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Coupon Test of an Elbow Component by Using Vision-based Measurement System

S.W. Kim & N.S. Kim
Structural Dynamics Laboratory
Pusan National University

B.G. Jeon & H.S. Choi
KOCED Seismic Simulation Test Center
Pusan National University

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Introduction

❖ Vision-based Measurement System

- Not easy to measure displacements by using conventional sensors
- Displacement measurement can be performed simply and easily
- In places where it is unsuitable to install a contact sensor
- Measuring strain by using one of noncontact sensing systems
- Convenient and economic to measure the strain of the structure

❖ Presentation Outline

- Multi-point Measurement
- Pattern Matching
- Subpixel Estimation (Image Transform Function)
- Strain Measurement (Average Strain in 1D)
- Algorithm for Vision-based Measurement System
- Coupon Test
- Static Loading Tests (Elbow Component)
- Concluding Remarks

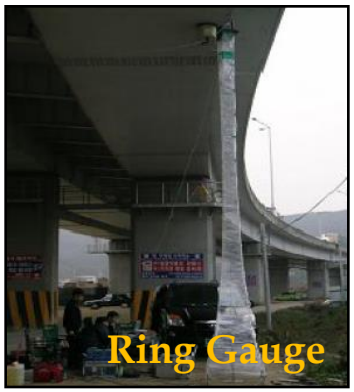
Multi-point Measurements

Conventional Sensors

- Required easy accessibility and support to fix sensor (LVDT)
- Necessity of additional equipment to protect sensor from wind (Ring Gauge)
- Difficult despite its excellent performance because it is very expensive (LDV)
- The electric resistance-type strain gauge can measure up to 3000με (Strain Gauge)
- Impossible to move from a spot to another spot after being installed on the structure

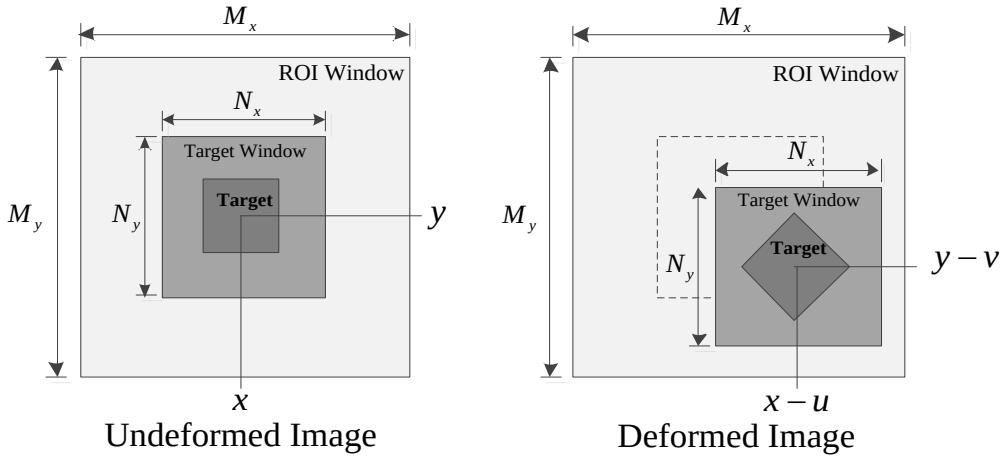
Digital Image Processing

- Multi-point displacements and strain measurements
- Subpixel measured by image transformation function (Improving resolution)



Pattern Matching

❖ Normalized Cross Correlation(NCC) Coefficient



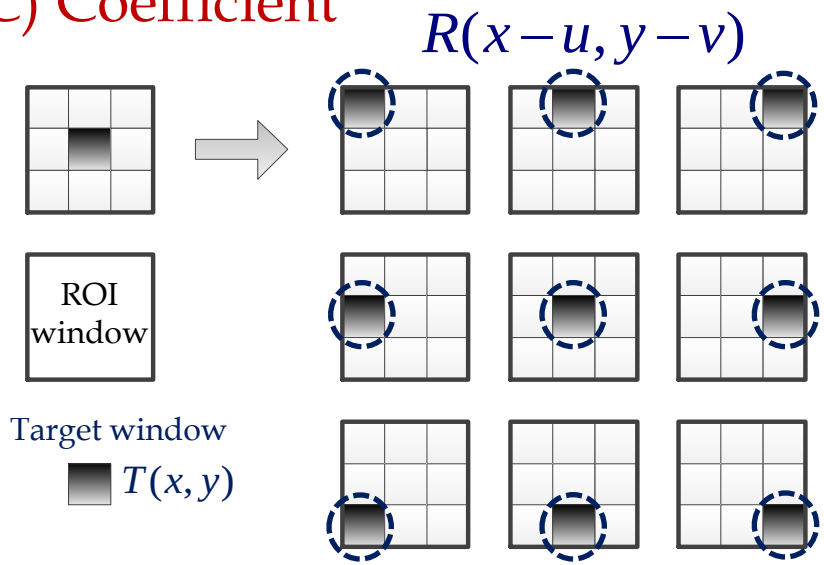


Image Before and After Deformation **NCC Coefficient Calculation**

$$\gamma_{u,v} = \frac{\sum_{xy}\left[T(x,y)-\bar{T}\right]\left[R(x-u,y-v)-\bar{R}_{u,v}\right]}{\sqrt{\sum_{xy}\left[T(x,y)-\bar{T}\right]^2 \sum_{xy}\left[R(x-u,y-v)-\bar{R}_{u,v}\right]^2}} = 1 \sim -1$$

$$\bar{T} = \frac{1}{N_x N_y}\sum_{x=0}^{N_x-1}\sum_{y=0}^{N_y-1} T(x,y) \qquad \bar{R}_{u,v} = \frac{1}{N_x N_y}\sum_{x=u}^{u+N_x-1}\sum_{y=v}^{v+N_y-1} R(x-u,y-v)$$

Subpixel Estimation

❖ Transform Functions for Control Points

Affine Transform Function

- Composition of linear transformations(rotation, scaling, shear, translation)

Projective Transform Function

- Composition of a pair of perspective projections(rigid motion, elastic behavior)

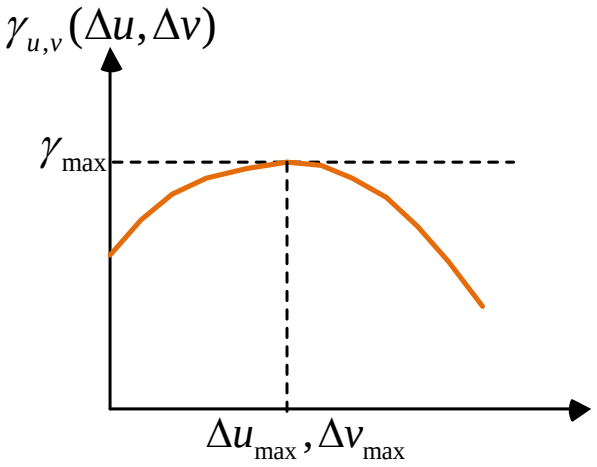
Polynomial Transform Function

- Use a set of patched points to generate a single optimal transform (bending, rigid motion, nonlinear motion)

For $\gamma_{\max}$,

$$\gamma_{u,v} = a_1 + a_2 x + a_3 y + a_4 xy + a_5 x^2 + a_6 y^2$$

$$\begin{Bmatrix} \frac{d\gamma_{u,v}}{dx} \\ \frac{d\gamma_{u,v}}{dy} \end{Bmatrix} = \begin{Bmatrix} a_2 \\ a_3 \end{Bmatrix} + \begin{bmatrix} 2 \cdot a_5 & a_3 \\ a_4 & 2 \cdot a_6 \end{bmatrix} \cdot \begin{Bmatrix} \Delta u_{\max} \\ \Delta v_{\max} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

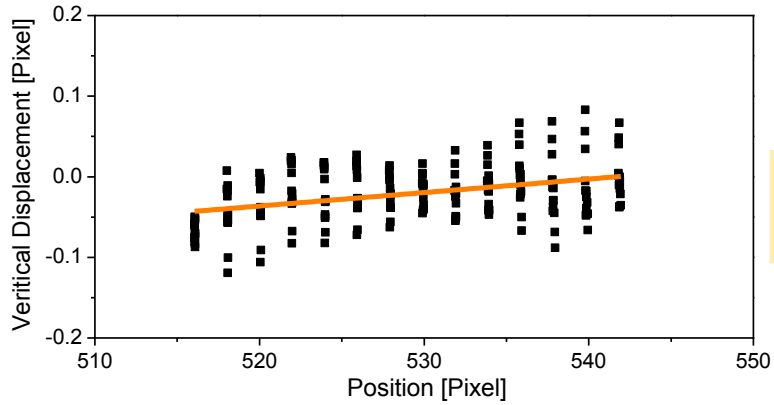


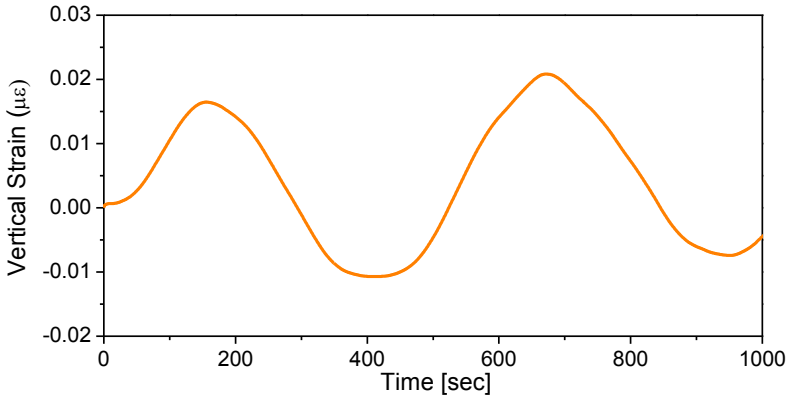
2nd Order Polynomial Transform Function

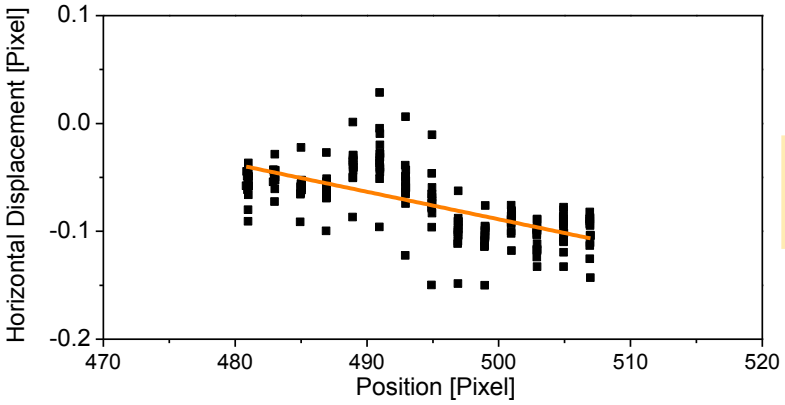
Strain Measurement

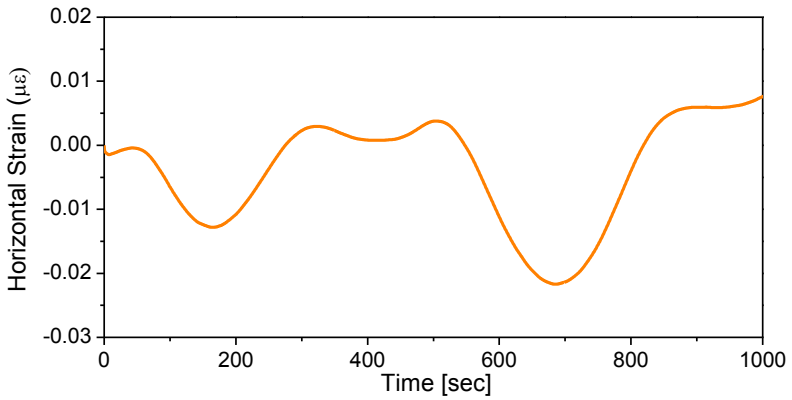
❖ Average Strain in 1D

- The axial displacement about axial direction is plotted for each image and then fitted by a linear function.
- The slope is the true strain.









Algorithm for Vision-based System

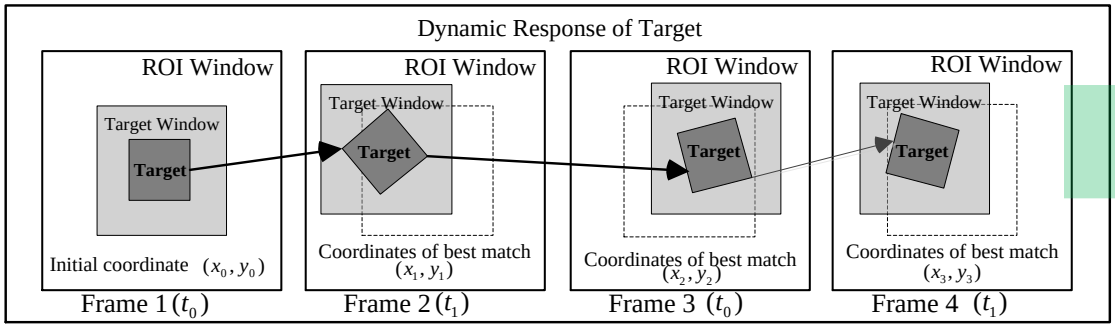
Image Arrangement (Image File)

Selecting Control Points (Number of Targets)

Defining the Correlation Size (Target and ROI Windows)

Calculating the maximum motion of the target window in order to efficiently set the ROI window

Normalized Cross Correlation Computation



Searching for the position where the maximum value of Normalized Cross Correlation Coefficient is obtained

Subpixel Estimation (Strain Measurement Using Image Transform Function)

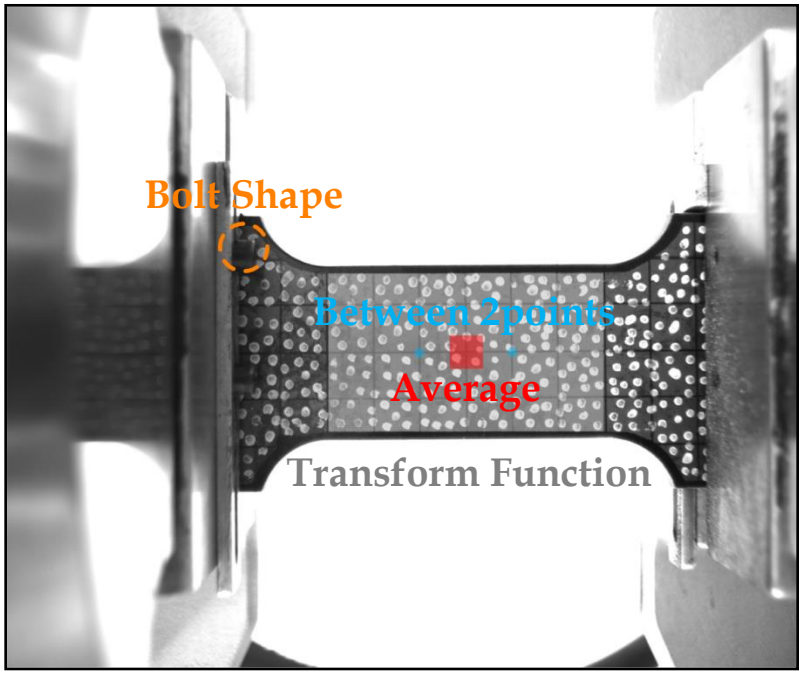
Enhancing the resolution of displacement responses by using the 2nd Order Polynomial Transform Function

Displacement Response Analysis

Strain Response Measurement (Average Strain)

Coupon Test

❖ Experimental Setup



Measurement Positions

UTM Loading : Bolt Shape

Between 2 points, Average, Shape Function

Sampling Rate

UTM : 10Hz

CMOS Camera : IMB-7050G, 2448 x 2048 pixels, 2Hz

Resolution

57mm/893pixel = 0.067mm/pixel

Error Analysis

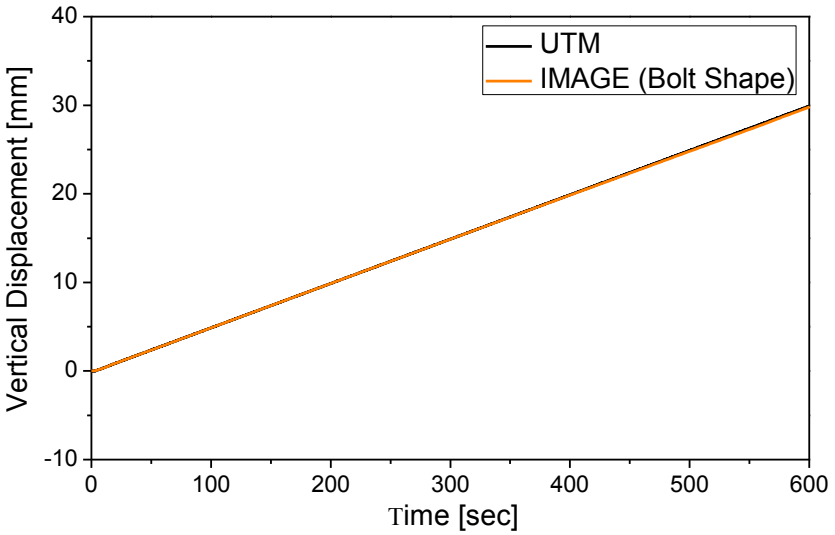
$$\text{Percent error} = \sum_{i=1}^{n}(\delta_m - \delta_c)^2 / \sum_{i=1}^{n}(\delta_m)^2$$

$$\text{RMS error} = \sqrt{\sum_{i=1}^{n}(\delta_c - \delta_m)^2 / n}$$

δ_m : measured data

δ_c : estimated data

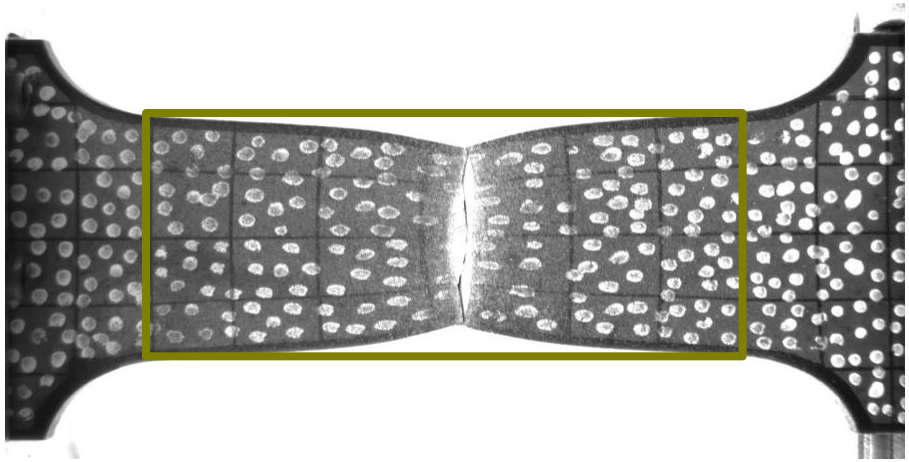
n : number of measured data

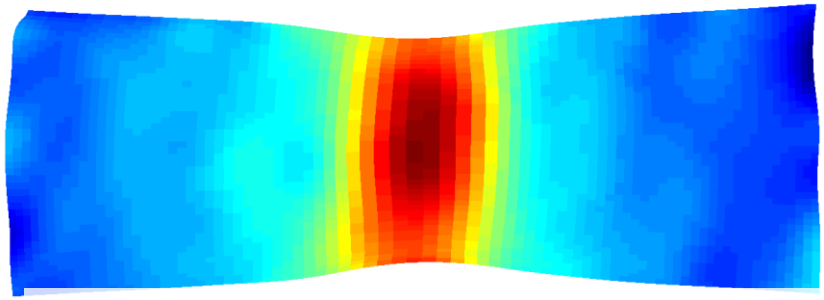


RMS error=0.21mm, Percent error=0.014%

Coupon Test

❖ Strain





Deformed Grid

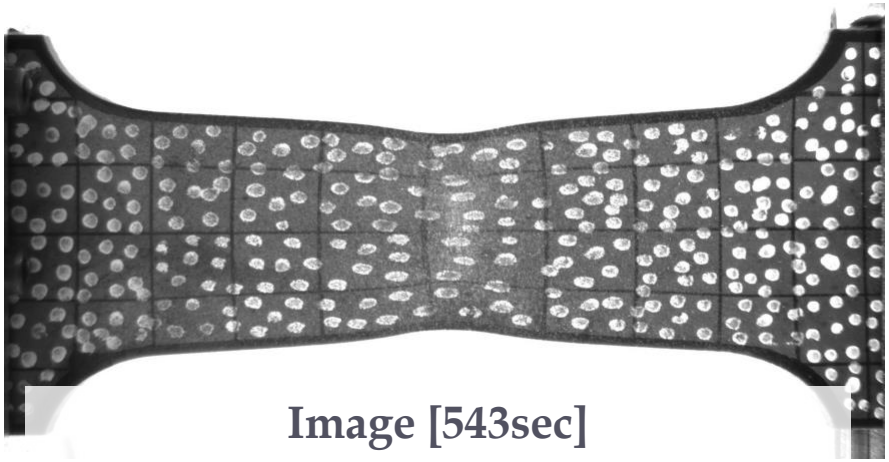
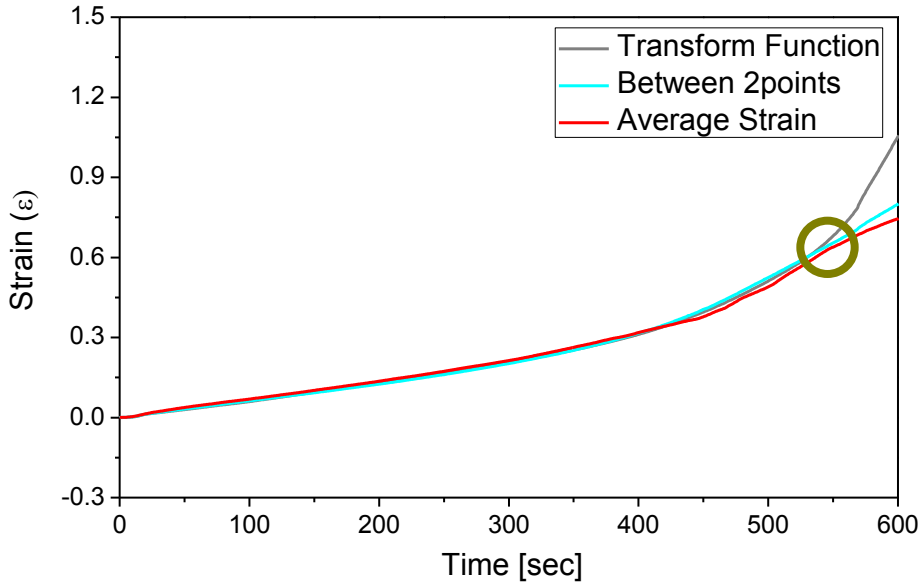
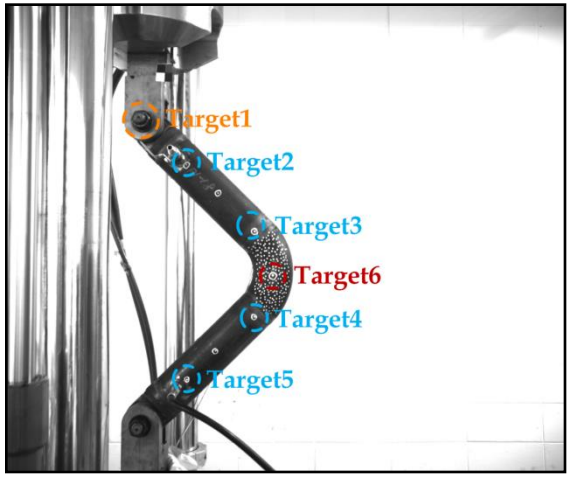


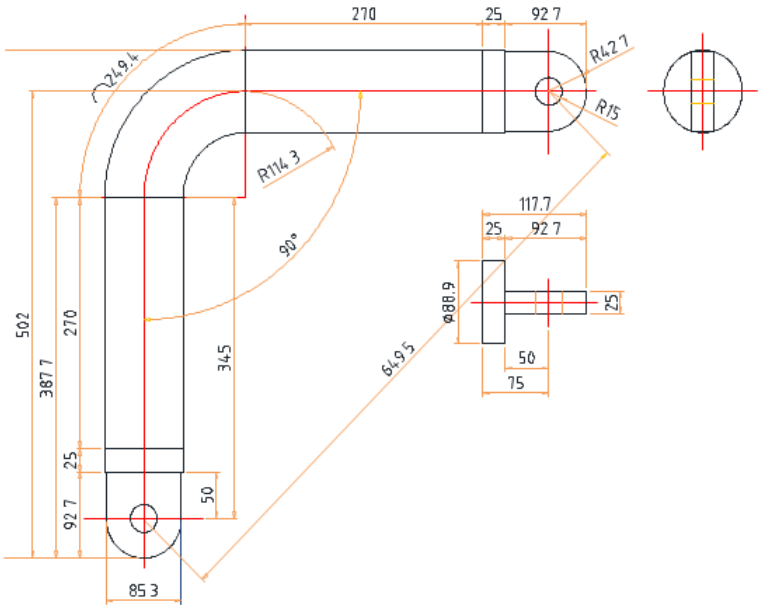
Image [543sec]



Static Loading Test

❖ Experimental Setup





Pipe : ASME B36. 10, SA-106 STEEL

3in SCH. 40(STD), 0D.=88.9mm THK.=5.49mm

Elbow : ASME B36. 10, SA-106 STEEL

3in SCH. 40(STD), R=114.3mm THK.=5.49mm

Measurement Positions

UTM Loading : Target 1 (Bolt Shape)

Elbow Angle : Target s 2, 3 ,4 , and 5

Elbow Angle (Image Analysis)

Strain : Target 6 (Strain Gauge and Image)

Sampling Rate

UTM : 1Hz

Strain Gauge : 1Hz

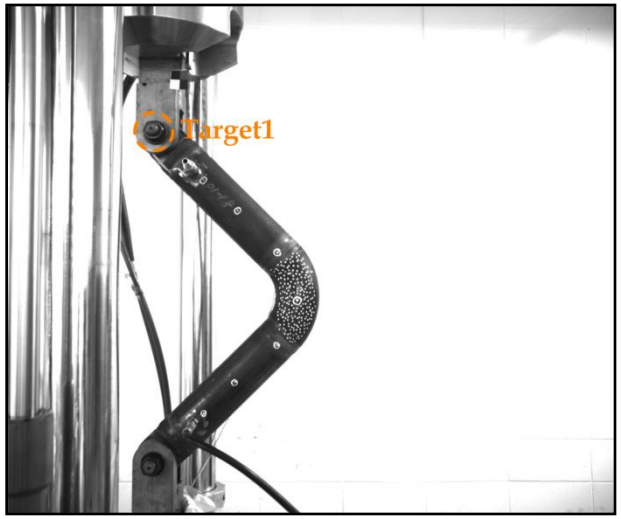
CMOS Camera : IMB-7050G, 2448 x 2048 pixels, 2Hz

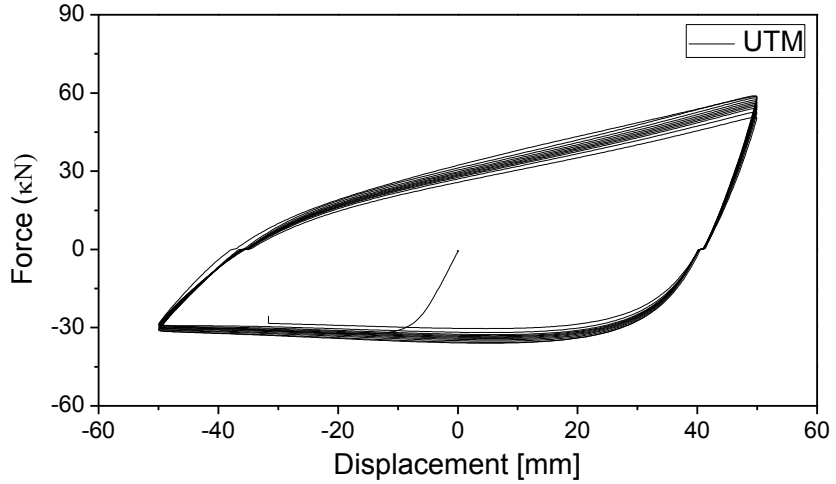
Resolution

85.3mm(Diameter)/174pixel = 0.49mm/pixel

Static Loading Test

❖ UTM Loading





Error Analysis

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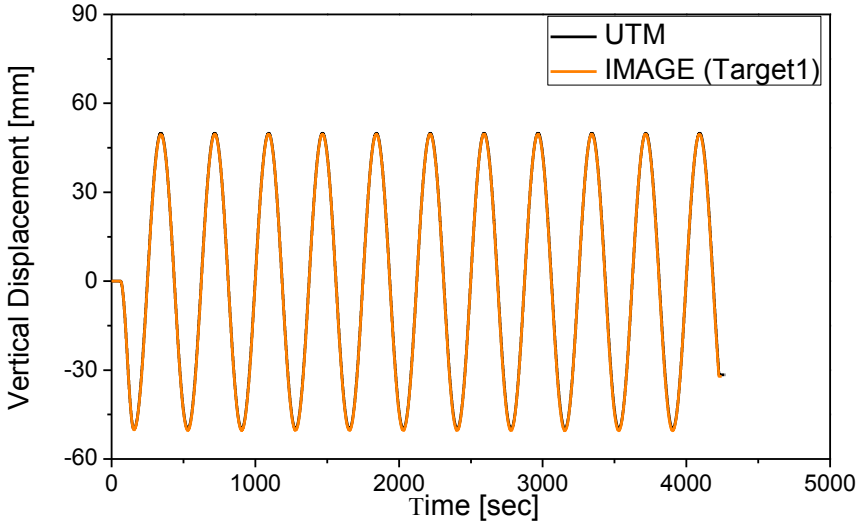
$$\text{RMS error} = \sqrt{\sum_{i=1}^{n}(\delta_c - \delta_m)^2 / n}$$

δ_m : measured data

δ_c : estimated data

n : number of measured data



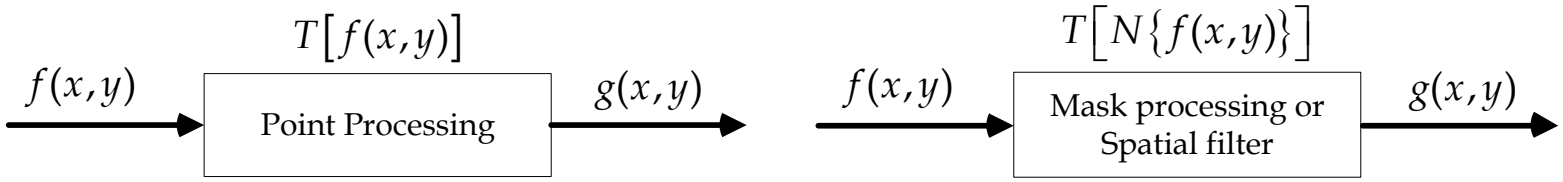
RMS error=0.416mm, Percent error=0.015%

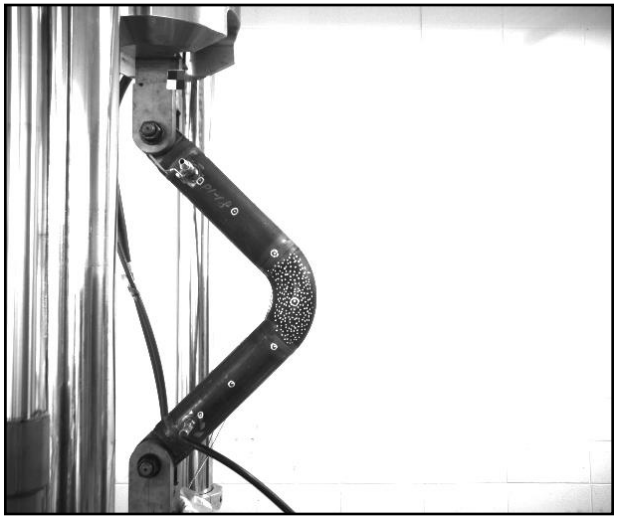
Static Loading Test (Elbow Angle)

❖ Spatial Filter

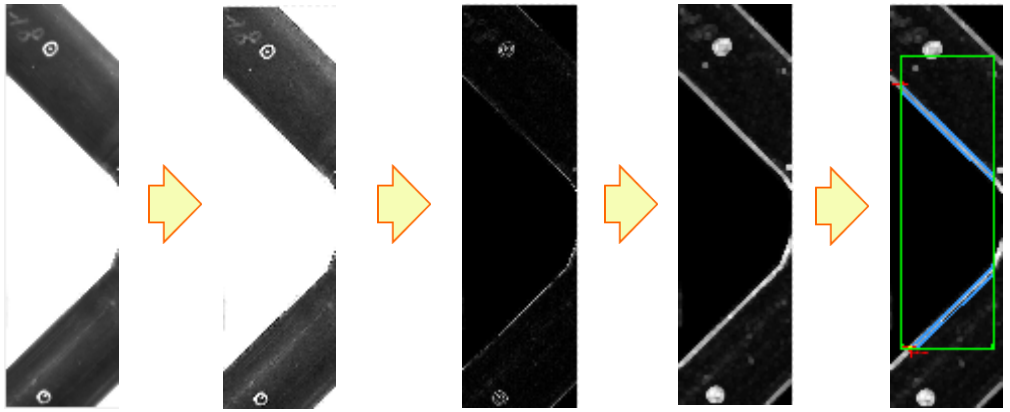
Purpose

- Process image so that the result is more suitable than the original image for a specific application
- Blur or noise reduction, Highlight fine detail or enhance detail that has been blurred





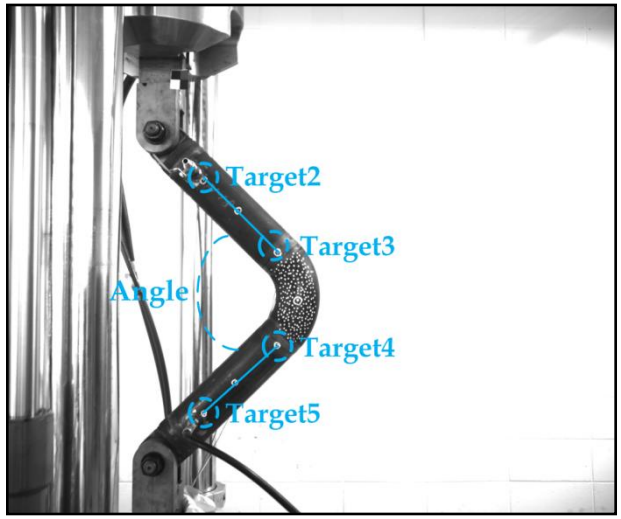
Original Image

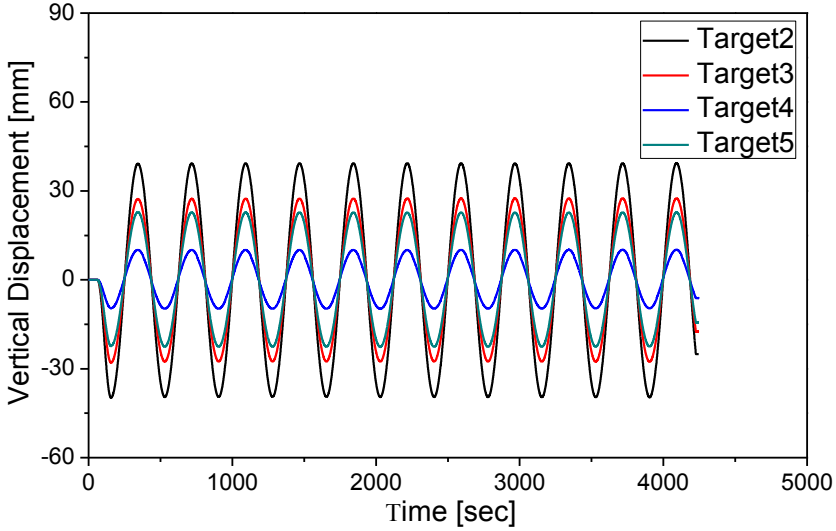


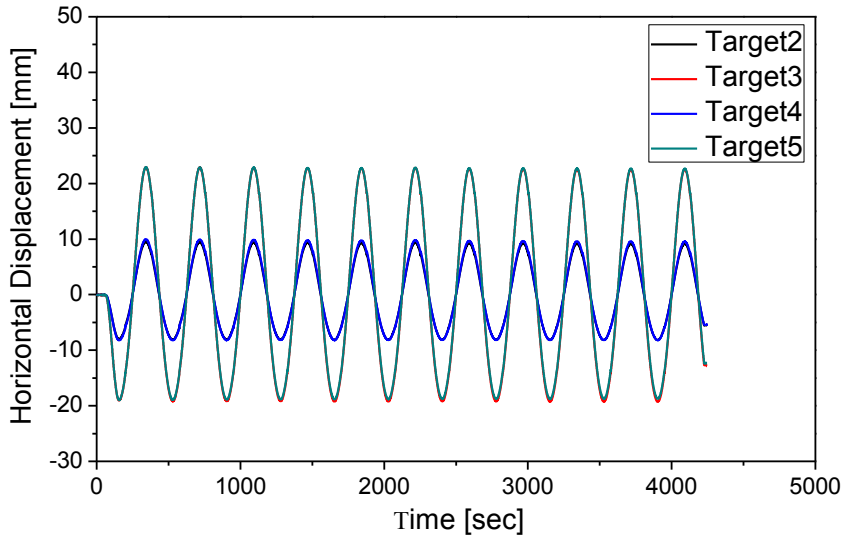
ROI → Convolution → Sobel → Dilate → Curve Extraction

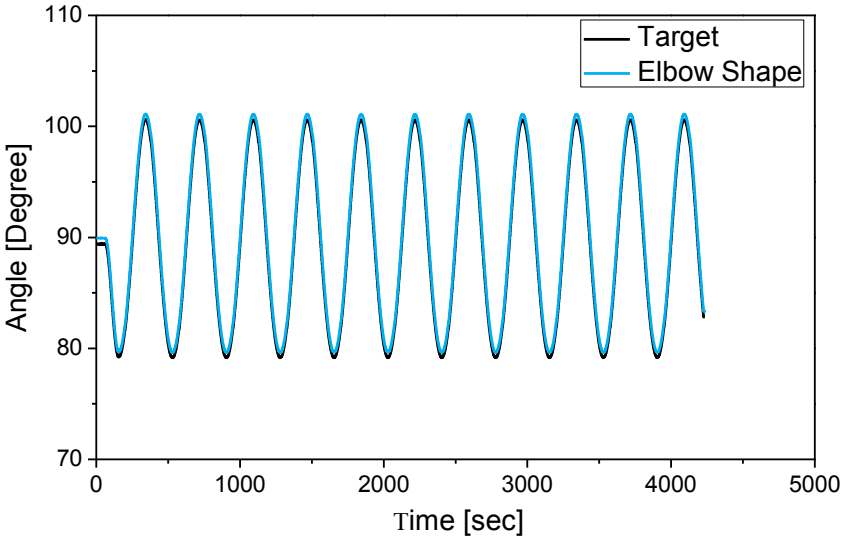
Static Loading Test

❖ Elbow Angle





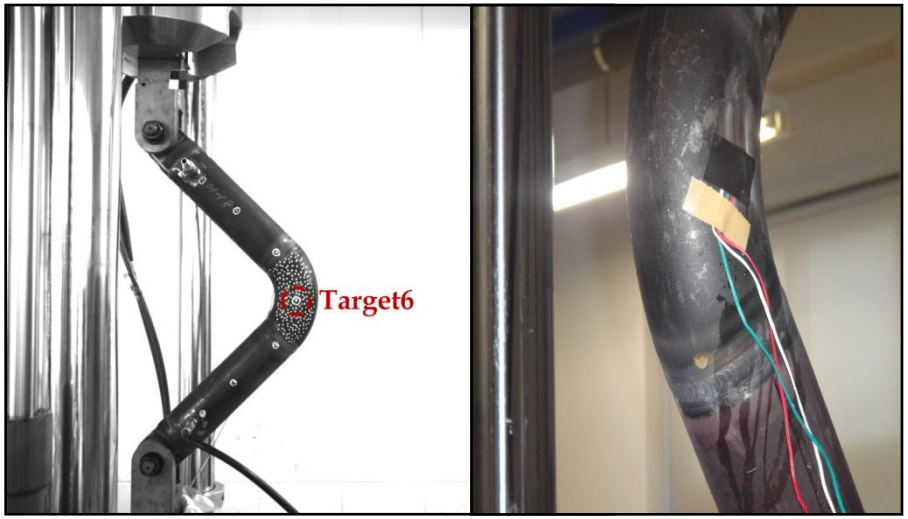


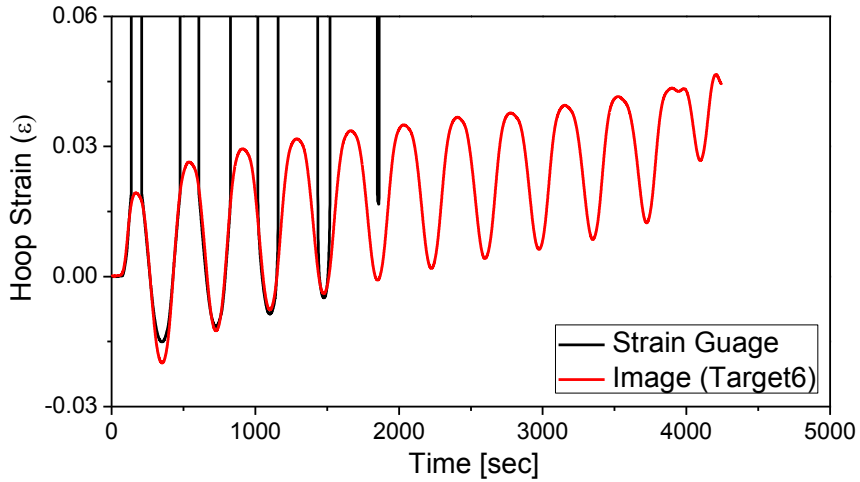


RMS error=0.510˚, Percent error=0.003%

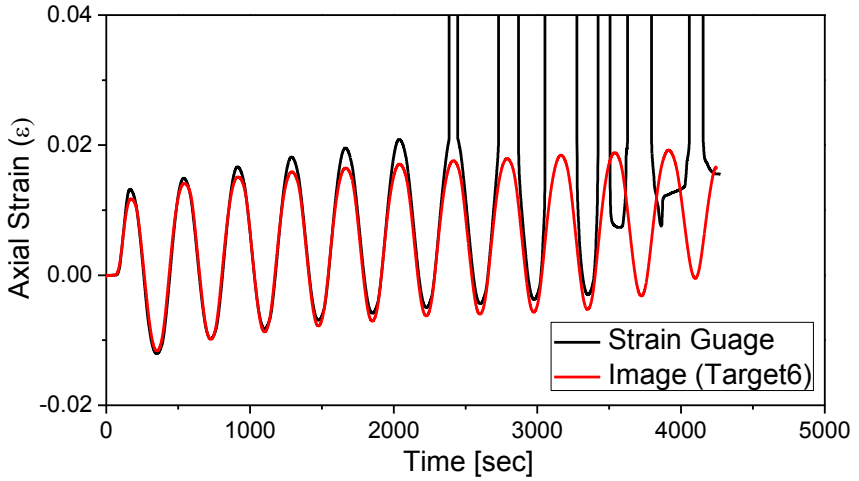
Static Loading Test

❖ Strain





RMS error=0.00013, Percent error=2.158%
(0~100sec)



RMS error=0.00039, Percent error=0.687%
(0~2300sec)

Concluding Remarks

- The estimated displacements by digital Image processing has a good agreement with measured displacements.
- It is possible to use the sensor to estimate the displacements through the bolt shape without installing a target on the piping system.
- The electric resistance-type strain sensor can measure up to 3000με, where similar results(strain gauge and image) are presented.
- It is possible to measure the angle using the shape without installing a target on the structure.