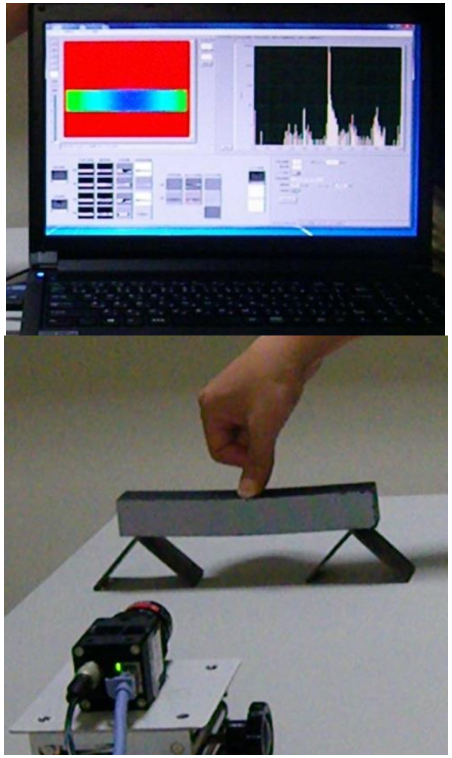
1) Grating projection method using whole space tabulation method (Shape)
2) Grating projection method using LED line light sources (Shape)
3) Sampling moiré method (Displacement and shape)
4) One-Pitch Phase Analysis (OPPA) method (Shape and displacement)

4D Sensor Inc., Wakayama

Venture Company generated from WU

Products





3D camera **4D camera** **Shadow moiré camera** **Sampling moiré camera**

High-speed. high accuracy, compact and low price

Academic Societies for Exp. Mech.

1847 Institution of Mechanical Engineers

1880 American Society of Mechanical Engineers

1916 Optical Society of America

1941 American Society for Non-destructive Testing

1943 (1985) Society for Experimental Mechanics (SESA, SEM)

1955 International Society for Optical Engineering (SPIE)

1959 (1998) European Association for Experimental Mechanics (EURASEM)

1964 British Society for Strain Measurement (BSSM)

Academic Societies for Exp. Mech. in Japan

1879 Japan Society of Civil Engineers
1886 Architectural Institute of Japan
1897 The Japan Society of Mechanical Engineers
1933 The Japan Society for Precision Engineering
1934 The Japan Society for Aeronautical and Space Sciences
1952 The Japanese Society for Non-Destructive Inspection
1952 The Optical Society of Japan
1952 The Society of Materials Science, Japan
1975 Japanese Society for Moiré Contourography
1979 (2001) The Japanese Society for Experimental Mechanics (JSP, JSEM)

Int. Conf. on Exp. Mech.

- XIII SEM Int. Congress 2016 (SEM, every four years)
- International Conference on Experimental Mechanics ICEM 17 (2016). (EURASEM, every four years →every two years)
- The 14th Asian Conference on Experimental Mechanics (ACEM14) (ACEM→ASEM, every year)
- The International Conference on Advanced Technology in Experimental Mechanics 2015 (JSME, every two years→every four years in ACEM)
- 10th International Conference on Advances in Experimental Mechanics (BSSM, every two years)
- The 10th International Symposium on Advanced Science and Technology in Experimental Mechanics (JSEM, Every year)
- 30th DANUBIA-ADRIA, SYMPOSIUM ON ADVANCES IN EXPERIMENTAL MECHANICS (every year)

History of ATEM and ACEM

- ATEM organized by JSME-MMD
- 1st ATEM, Kanazawa, 1993 (Miyano)
- 2nd ATEM, Tokyo, 1995 (Takashi)
- 3rd ATEM, Wakayama, 1997 (Morimoto)

  :

- SEM &ICEM
- Big conf. in Asia
- To adjust, certify and support

- Asian Liaison Committee on Exp. Mech. (ACEM) established in 1997
- Asian Conference on Experimental Mechanics (ACEM) organized by Asian Committee for Experimental Mechanics (ACEM)
- 1st ACEM, Taipei, 2002
- 2nd ACEM, Nagoya, 2003
- 3rd ACEM, Singapore 2004

  :

- Asian Conference on Experimental Mechanics (ACEM) was renamed as Asian Society for Experimental Mechanics (ACEM) in Singapore, 2009

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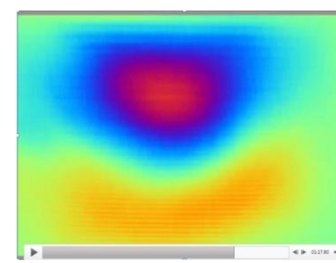
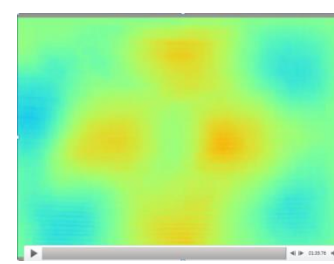
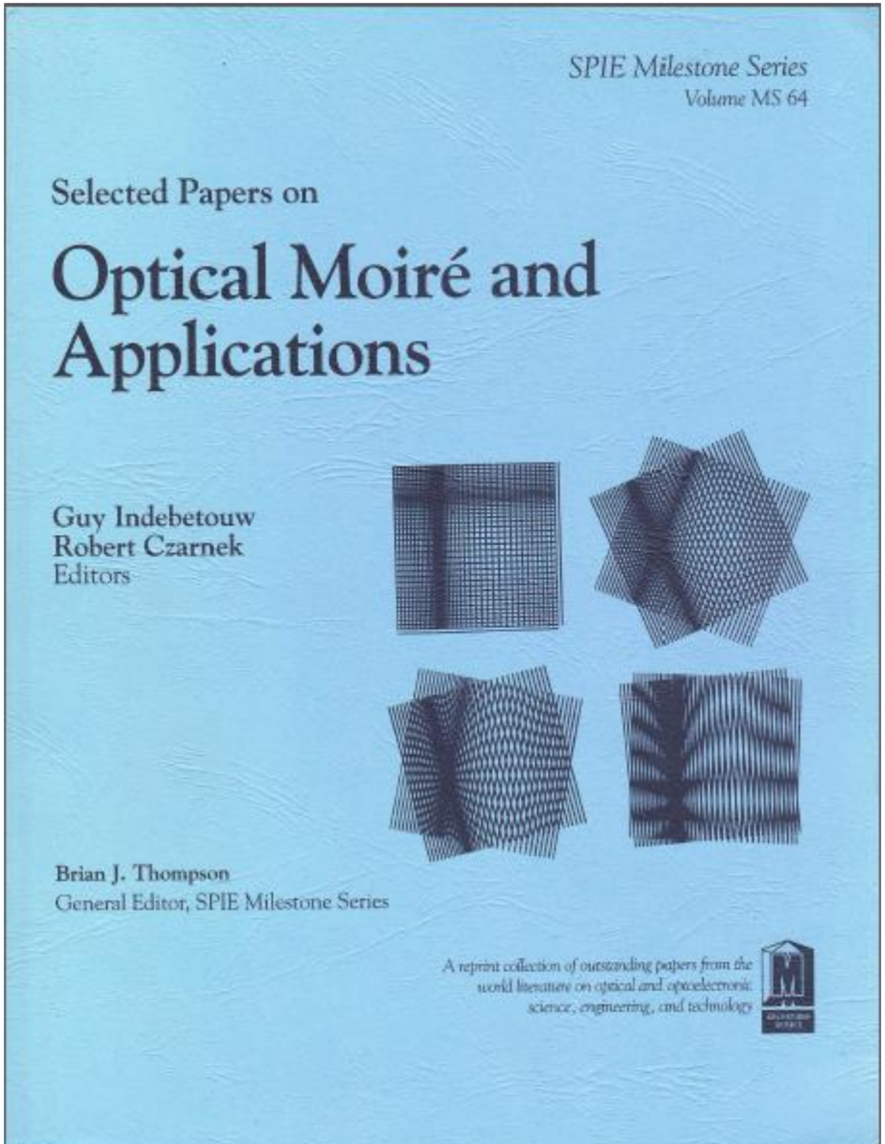




Vibration Mode

Historical review of moiré method



Selected Papers on Optical Moiré and Applications

Editor(s): Guy J. M. Indebetouw; Robert Czarnek, 1992

92 papers from 1874-1984
648 pages

Spie Press Book • on sale

Member Price	$85.00 ~~$100.00~~
Non-Member Price	$100.00 ~~$118.00~~

Historical review of moiré method

(There are too many important other papers)

- 1874 Rayleigh
- 1948 Weller & Shepard
- 1956 Guild
- 1967 Sciammarella & Sturgion
- 1968 Chiang, Parks & Durelli
- 1969 Theocaris
- 1970 Takasaki
- 1971 Post
- 1971 Hovanesian & Hung
- 1974 Bruning et. al.
- 1977 Idesawa, Yatagai & Soma
- 1982 Takeda, Ina & Kobayashi

- 1874 Manufacture and theory of diffraction-gratings
- 1948 Displacement measurement
- 1956 Moiré interferometry
- 1967 Multiplication and digital filtering
- 1968 Moiré-fringe interpolation and multiplication
- 1969 Isopachics (Shadow moiré)
- 1970 Moiré topography
- 1971 Moiré fringe multiplication
- 1971 Moiré contour-sum contour-difference, and vibration
- 1974 Phase-shifting method
- 1977 Scanning moiré method
- 1982 Fourier-transform method

On the manufacture and theory of diffraction-gratings, **Lord Rayleigh** (London, Edinburgh, and Dublin Philosophical Magazine 1874 & 1881)

Digital wavefront measuring interferometer for testing optical surfaces and lenses

J.H. Bruning, D.R. Herriott, J.E. Gallagher, D.P. Rosenfeld, A.D. White, D.J. Brangaccio (Applied Optics 1974)

Japanese papers from Selected Papers on Optical Moiré and Applications

92 papers, Editor(s): Guy J. M. Indebetouw; Robert Czarnek, 1992

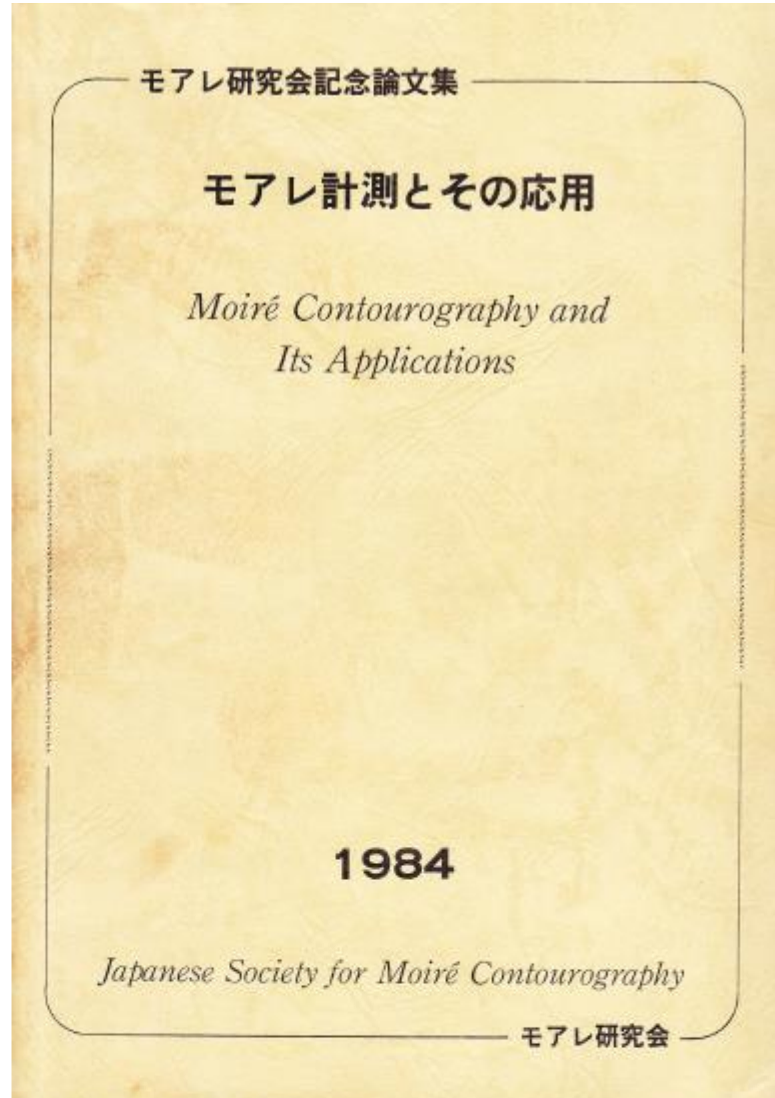
- A new type of interference fringes observed in electron-micrograph of crystalline substance **T. Mitsuishi**, H. Nagasaki, R. Uyeda (Proceedings of the Japan Academy 1951)
- Moiré patterns: their application to refractive index and refractive index gradient measurements **Y. Nishijima**, G. Oster (Journal of the Optical Society of America 1963)
- Moiré patterns G. Oster, Y**. Nishijima** (Scientific American 1963)
- Interferometric generation of contour lines on opaque objects **T. Tsuruta**, Y. Itoh (Optics Communications 1969)
- Moiré topography **H. Takasaki** (Applied Optics 1970)
- Interpretation of the moiré method for obtaining contours of equal slope from an inteferogram **S. Yokozeki**, T. Suzuki (Applied Optics 1970)
- Shearing interferometer using the grating as the beam splitter **S. Yokozeki**, T. Suzuki (Applied Optics 1971)
- Shearing interferometer using the grating as the beam splitter. Part 2 **S. Yokozeki**, T. Suzuki (Applied Optics 1971)
- Moiré topography by means of a grating hologram **Y. Yoshino**, M. Tsukiji, H. Takasaki (Applied Optics 1976)
- Scanning moiré method and automatic measurement of 3-D shapes **M. Idesawa,** T. Yatagai, T. Soma (Applied Optics 1977)
- Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry **M. Takeda**, H. Ina, S. Kobayashi (Journal of the Optical Society of America 1982)
- Interactive fringe analysis system: applications to moiré contourogram and interferometry T**. Yatagai**, M. Idesawa, Y. Yamaashi, M. Suzuki (Optical Engineering 1982)

Historical topics of moiré in Japan

1975 Establishment of Japanese Society for Moiré Contourography

1984 Book Publishing of Moiré Contourography and Its Applications : 10th Annual Meeting : Selected Papers and Abstracts, Japanese Society for Moiré Contourography (in Japanese)

59 papers from 1970-1984, 474 pages



Moiré Contourography and Its Applications:

10th Annual Meeting : Selected Papers and Abstracts, 1984

Japanese Society for Moiré Contourography (in Japanese)

Contents

A new type of interference fringes observed in electron-micrograph of crystalline substance

T. Mitsuishi, H. Nagasaki, R. Uyeda (Proceedings of the Japan Academy 1951)

Moiré patterns: their application to refractive index and refractive index gradient measurements, G. Oster, **Y. Nishijima** (Scientific American 1963)

Moiré patterns G. Oster, **Y. Nishijima** (Scientific American 1963)

Moiré topography
H. Takasaki
(Applied Optics 1970)

Scanning moiré method and automatic measurement of 3-D shapes,
M. Idesawa, T. Yatagai, T. Soma
(Applied Optics 1977)

Interactive fringe analysis system: applications to moiré contourogram and interferometry
T. Yatagai, M. Idesawa, Y. Yamaashi, M. Suzuki
(Optical Engineering 1982)

Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry
M. Takeda, H. Ina, S. Kobayashi
(Journal of the Optical Society of America 1982)

Current research by authors

Purpose

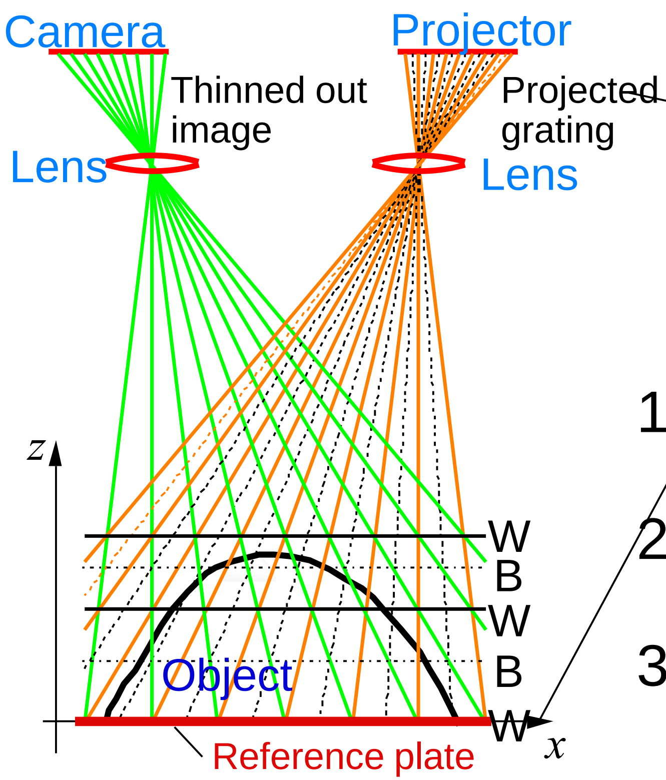
To develop high-speed, high-accuracy, compact and low-cost
Shape measurement systems for moving objects

- Grating method
- Moiré method

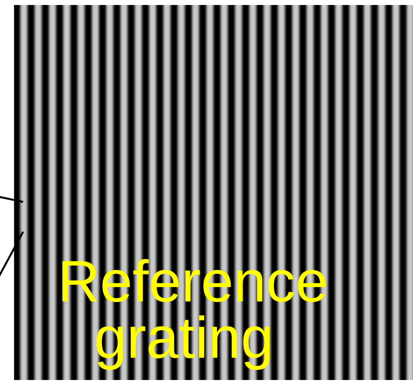
Techniques

- Phase shifting method
- Whole-Space Tabulation Method (WSTM)
- Light-source-stepping method
- Light-source-stepping shadow moiré method
- Sampling moiré method
- One-Pitch Phase Analysis (OPPA) method

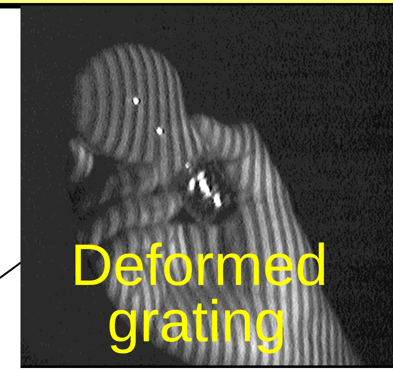
Procedure of shape measurement using grating projection method

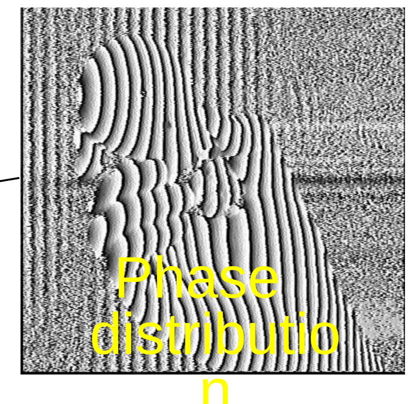


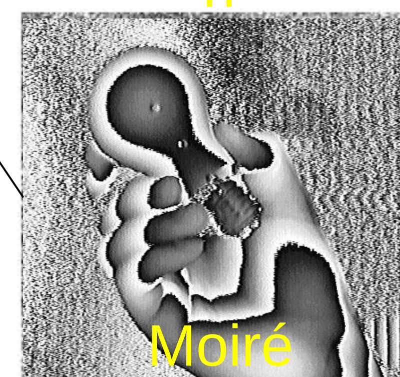
Moiré topography



1. Projected grating
2. Phase analysis
3. Phase difference between object and reference plane

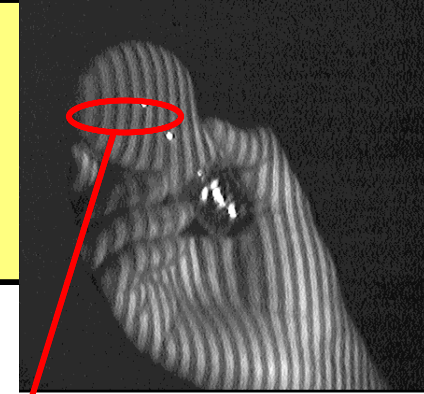






Lens, grating and image plane should be parallel to reference plane

Phase analysis of fringe or grating pattern



Intensity (Brightness)

$$I = a\cos\theta + b$$

a: Amplitude
θ: Initial phase
b: Background
} Unknown

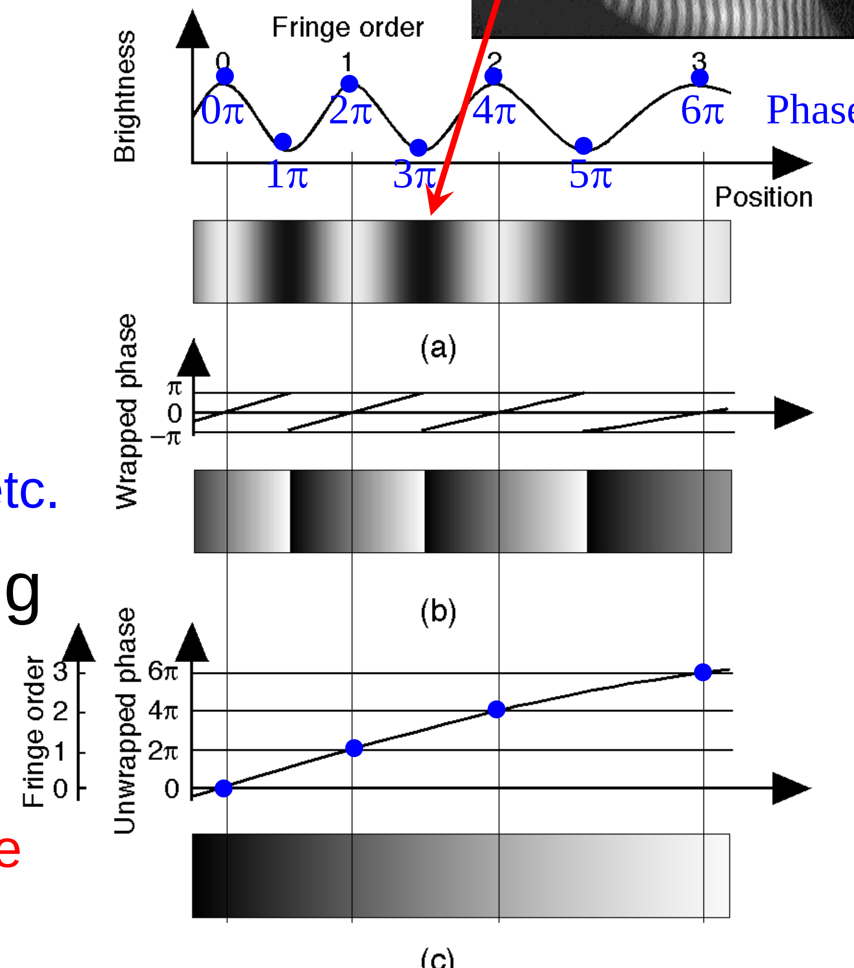
The phase θ of fringe or grating corresponds to displacement, height, etc.

Intensity during phase-shifting

$$I = a\cos(\theta + \alpha) + b$$

α: Phase-shift

- Phase analysis provides accurate shape (Resolution: 1/100~ 1/1000 of pitch)
- Unwrapping provides a large dynamic range.



Relationship between brightness and phase of grating pattern

Phase-shifting method using many images

Intensity (brightness) distribution

N : Number of grating or fringe images for one period

Phase-shift amount

$$\Psi = \frac{2\pi}{N} \qquad \alpha = n\Psi$$

N should be an integer.

Brightness of nth image

$$I_n = a\cos(\theta + n\Psi) + b$$

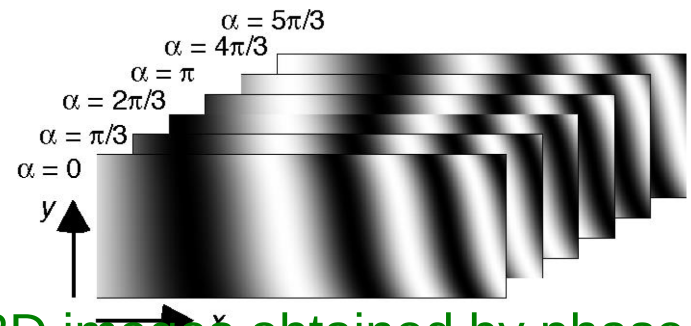
Initial phase θ

$$\tan\theta = -\frac{\sum_{n=0}^{N-1} I_n \sin(n\frac{2\pi}{N})}{\sum_{n=0}^{N-1} I_n \cos(n\frac{2\pi}{N})}$$

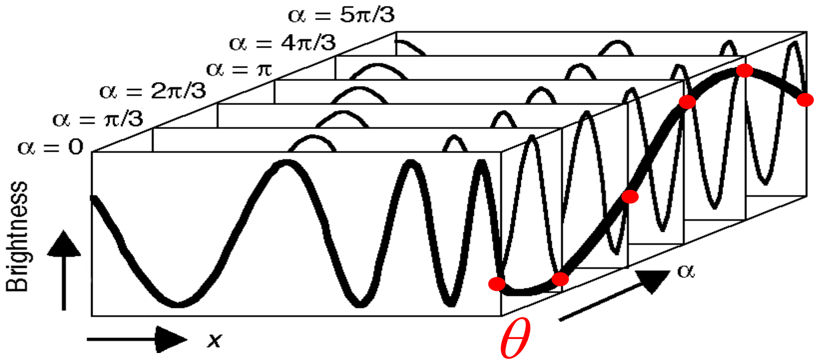
It corresponds to the extraction of frequency 1 of Fourier transform

(Smoothest wave extraction)

$$I = a\cos\theta + b$$



3D images obtained by phase-shifting



Brightness distribution and brightness change

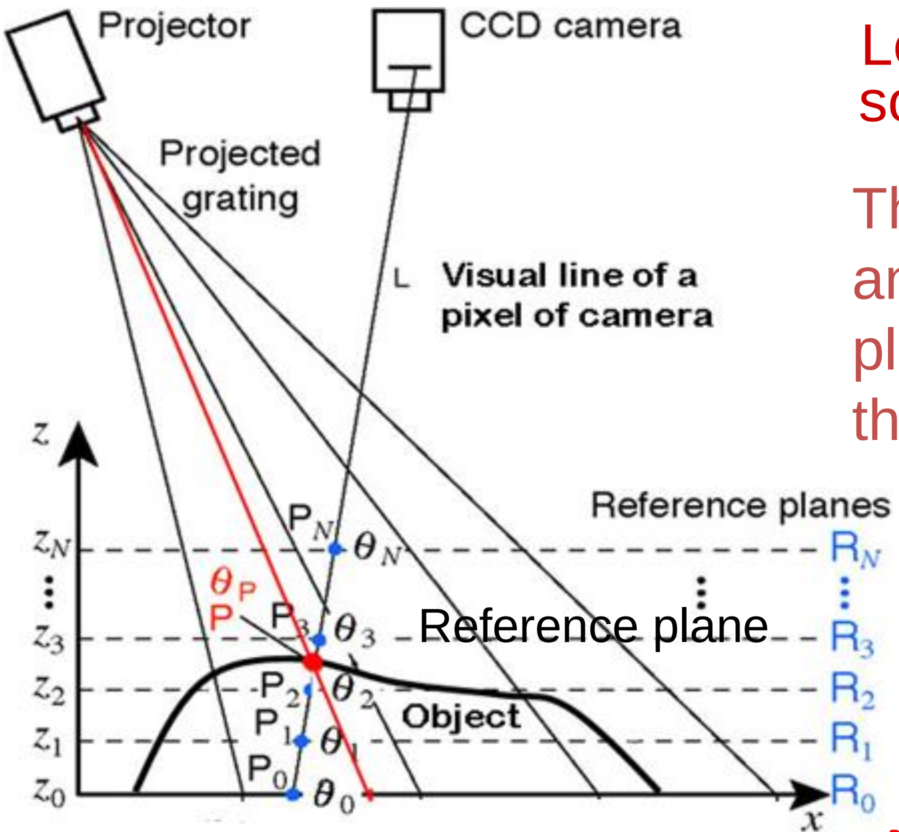
Usually, N=4 is used.

Large number of phase shifting provides accurate result. (N=16)

Whole-Space Tabulation Method (WSTM) for triangulation

The calculation of triangulation is time-consuming.

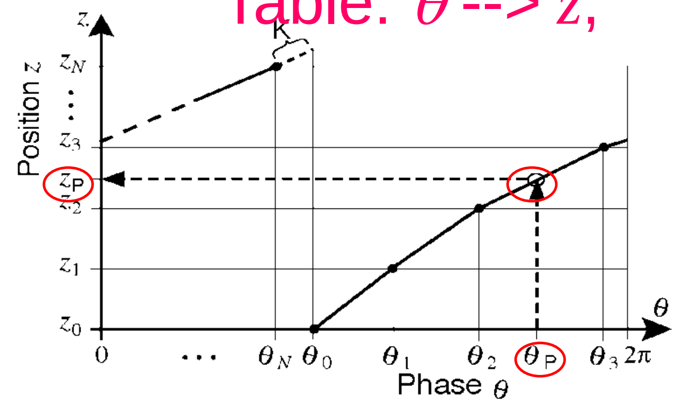
Lens, grating and image plane have some errors.



Triangulation optical system

The correspondence among phase θ and z coordinate on each reference plane can be obtained at each pixel of the camera.

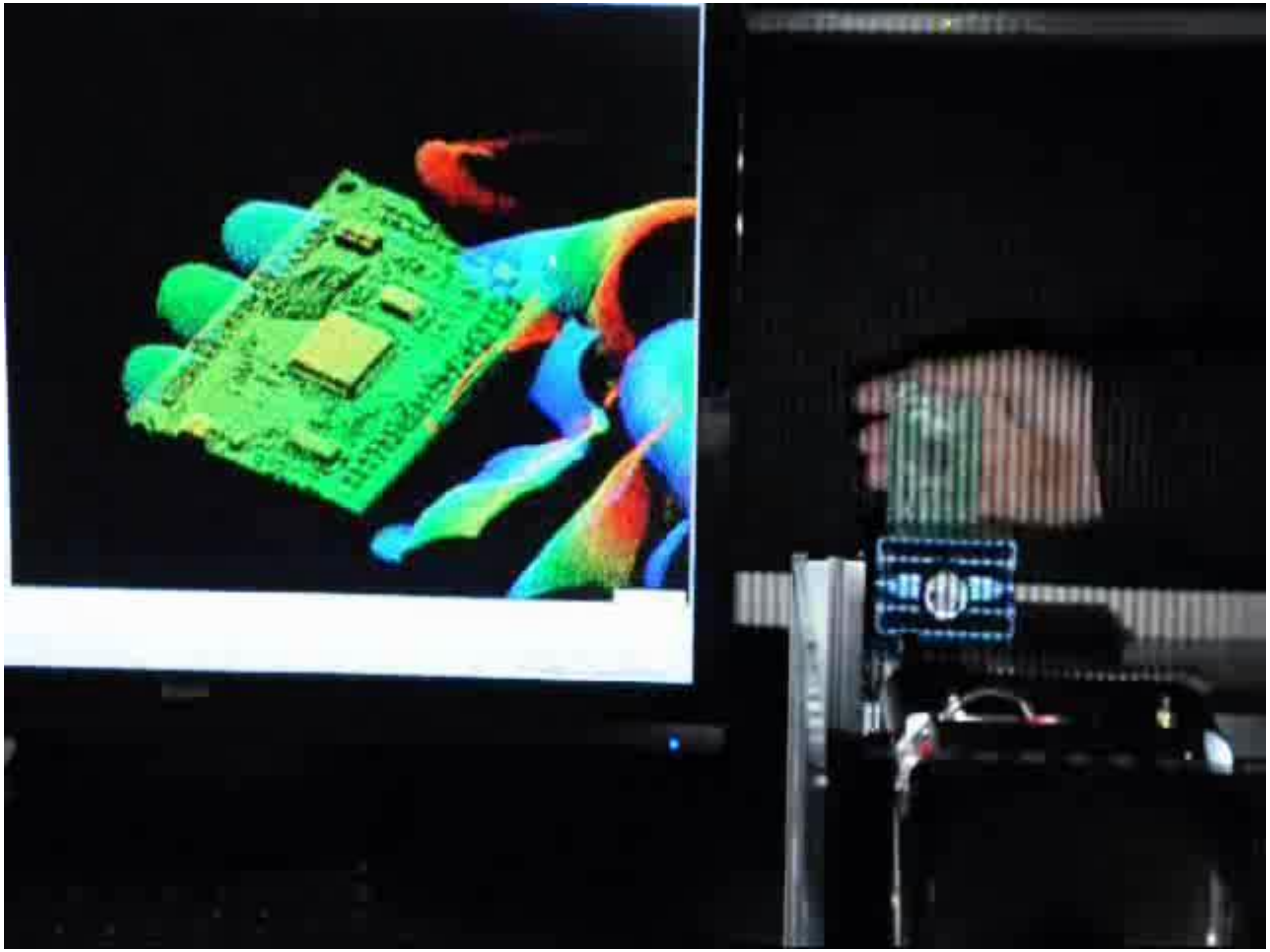
Table: θ --> z,



No calculation: High speed

Automatic error cancellation: High accuracy

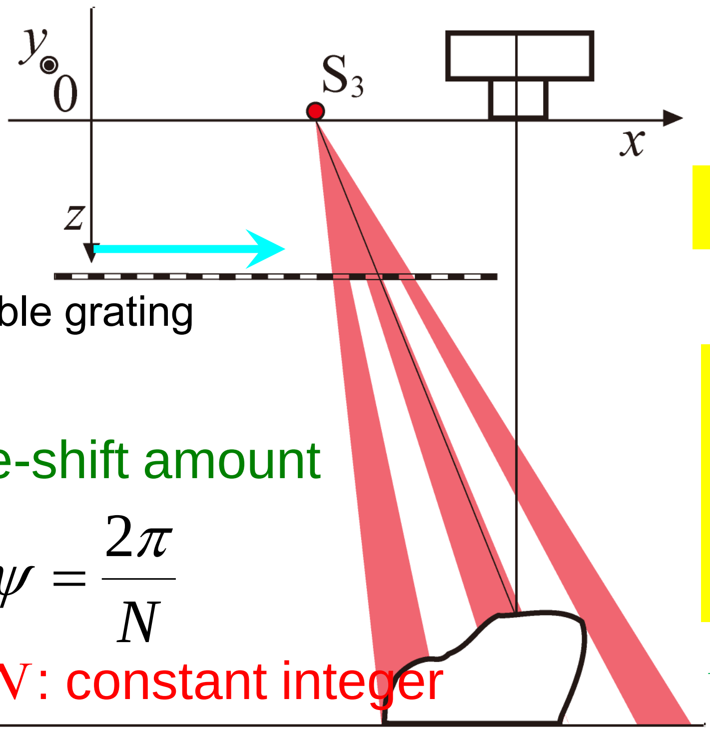
Examples of real-time shape measurements by whole space tabulation method



Light-source stepping method

Conventional projector

Phase-shifting method
using single light source



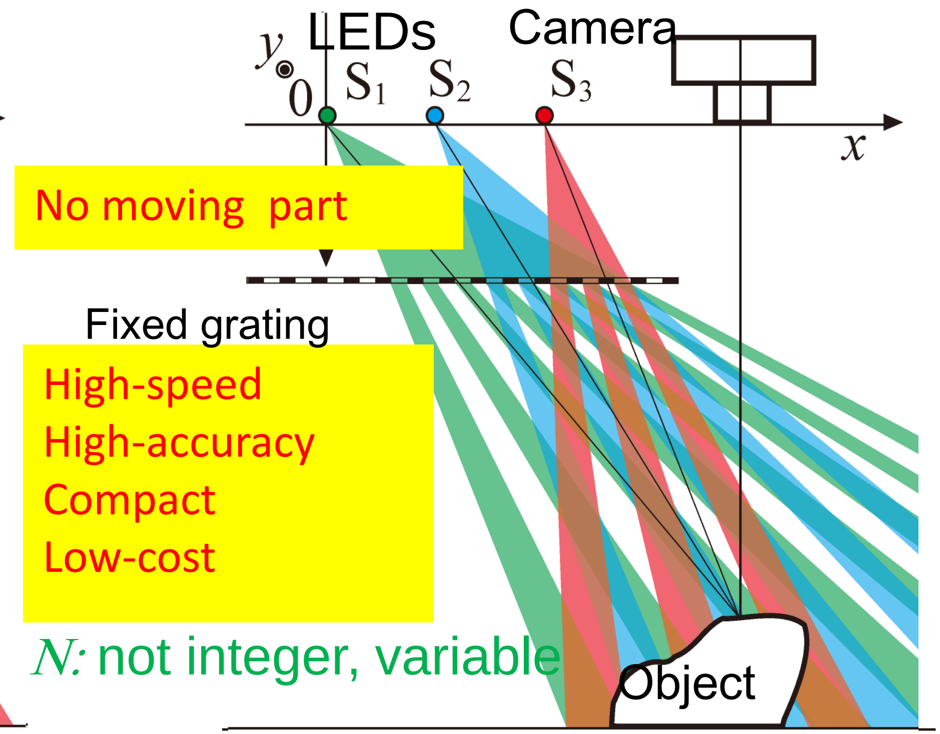
Phase-shift amount

$$\psi = \frac{2\pi}{N}$$

N : constant integer

Proposed projector using LEDs

Light-source-stepping method
using multi-light sources



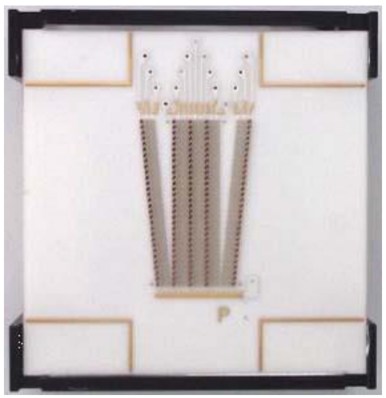
N: not integer, variable

4D camera (Light-source-stepping)

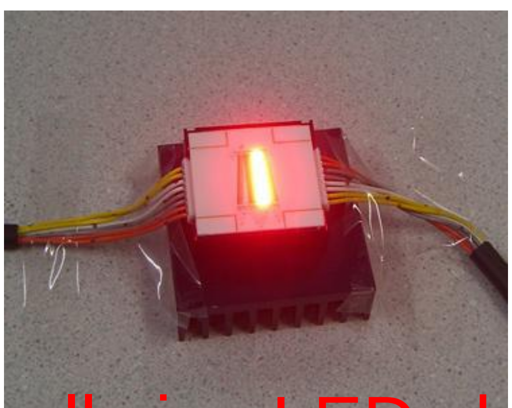
9-line for shape measurement

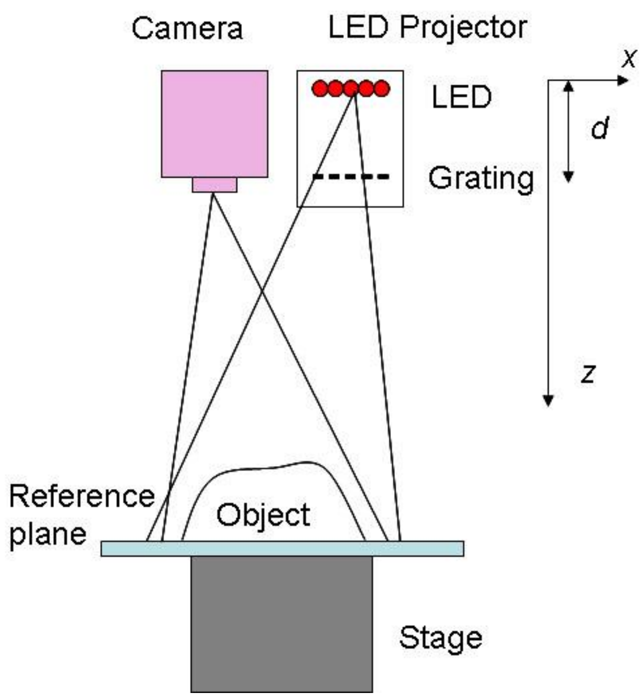
6-line for photograph recording

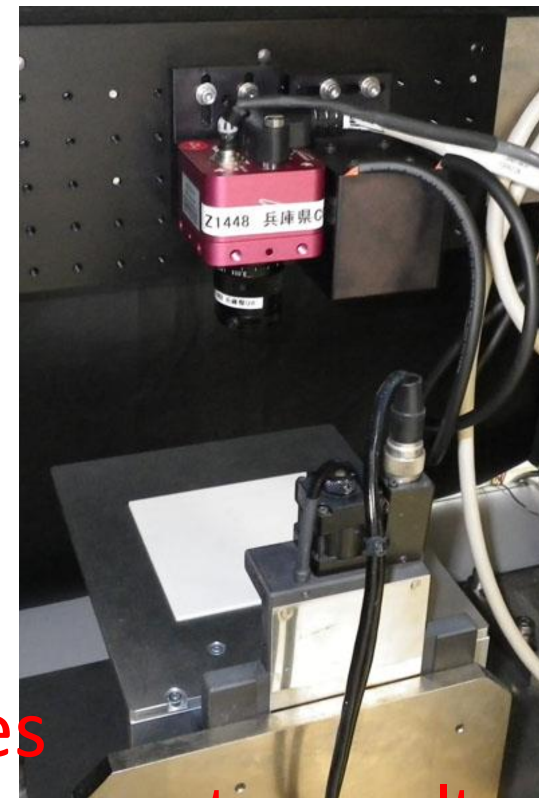
Each line has 30 chips with 350μm by 350μm



LED board



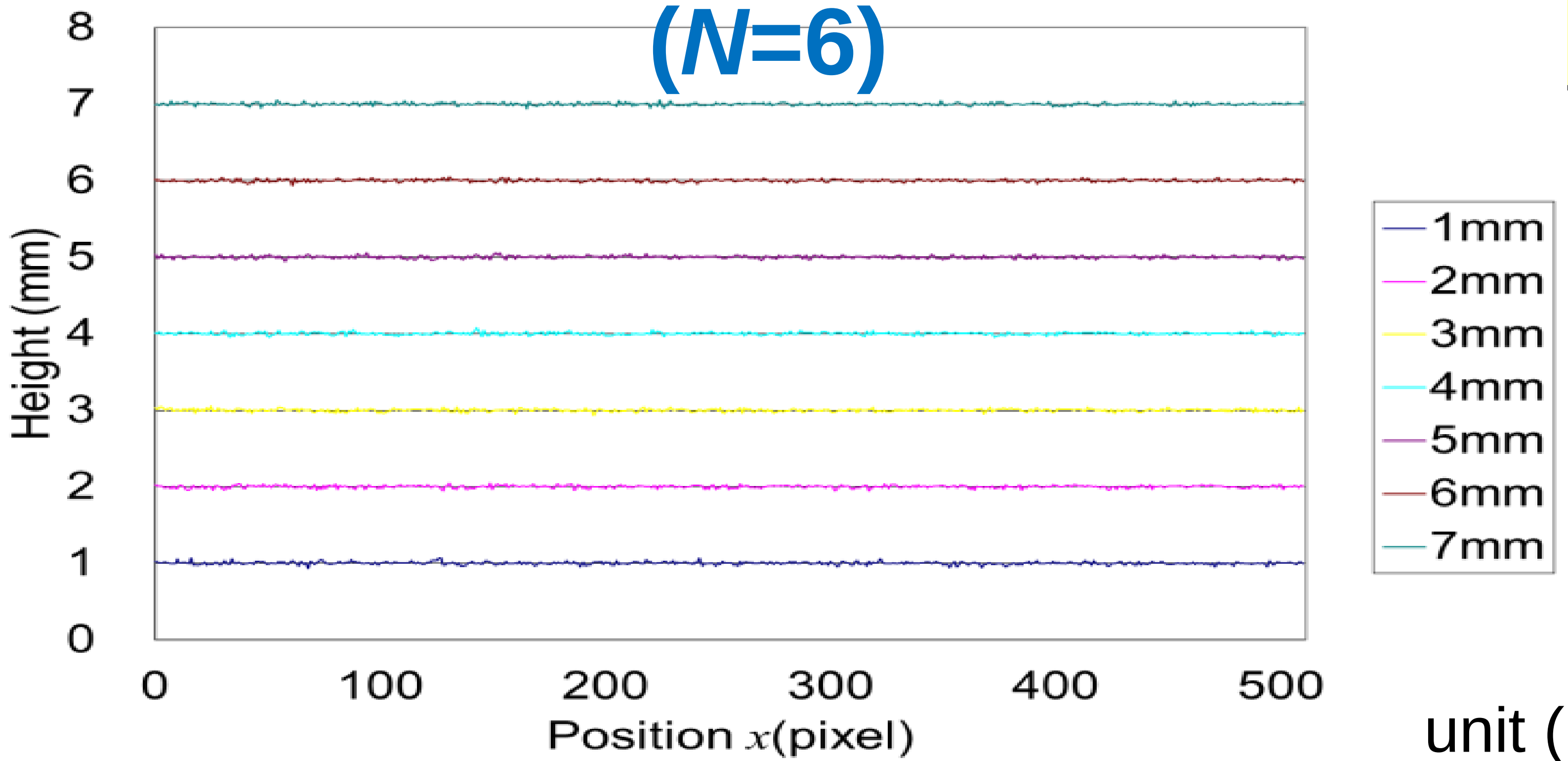




Use of original devices

Small size LED chip and small pitch for accurate result

Height measurement of flat plate (*N*=6)



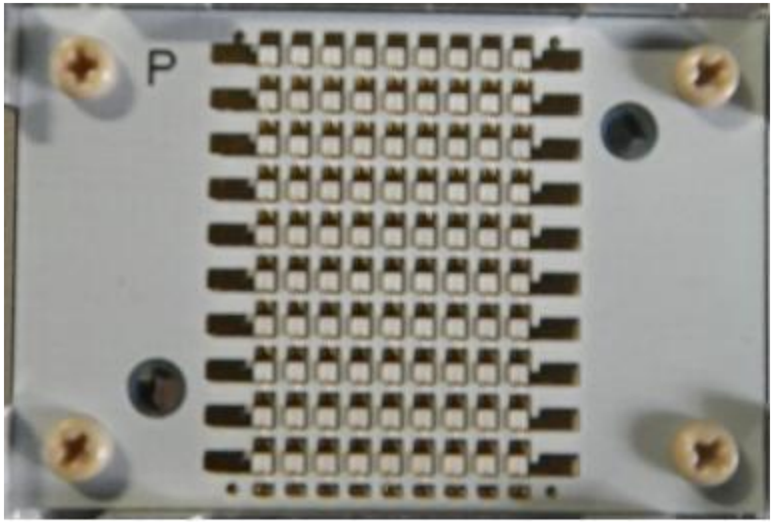
unit (mm)

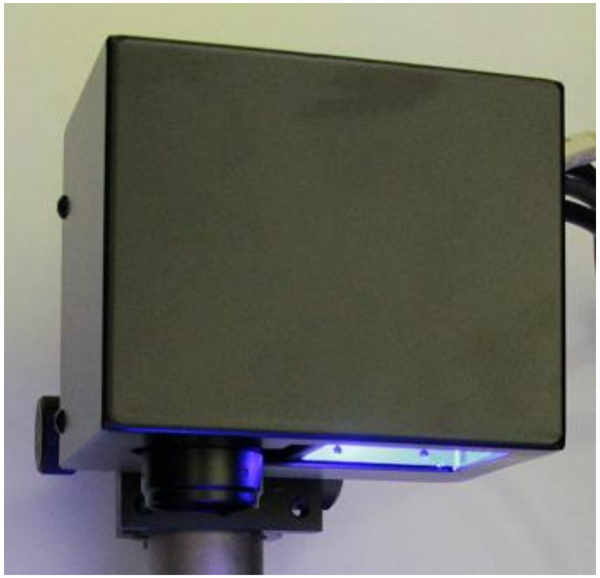
Height	1mm	2mm	3mm	4mm	5mm	6mm	7mm
Average	1.005	2.003	3.004	4.002	5.001	6.002	7.000
Error	0.005	0.003	0.004	0.002	0.001	0.002	0.000
Standard deviation	0.013	0.013	0.012	0.012	0.012	0.012	0.011

Accuracy：13μm

Data of 500 pixels along a line

4D camera (using high-power LED for high-speed)

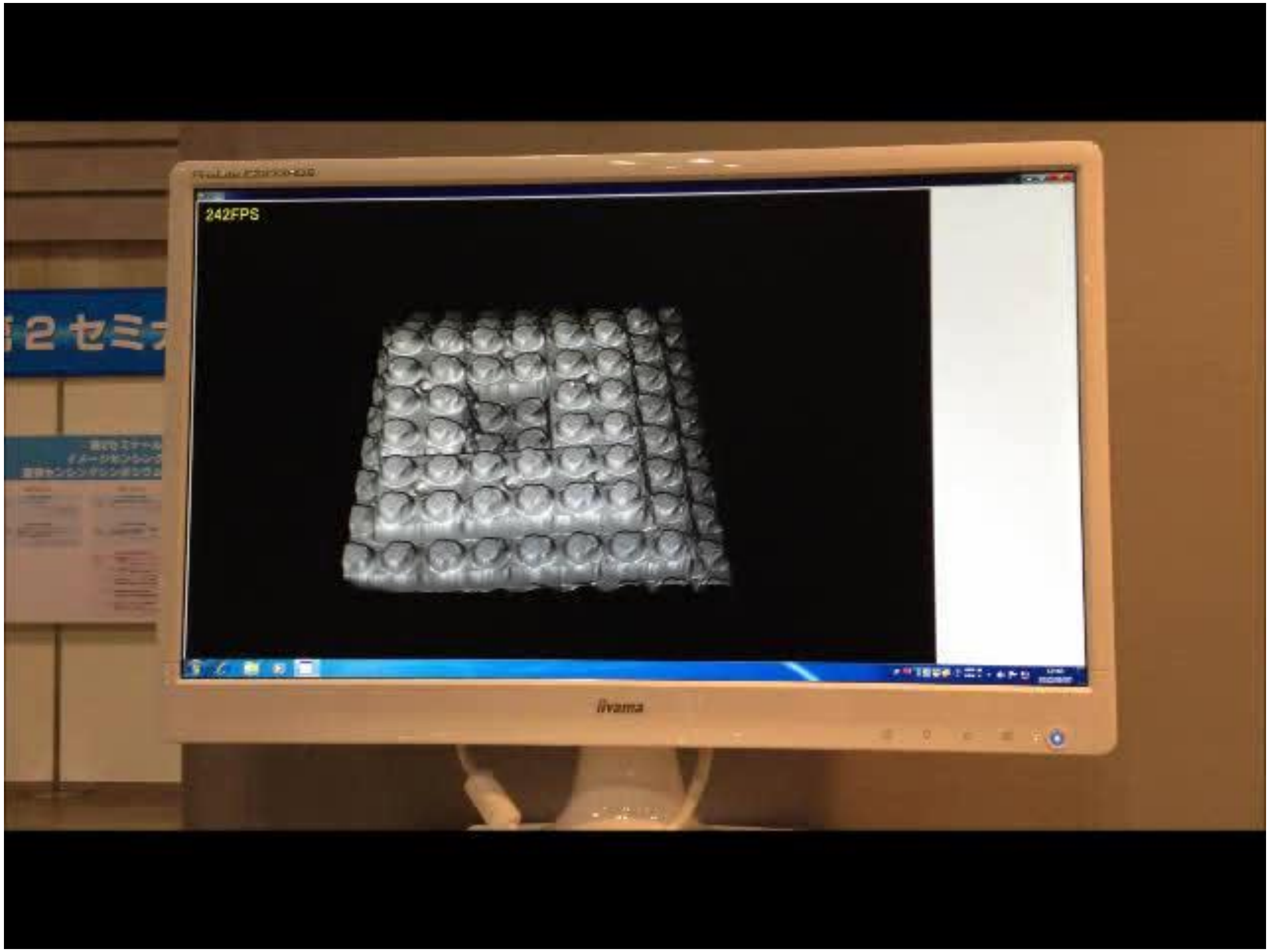




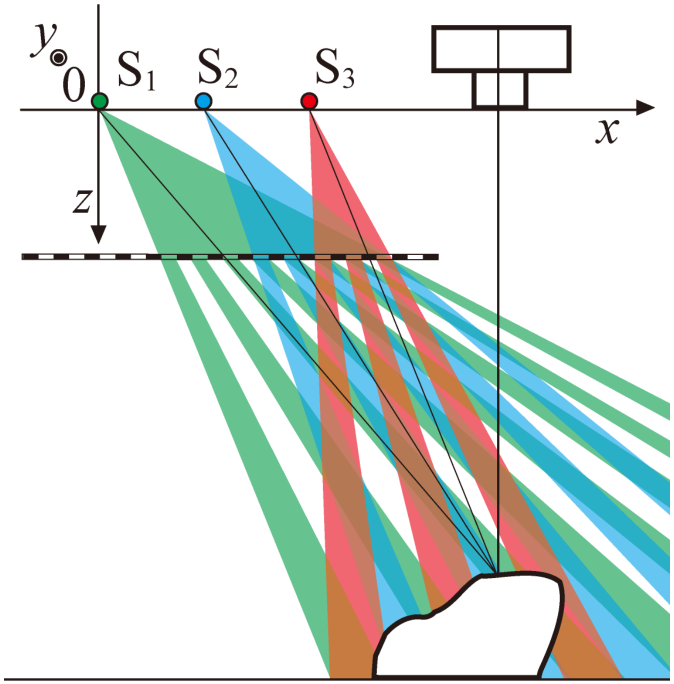
High power LED board

LED chip size	1mm × 1mm
Area size	100mm×100mm×25mm
Accuracy	0.04mm(σ)
Cycle time	0.08sec
Weight	Less than 1Kg

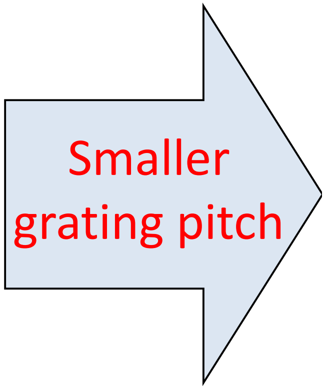
Real-time 3D shape measurement by 4D camera at 230 fps

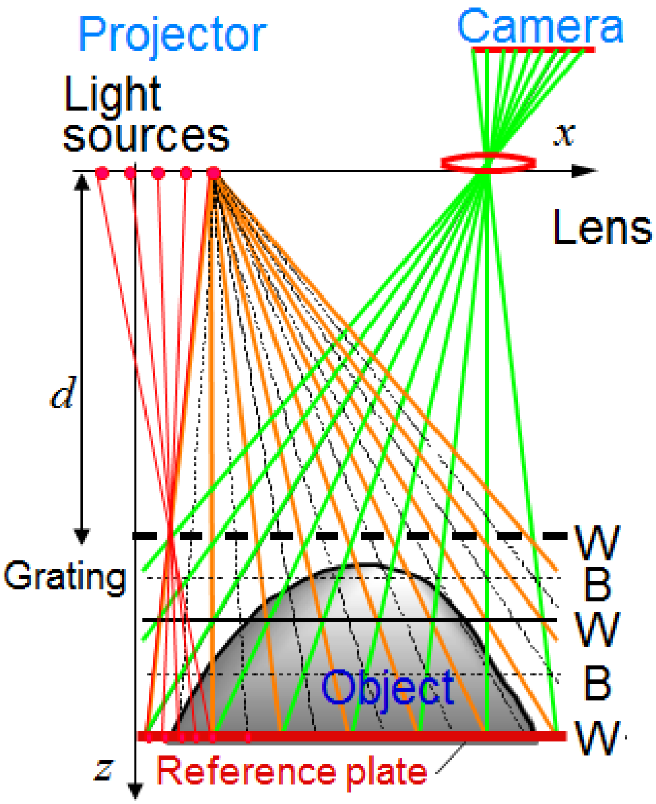


Light-source-stepping shadow moiré method



The pitch of a projected grating on an object is large.



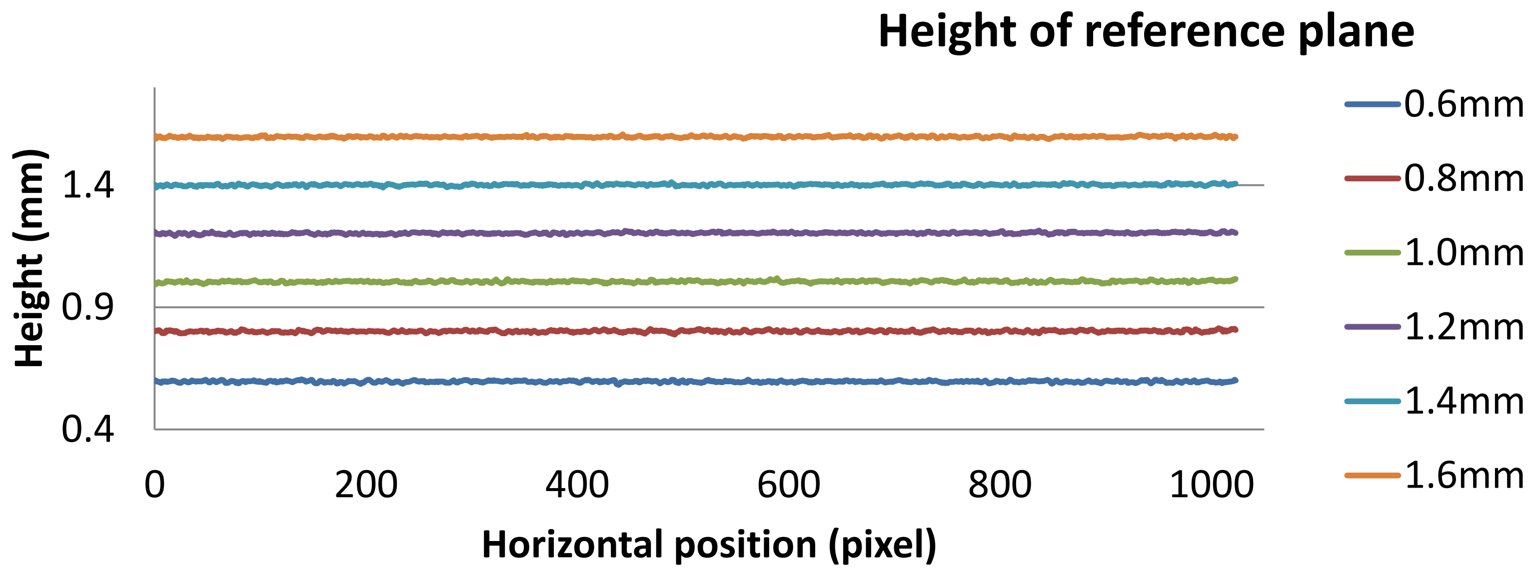


Since a smaller pitch of a projected grating is used for shadow moiré, the accuracy is better.

A moiré fringe pattern between the grating and the shadow of the grating is analyzed.

Light-source stepping method provides phase-shift easily and speedy.

Accuracy of shadow moiré camera



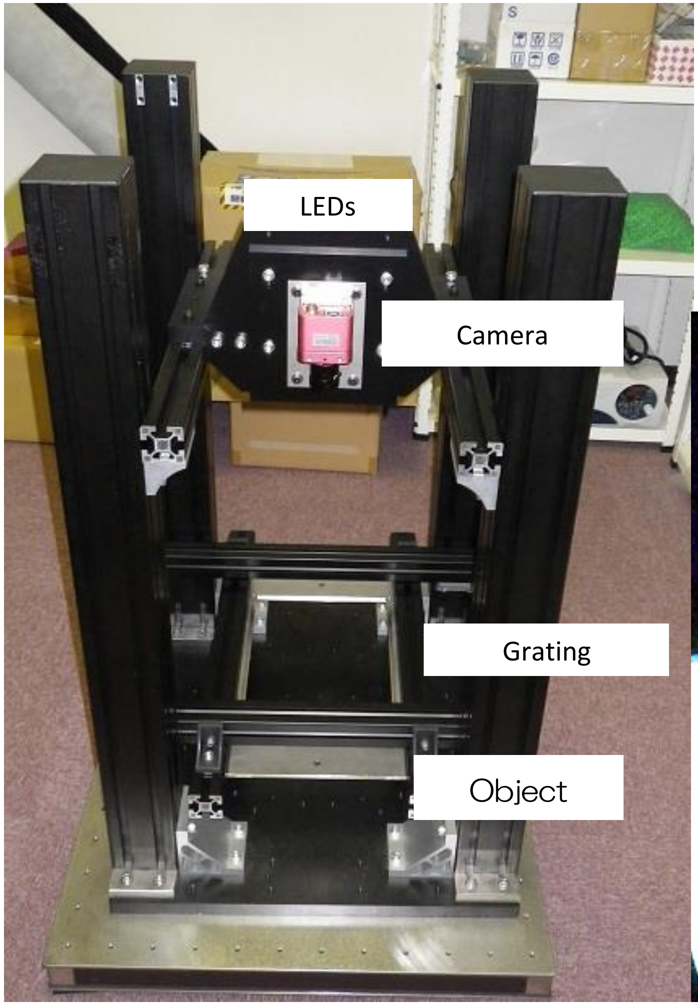
（unit：mm）

Position	0.6	0.8	1	1.2	1.4	1.6
Average	0.600	0.800	1.003	1.203	1.402	1.599
Error	0.000	0.000	0.003	0.003	0.002	−0.001
S.D. σ	0.003	0.003	0.003	0.003	0.003	0.003

Accuracy is 3μm

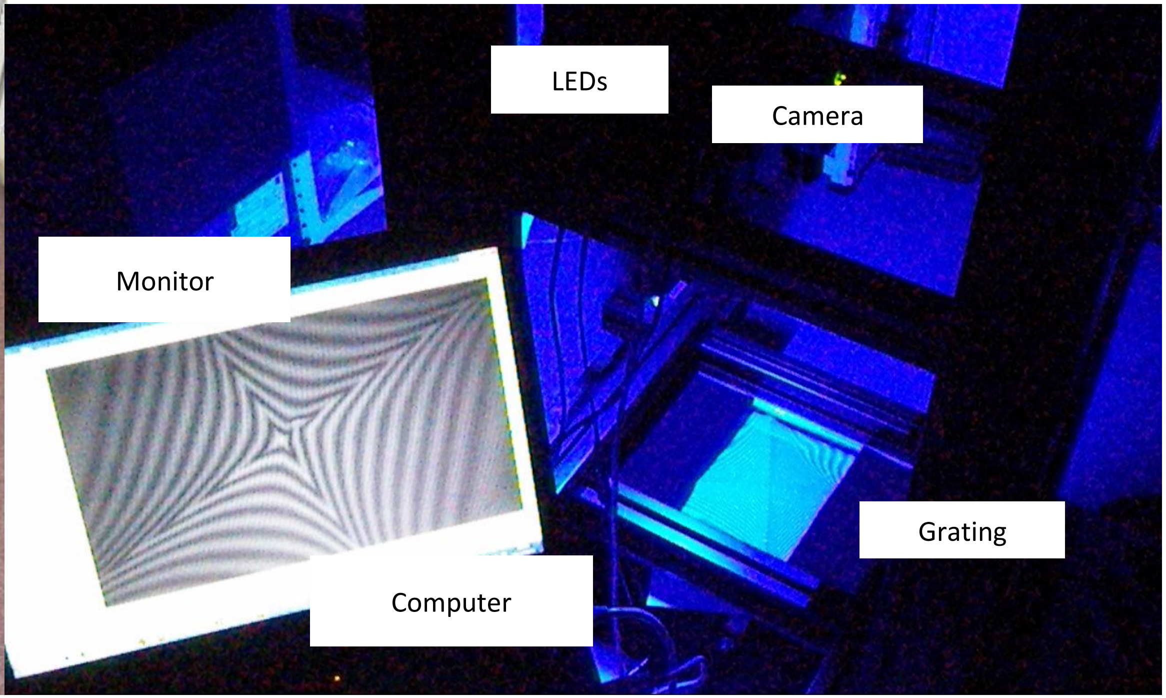
Data ：100 by 100 pixels near center

Shadow moiré camera



Equipment

Display and equipment in working

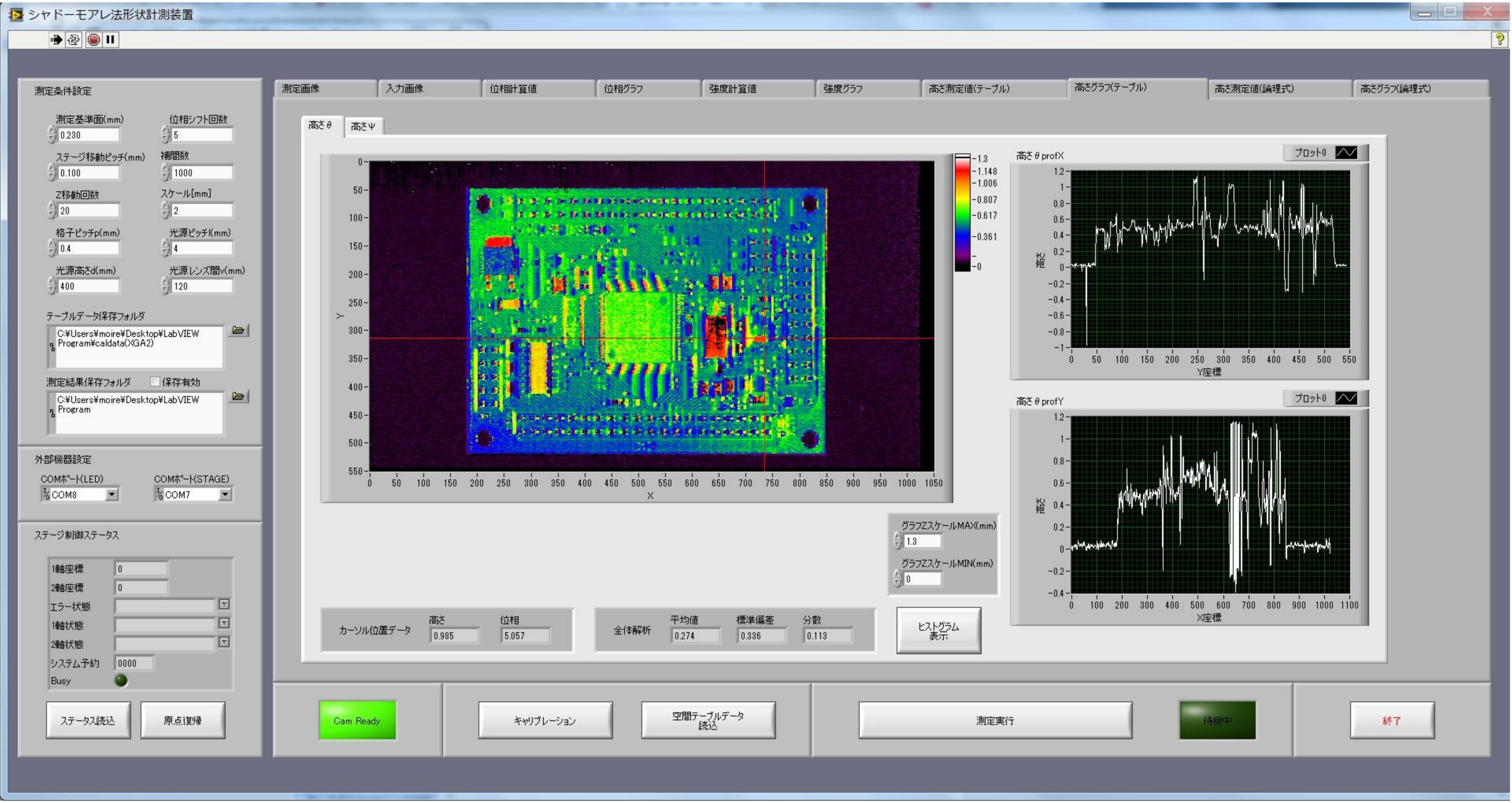


Accurate small-pitch grating made by laser etching provides accurate result.

Application of Shadow moiré camera

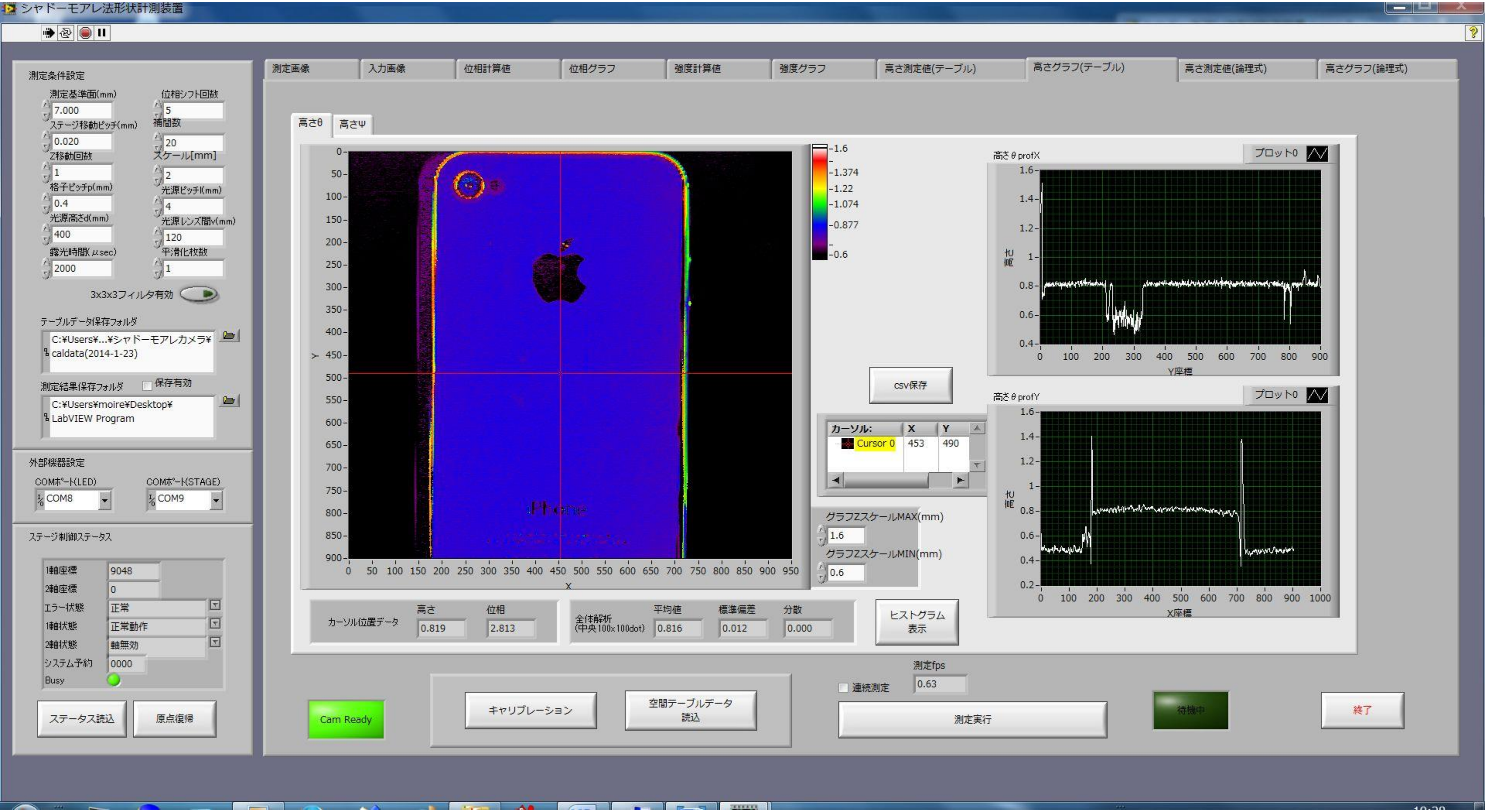
A grating with small pitch is put near the objects

Application to flatness measurement for electronic substrate

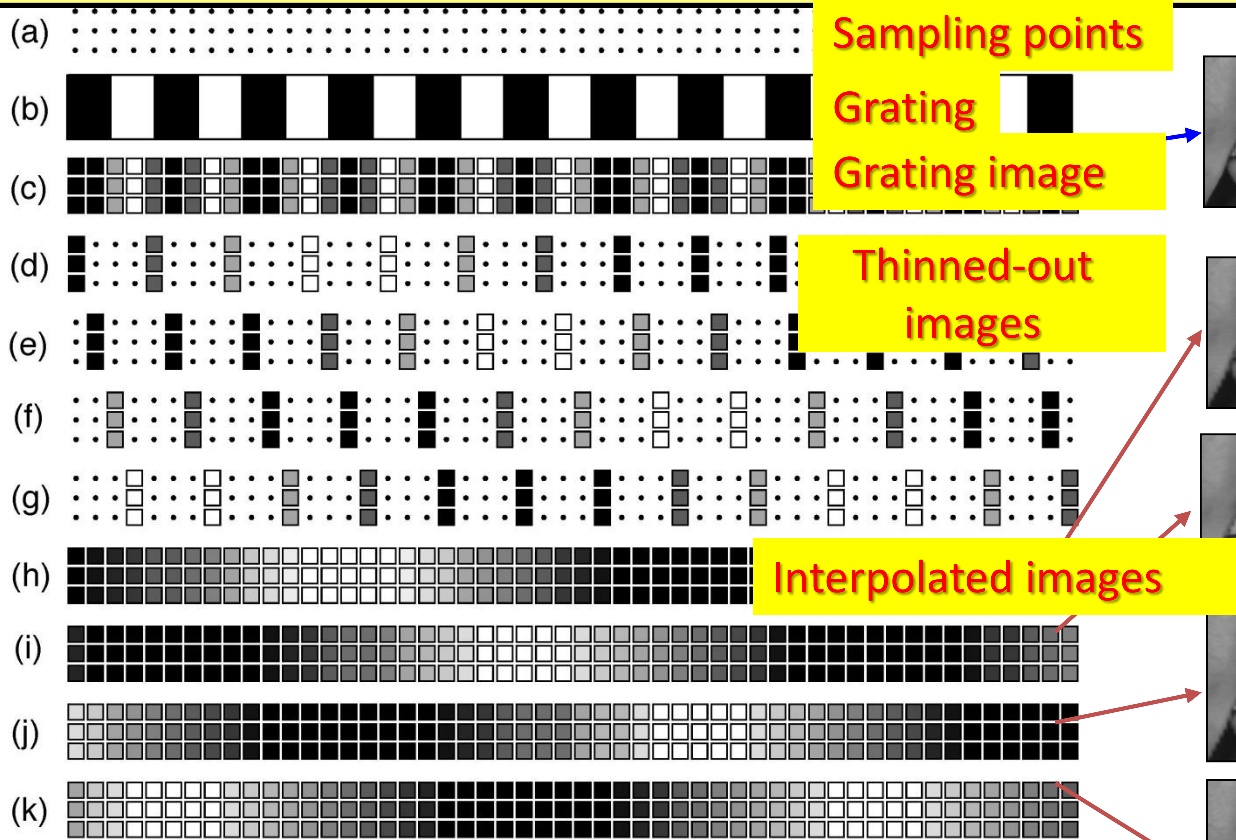


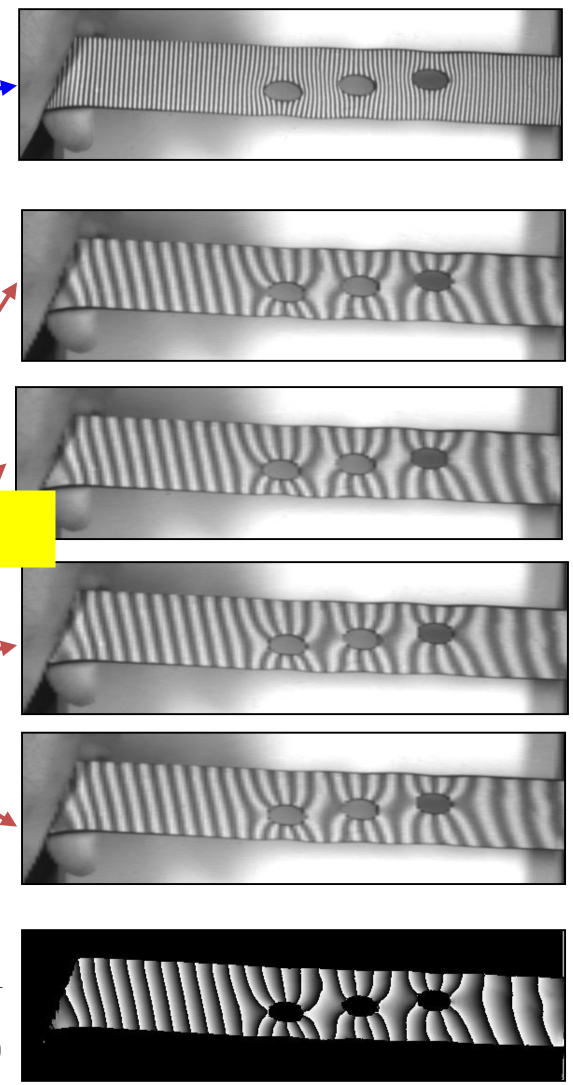
Program is developed by LabVIEW

Application to flatness measurement for mobile phone



Sampling moiré method





Intensity

$$I_k(i,j)=I_a(i,j)\cos[\phi(i,j)+k\frac{2\pi}{N}]+I_b(i,j)$$

Phase of moiré

$$\tan\theta=-\frac{\sum_{n=0}^{N-1}I_n\sin(n\frac{2\pi}{N})}{\sum_{n=0}^{N-1}I_n\cos(n\frac{2\pi}{N})}$$

In sampling moiré method, phase is analyzed from one image.

S. Ri, M. Fujigaki, Y. Morimoto, **Exp. Mech.**, **50**, 501 (2010).

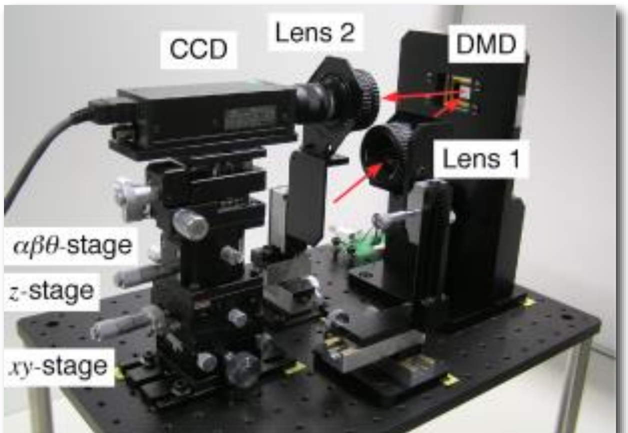
Each pixel of CCD Camera with individual shutter using DMD

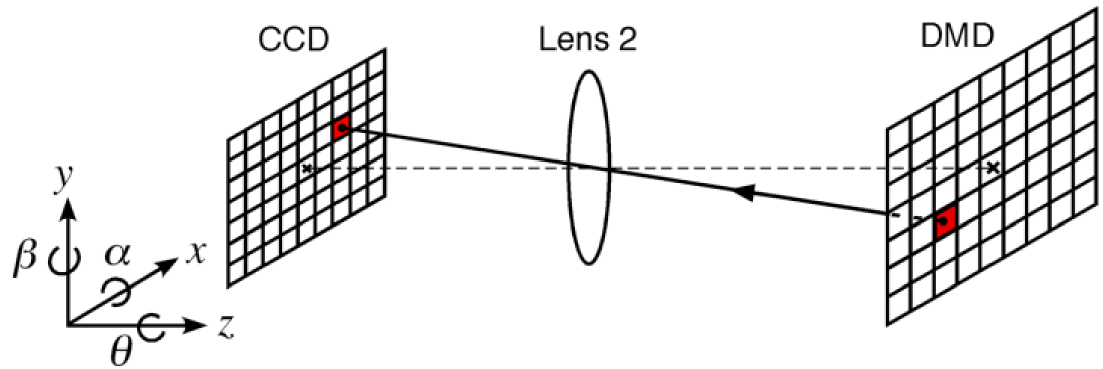
[1] S. Ri, M. Fujigaki, T. Matui, Y. Morimoto, **SEM conf.**, **Portland, USA** (2005)

[2] S. Ri, M. Fujigaki, T. Matui, Y. Morimoto, **Experimental Mechanics**, **46,** 67 (2006)

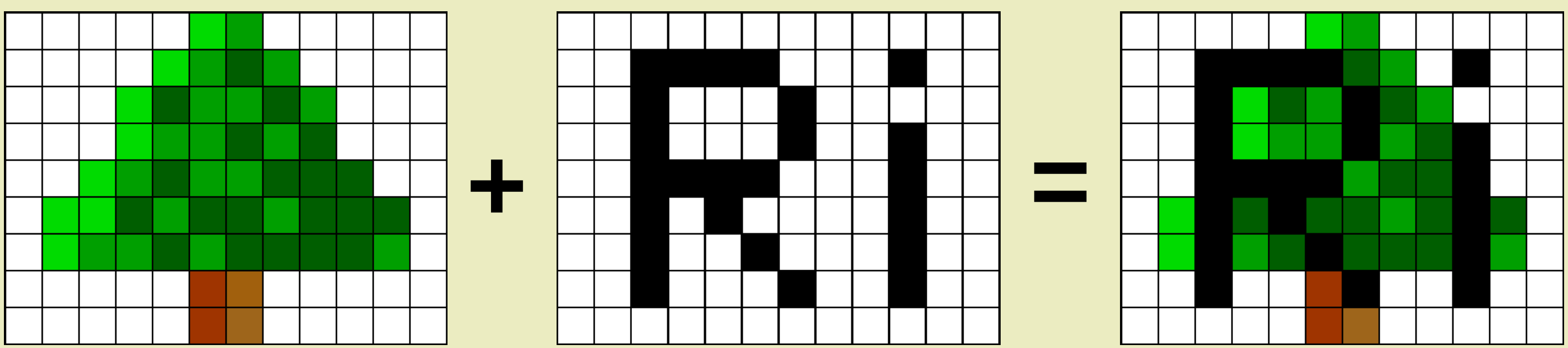
[4] S. Ri, M. Fujigaki, T. Matui, Y. Morimoto, **Applied Optics**, **45,** 6940 (2006)

Set-up of DMD camera



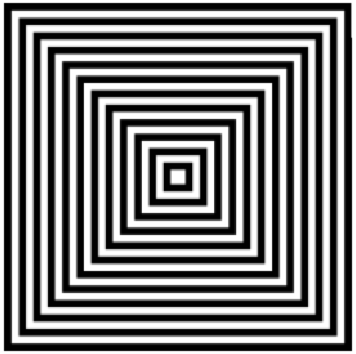


Illustration

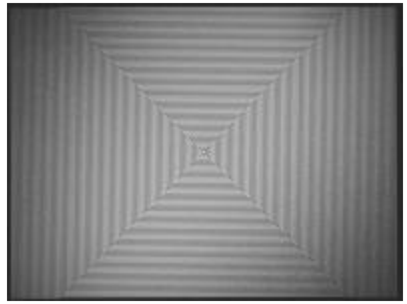


Object **DMD "on/off" pattern** **Captured image**

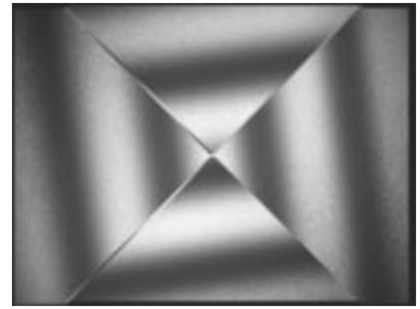
Adjustment of camera position to grating



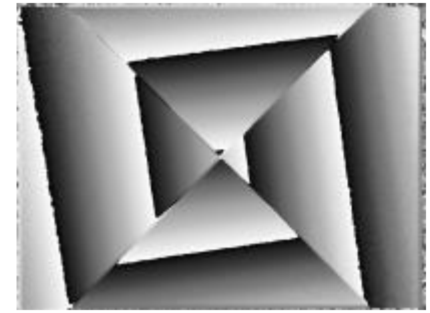
Binary grating with
4-pixel pitch



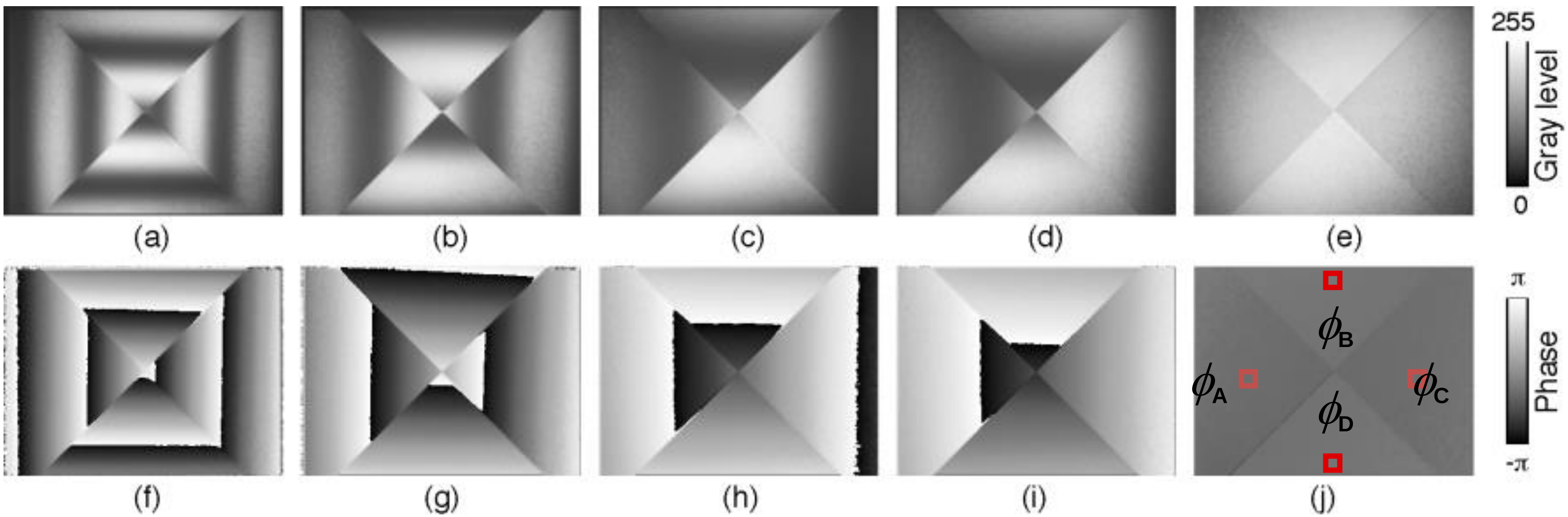
Grating image



Moiré image



Phase of moiré



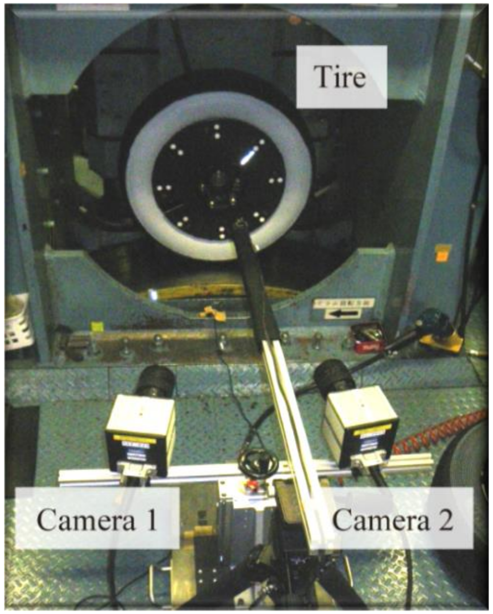
X-directional phase difference: $|\phi_A - \phi_c|=0.061$, correspond to 1/25 pixels.
Y-directional phase difference: $|\phi_B - \phi_D|=0.043$, correspond to 1/37 pixels.

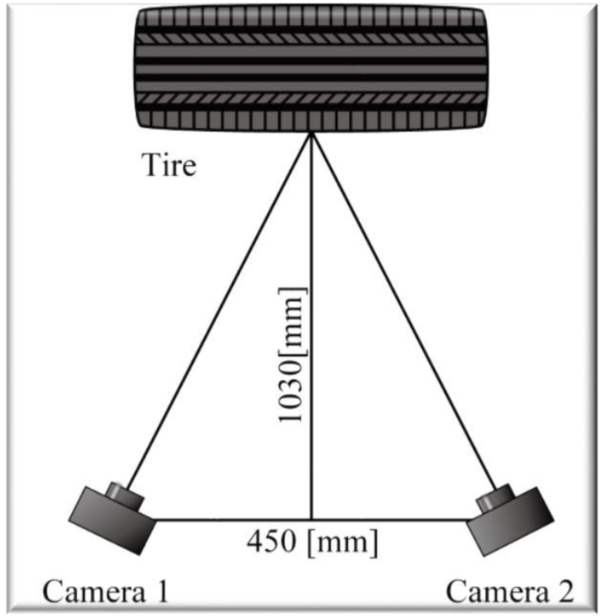
[4] S. Ri, M. Fujigaki, T. Matui, Y. Morimoto, **Applied Optics**, **45,** 6940 (2006)

Prototype of High-speed Camera Switching System for 3D Shape and Strain Measurement

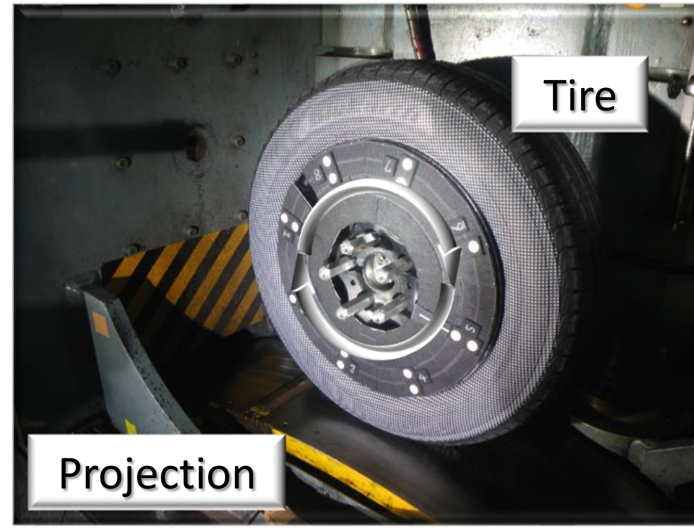
Motoharu FUJIGAKI, University of Fukui
Takaaki YOSHIKAWA, Wakayama University
Yorinobu MURATA , Wakayama University

Dynamic strain distribution measurement

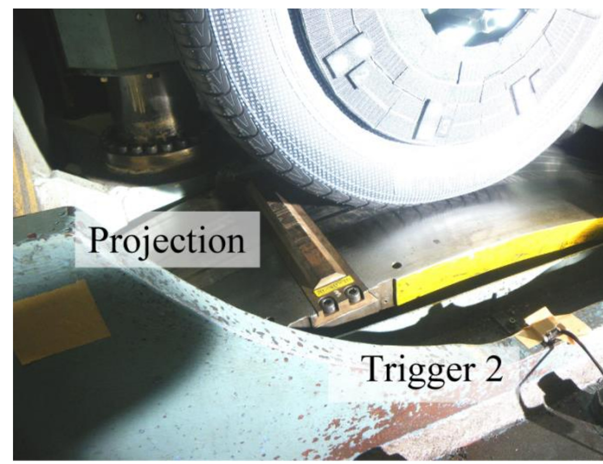




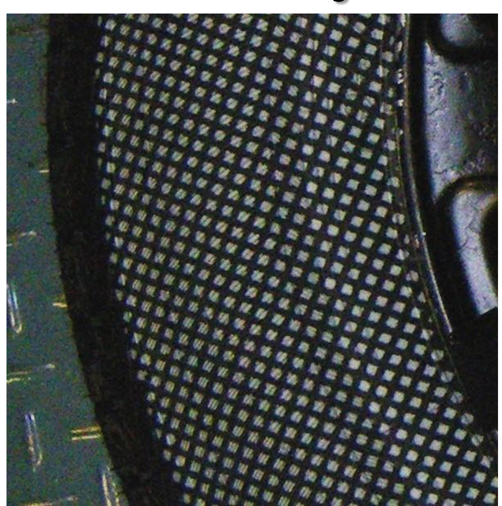
Two high-speed cameras and object



Frame rate: 1000 fps
Velocity of tire: 60 km/h



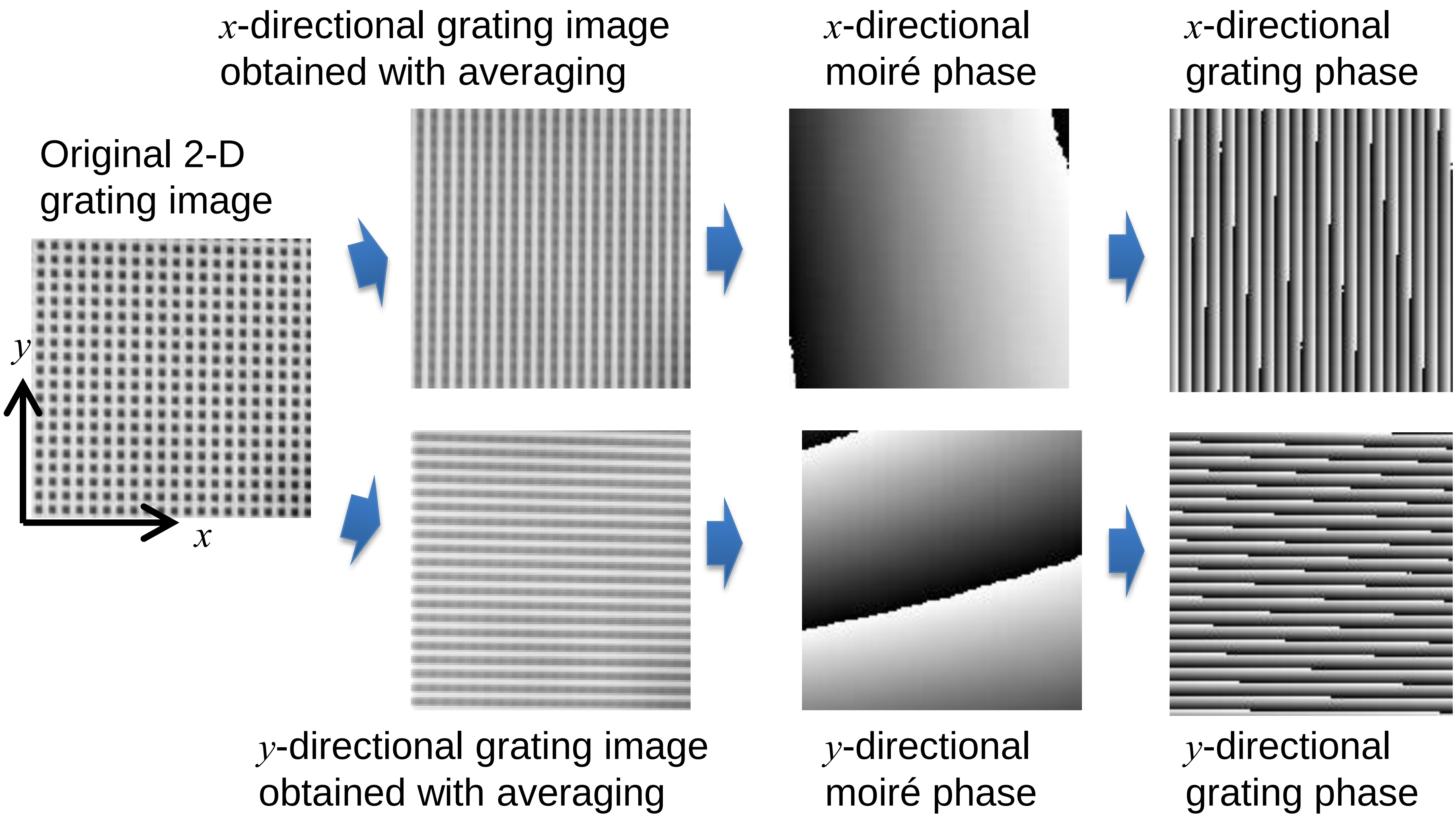
Tire treads a projection



2D-grating printed on the surface of tire

Experiment

2-D phase analysis by sampling moiré method



2-D phases analysis can be performed from a 2-D grating image.

Principle of shape and strain measurement (Stereoscopic method)

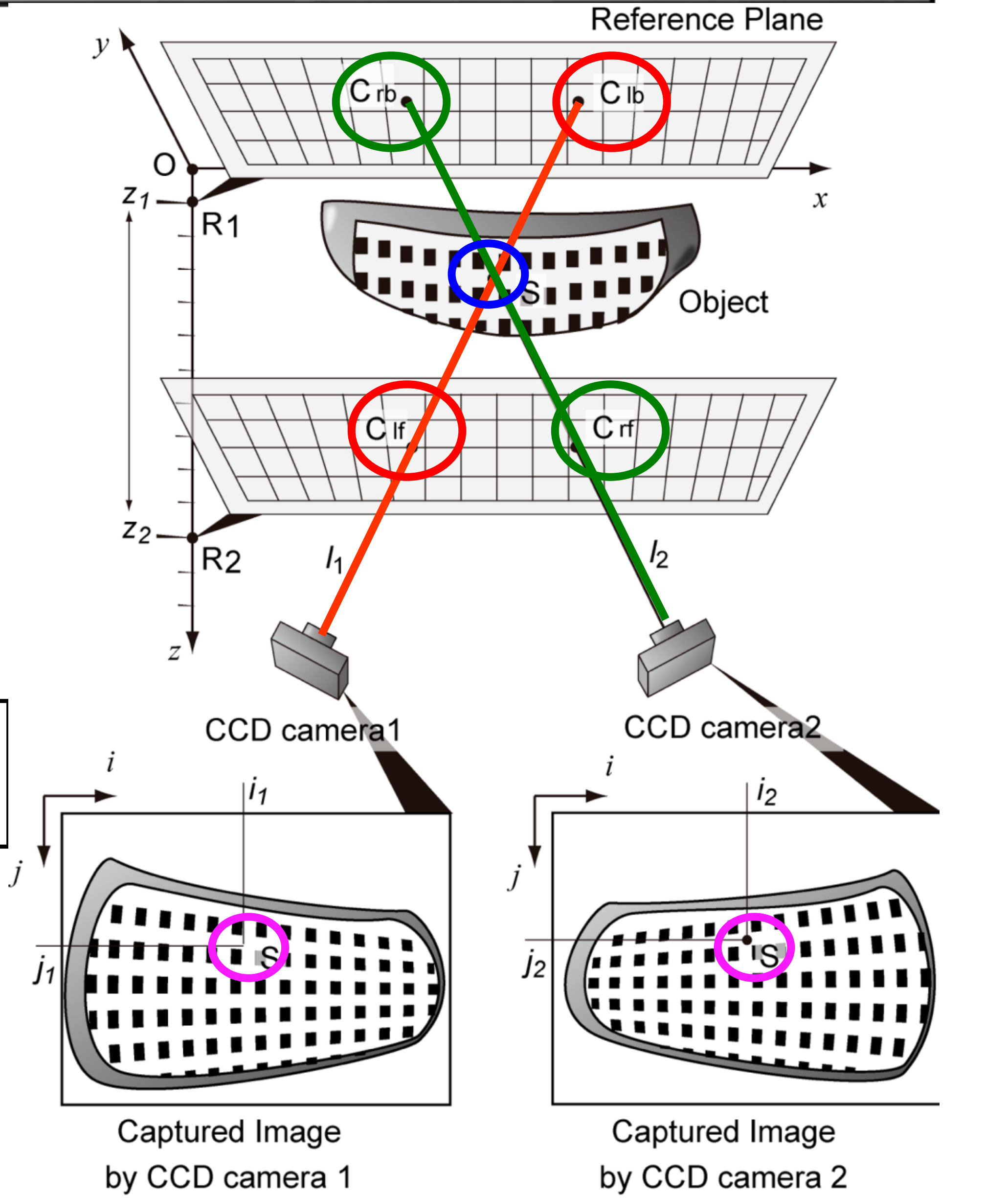
2-D grating images are taken by two cameras.

2-D phase is analyzed by sampling moiré method.

Corresponding pixels on each camera image are obtained from the 2-D phase.

Line l_1 and line l_2 can be obtained from the corresponding pixels.

The 3-D coordinates of point S are obtained as the intersection of the two lines l_1 and l_2.

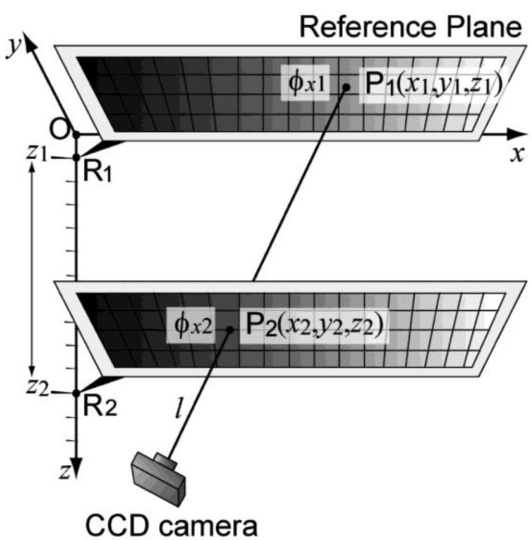


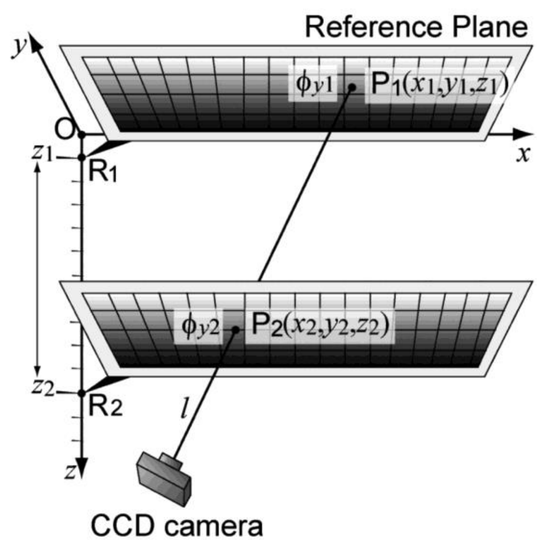
Calibration

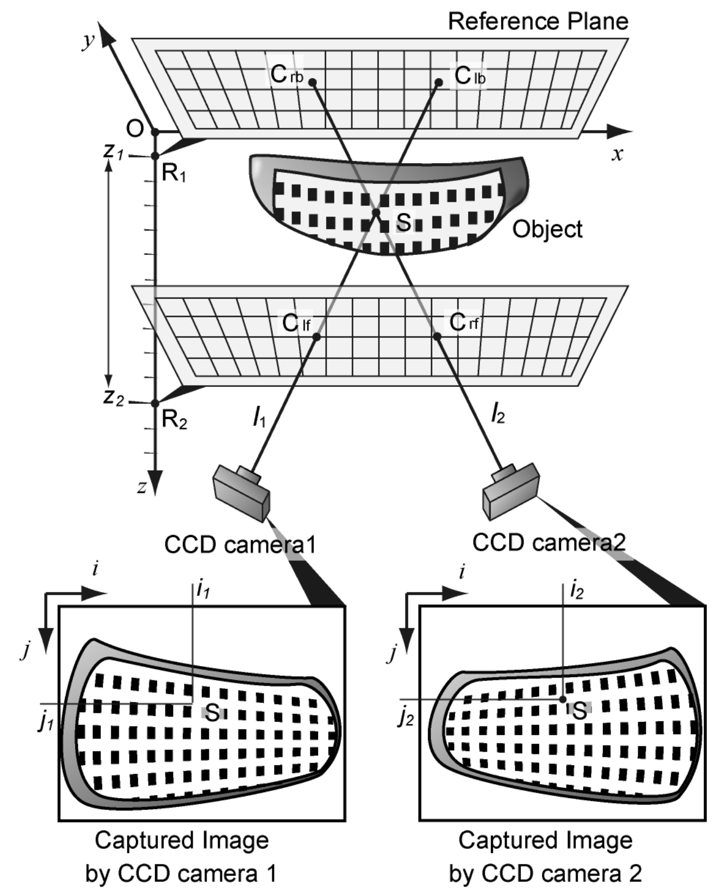
An LCD monitor is used as a reference plane.
2-D grating is displayed on the monitor.
The reference plane is placed on two positions, z_1 and z_2.

2-D phase gives (x, y) coordinates on the reference plane.

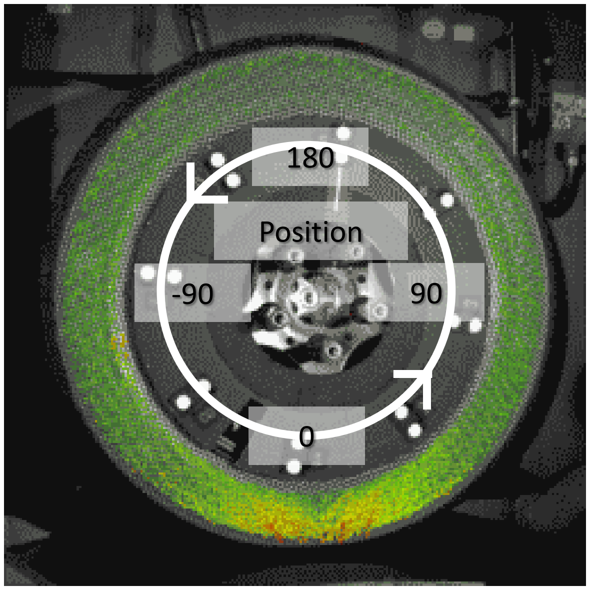
Ray lines corresponding to all pixels of each camera are obtained.

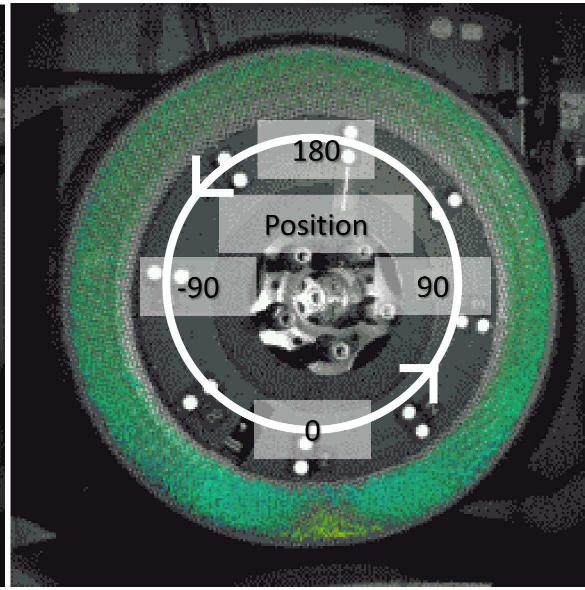


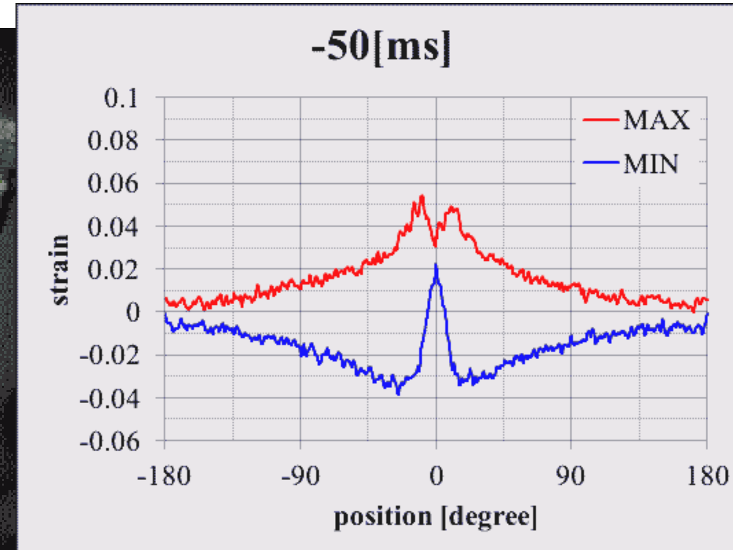




Dynamic strain distribution measurement







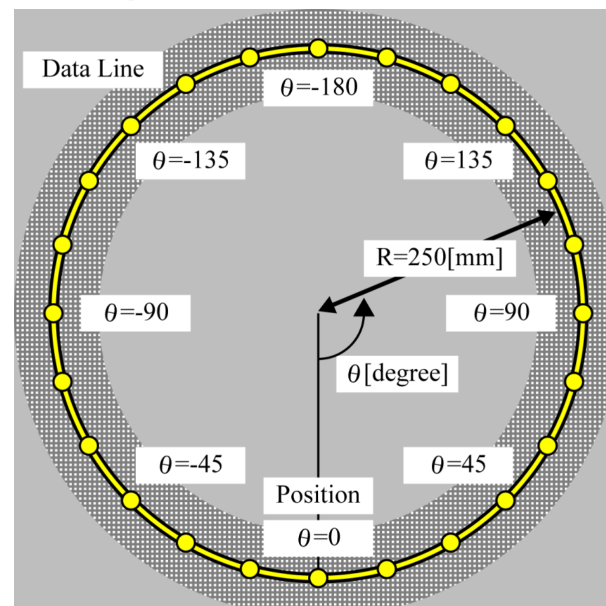
-0.10 0.10

Maximum principal strain distribution

-0.10 0.10

Minimum principal strain distribution

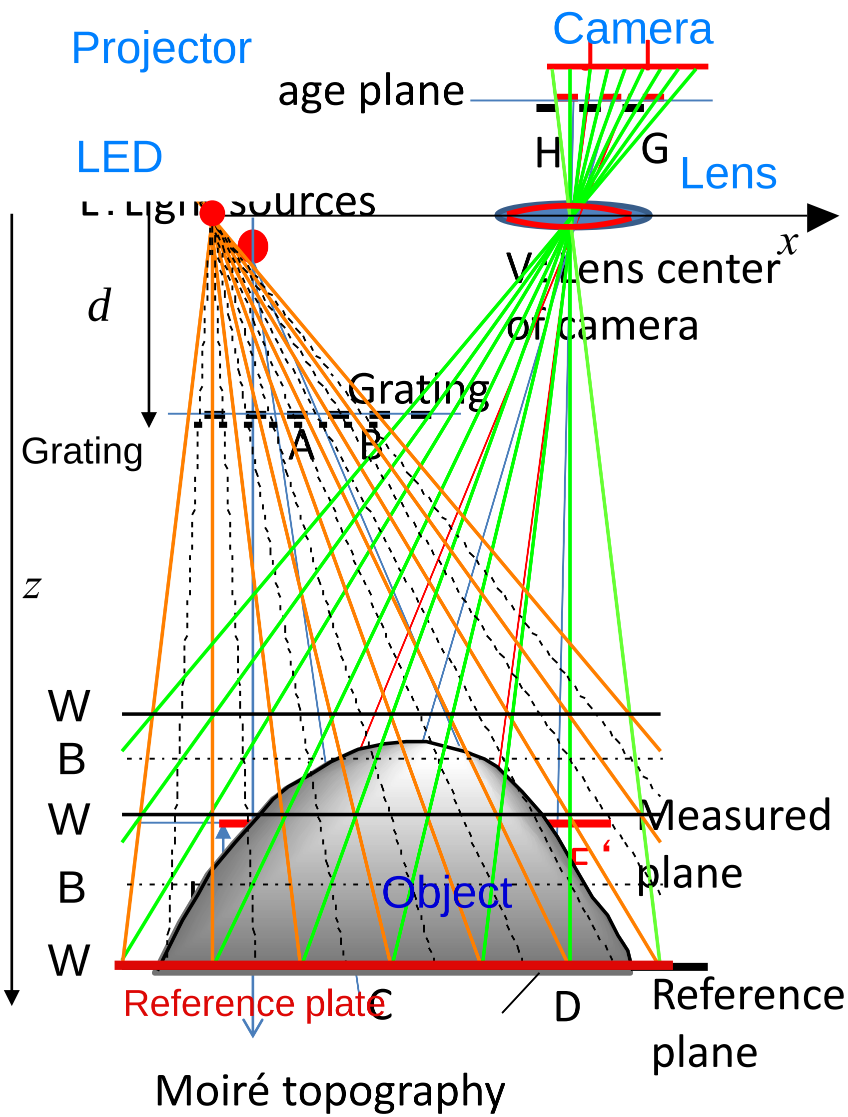
Principal strain distribution



-50 ms
0 ms
+150 ms

Tire treads a projection

One-Pitch Phase Analysis (OPPA) Method [53]
using sampling moiré method



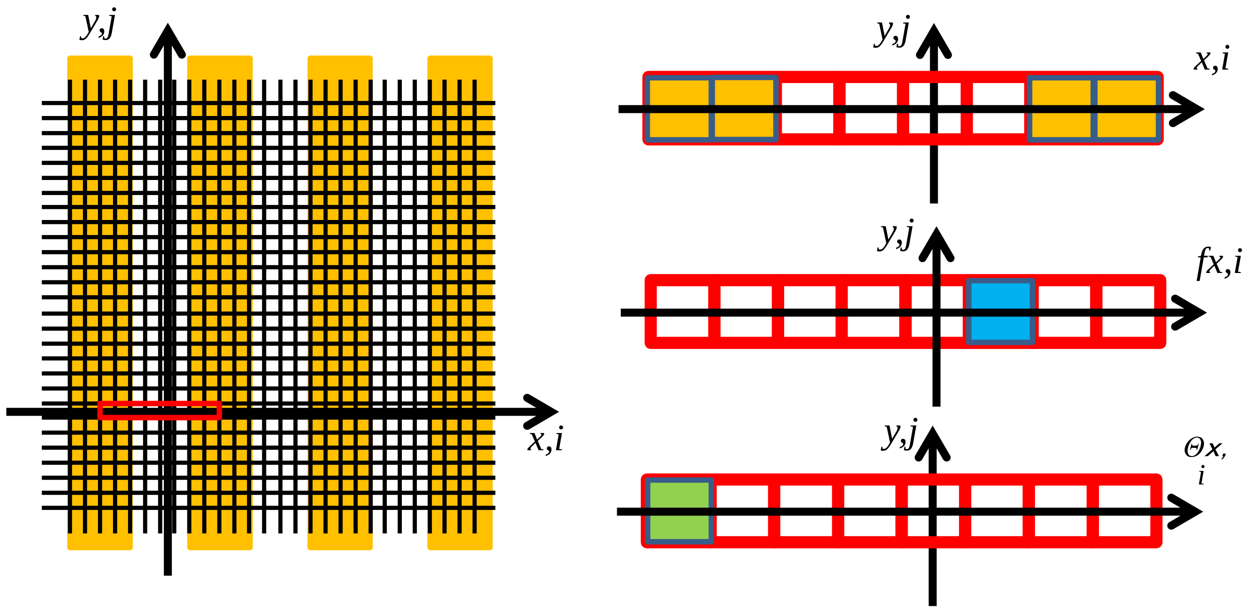
The lens center is the same height of the LED light source from the reference plane.

The grating pitch on the camera CCD pixels is constant at any height.

Only the phase of the grating is changed according to the height.

If *N* pixels are adjusted for one pitch of the grating, *N* pixels for one pitch is kept at any height.
Only the phase is different according to the height.

One dimensional grating projection
Phase analysis by sampling moiré



Extraction of one pitch grating

Fourier transform for one dimensional grating

Calculation of grating phase

That is, phase is obtained from *N* pixel data as follows

$$\tan\theta = -\frac{\sum_{n=0}^{N-1} I_n \sin(n\frac{2\pi}{N})}{\sum_{n=0}^{N-1} I_n \cos(n\frac{2\pi}{N})}$$

Application to modal analysis of vibrating plane (Optical system)

$$p = 1.2192\text{mm},$$
$$v = 500mm,$$
$$d = 200mm,$$
$$z_R = 500mm,$$
$$\Theta_M = 2\pi :$$
$$h = \frac{p\Theta_M {z_R}^2}{p z_R \Theta_M + 2\pi v d}$$
$$= 3.03mm$$

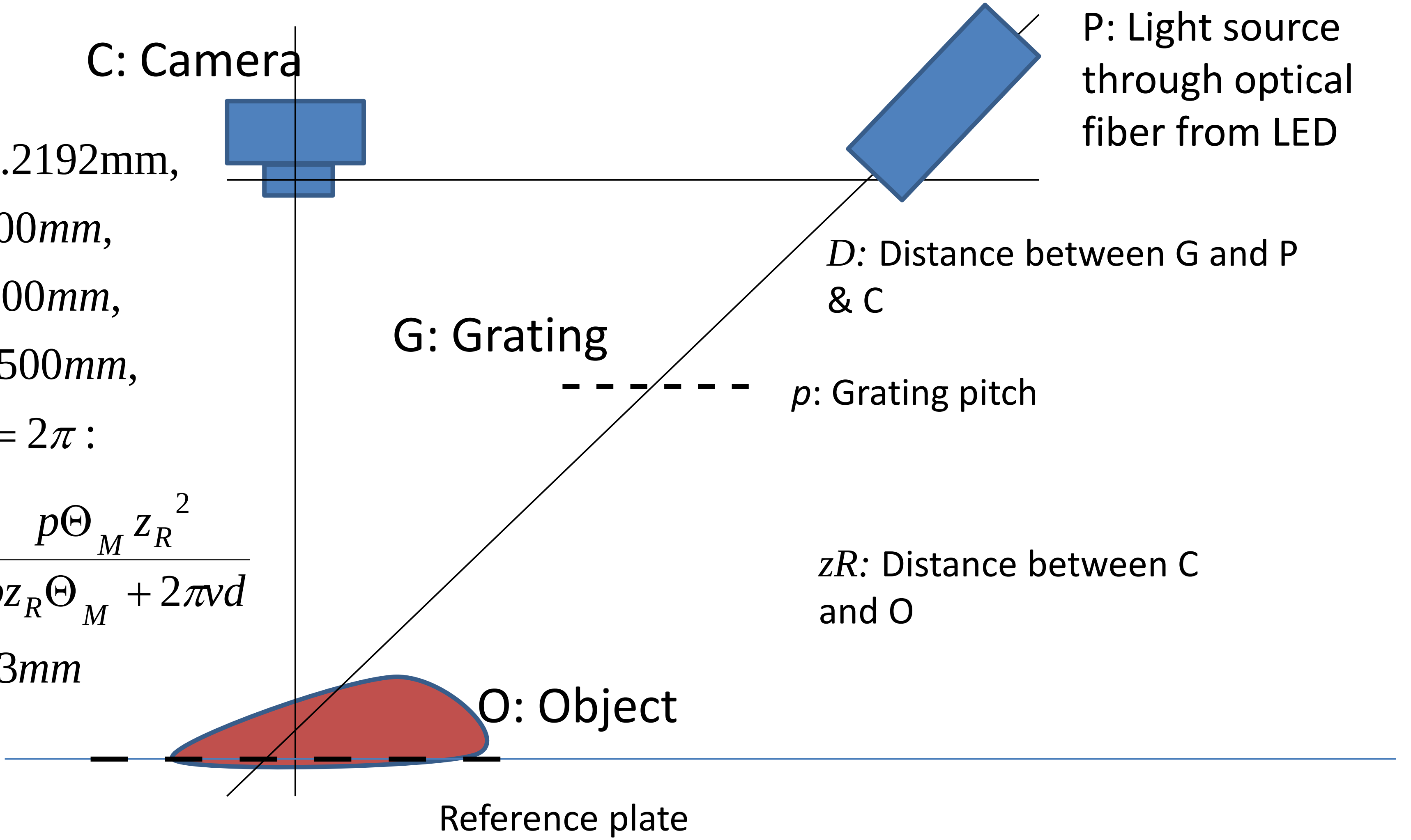
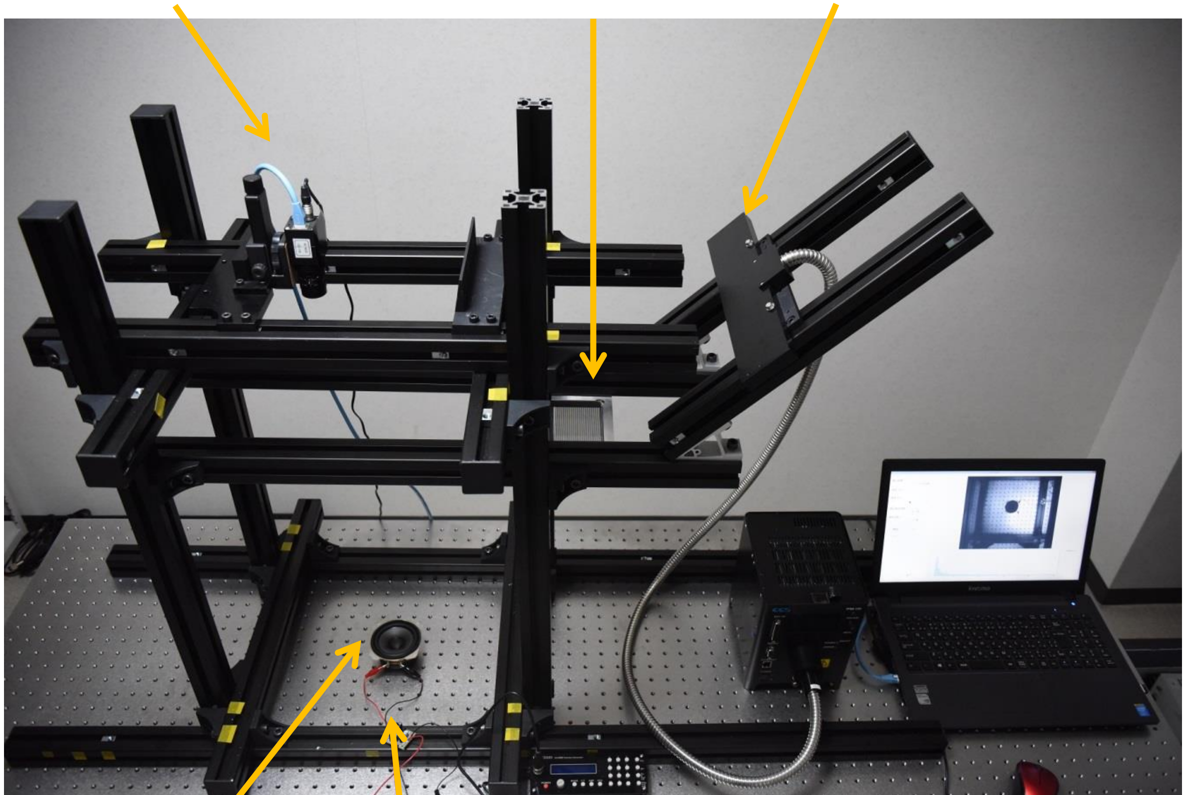


Photo of experimental system

Camera

Grating

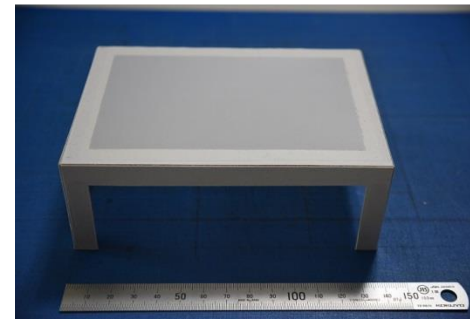
Light source



Specimen

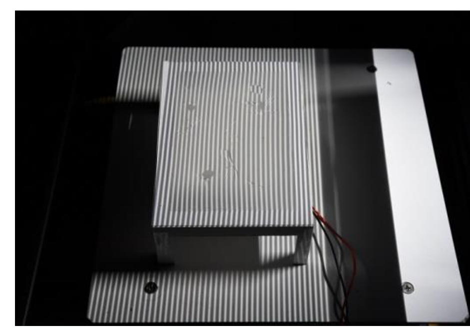
Speaker

p=1.22mm, h=p'=3.03mm



Specimen

120mm × 80mm



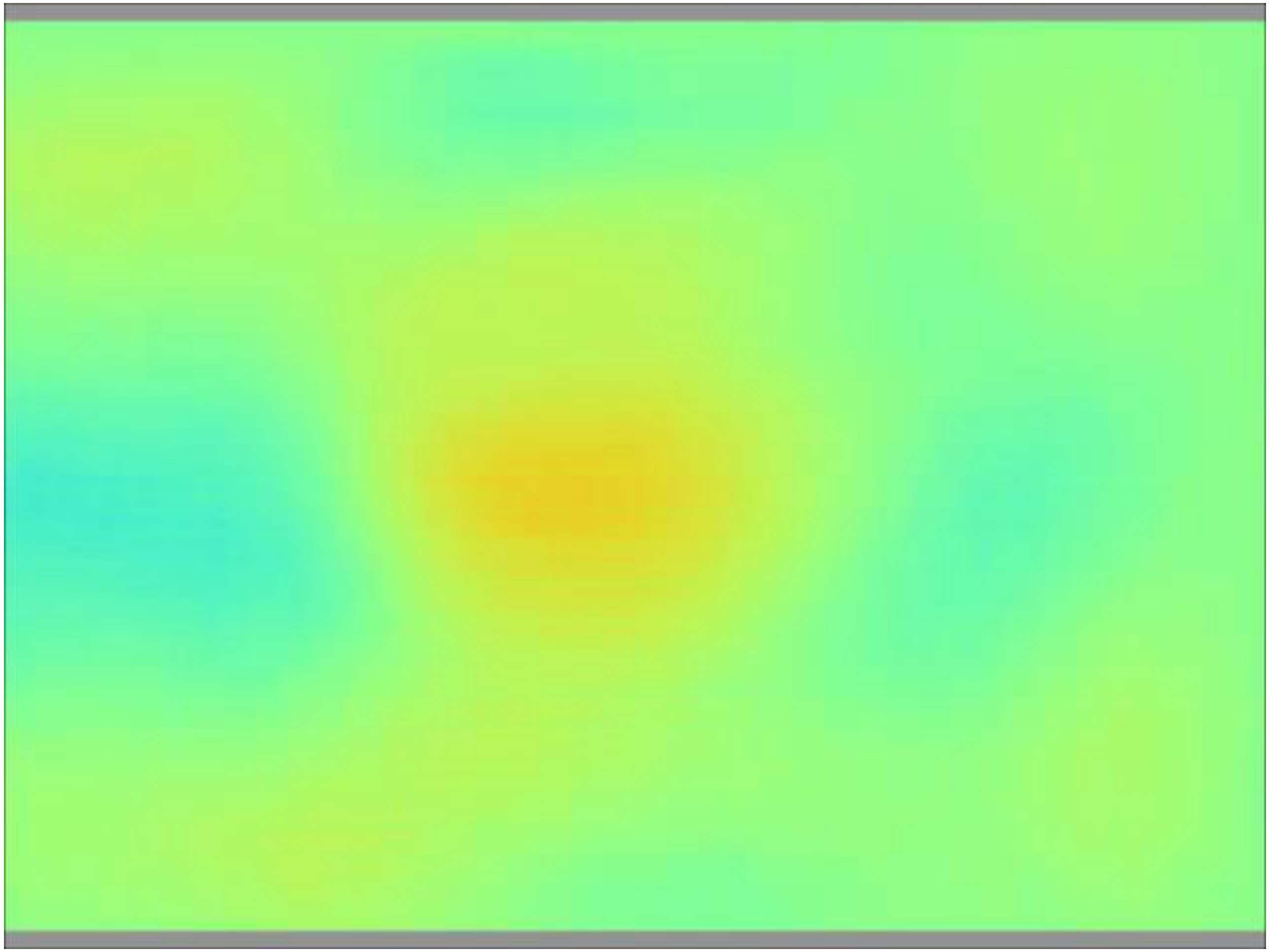
Specimen setting on speaker

Vibration mode change according to frequency

Height distribution when frequency changes 27Hz ～37Hz at 200 fps

Recording speed: 200 fps

Pixel size : 320 × 240 pixels



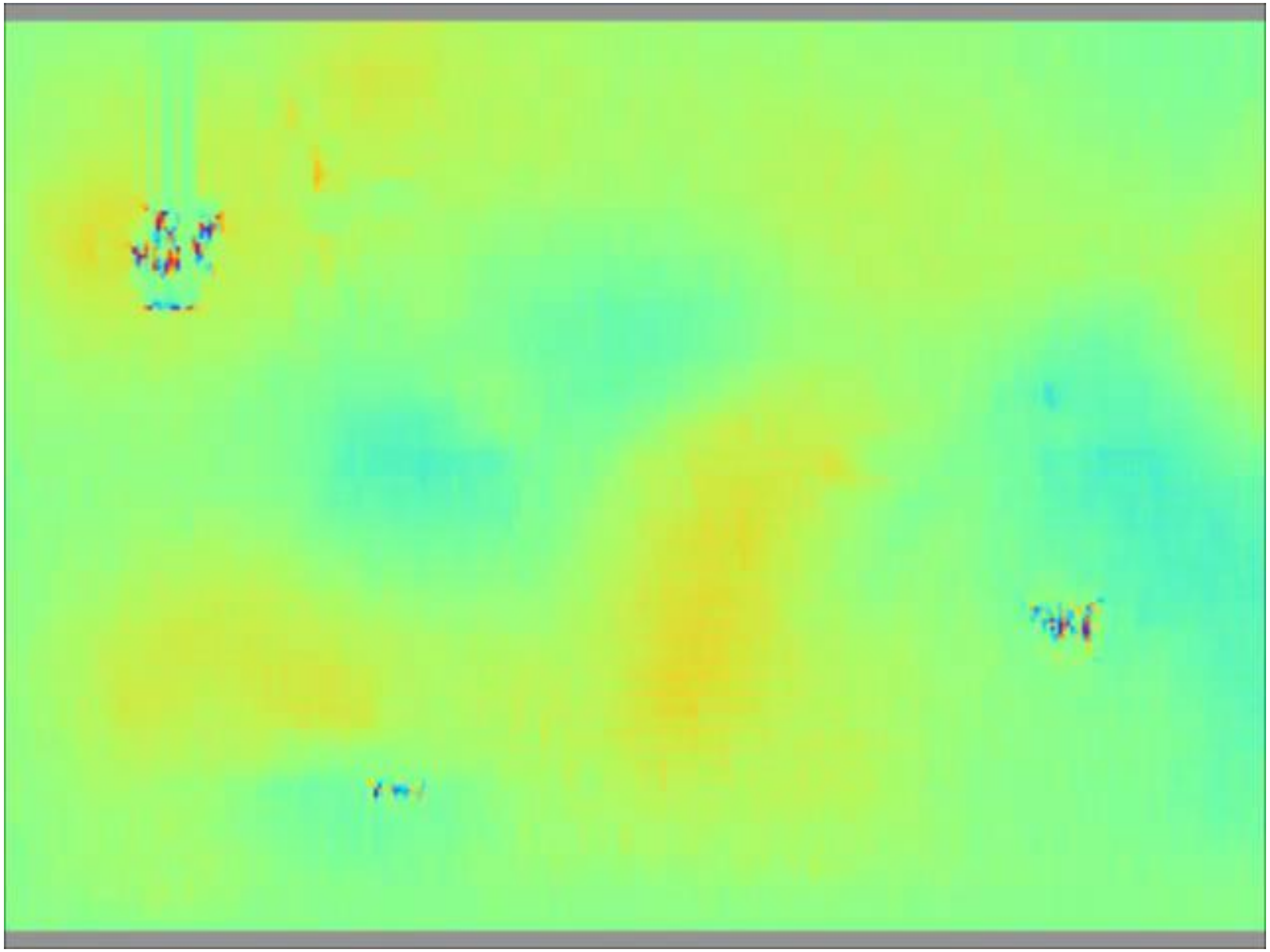
Slow motion movie

Modal analysis of vibrating rubber plate with defects

Height distribution when frequency changes 27Hz ～37Hz at 200 fps

Recording speed:
200 fps

Pixel size : 320 × 240 pixels



Features of SMM and OPPA

Merit

- Moving object analysis because of use of only one image
- Less thermal error because of one-line light source
- No controller for light source because of no switching
- Simple system

Demerit

- A little bad spatial resolution
- Less resolution for object with different pattern in one pitch

Conclusions

- Moiré methods are useful to analyze full-field displacement, strain and shape.
- New moiré methods such as sampling moiré method and OPPA method are proposed to analyze dynamic shape, displacement and strain.
- They are high-speed, high accuracy, compact and low cost systems.

Future work

Development

- High speed system (2000~50000fps)
- Ultra high-speed system (20Mfps)
- Compact and low-cost 3D camera

Applications

- On-line manufacturing inspection
- Human body motion
- MEMS
- Collision of car
- Stress wave propagation

Future projects

- Full-field -→ whole-space
- Real-time -→ High- speed
- Micro system
- Auto sensing
- Auto control
- Auto repair

- Eye for robot
- Speeding up
- Security and recognition
- Prolonging life of structure
- Energy saving
- Ubiquitous

- Fusion of DIC and Fourier transform method
- Strain measurement by Fourier analysis of natural pattern
- Digital holographic interferometry
- Stress wave propagation analysis

Acknowledgement

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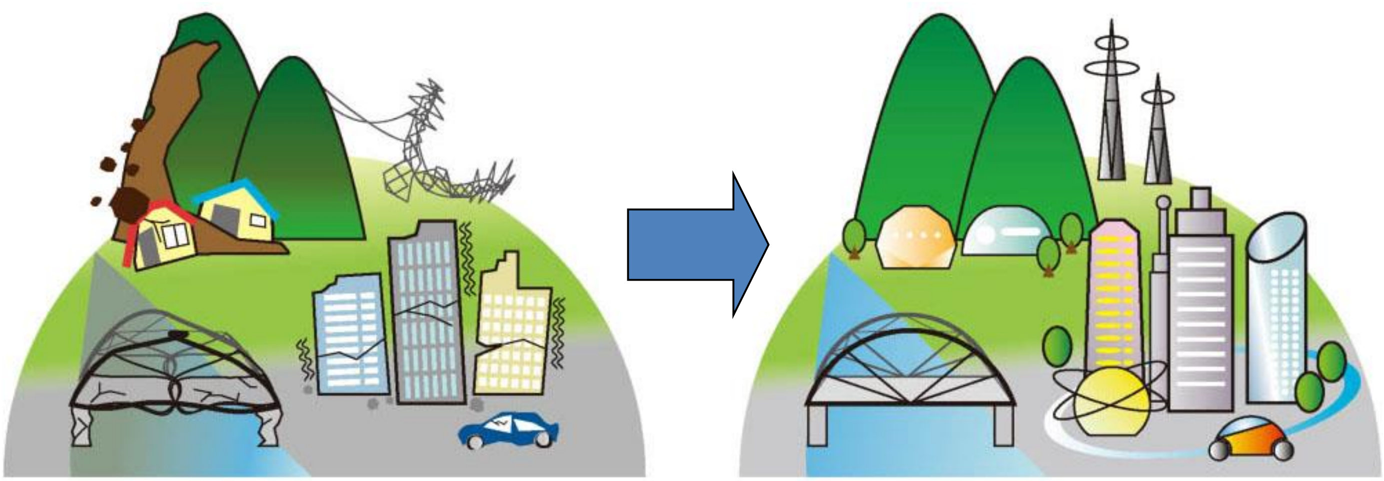
- Yuko Yamamoto
- Shien Ri

- Akihiro Masaya
- Akifumi Takagi
- Yoshiyuki Kusunoki
- Masaki Ueki

Thank you for your attention



Without exp. mech. With exp. mech.

Future town