A Pedagogical Image Processing Tool to Understand Structural Dynamics

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Virtual Measurement

The main goal is to develop/test a pedagogical framework to analyse vibration from video.

Project students demonstrate that, For this experimental rig, modal test with classical contact accelerometers is difficult/long
Whereas use virtual measurement is easy

Modeling a fishing rod is difficult (large displacement, NL)
Comparing different analytical theories (Bernouilli, stepped beam)

1 Introduction

2 Optical flow definition

3 Software validation

4 Case study: Dynamic parameters estimation of a flexible beam

Virtual Measurement: Previous works

Morlier, Joseph and Salom, Pierre and Bos, Frédéric (2007) New image processing tools for structural dynamic monitoring. Key Engineering Materials, vol. 347 . pp. 239-244. ISSN 1013-9826

Morlier, Joseph and Michon, Guilhem (2010) Virtual vibration measurement using KLT motion tracking algorithm. Journal of Dynamic Systems Measurement and Control, vol. 132 (n° 1). pp. 011003-011011. ISSN 0022-0434

OpenCV?

Develop a universal toolbox for research and development in the field of Computer Vision

It is an open source computer vision library developed by Intel.

It focuses mainly towards real-time image processing.

- Basic structures and operations
- Image Analysis
- Structural Analysis
- Object Recognition
- **Motion Analysis**
- **Object Tracking**
- 3D Reconstruction

-This is the process of locating a moving object in time using a camera

-An algorithm analyzes the video frames and outputs the location of moving targets within the video frame.

2. Optical flow definition

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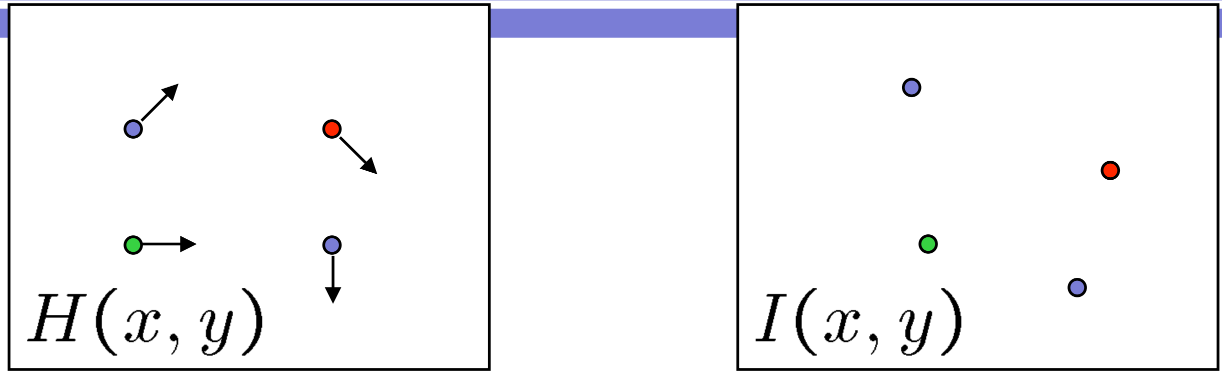
How to estimate pixel motion from image H to image I?

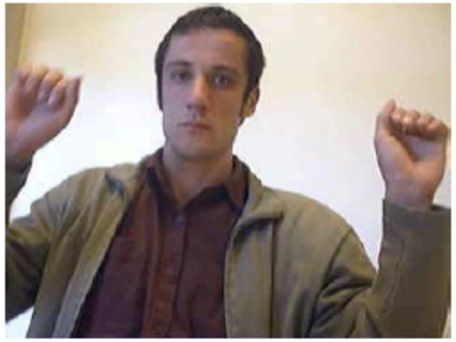


- Solve pixel correspondence problem
  - given a pixel in H, look for nearby pixels of the same color in I

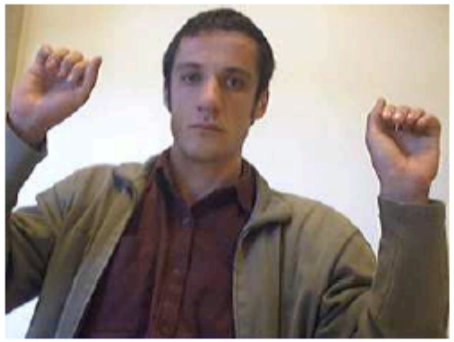
- Key assumptions
  - **color constancy:** a point in H looks the same in I
    - For grayscale images, this is **brightness constancy**
  - **small motion**: points do not move very far
- This is called the **optical flow** problem

Optical Flow

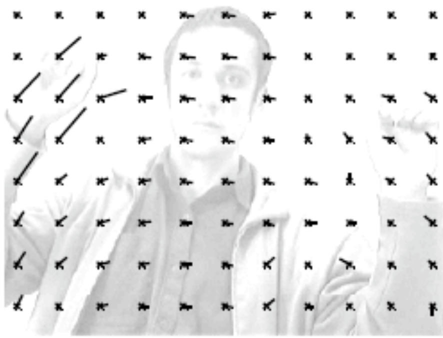
- If a vision-driven-gadget covers a region W we would like to estimate the 2D displacement d=[dx dy] (optical flow) of this patch W between two consecutive images that are captured by the camera.
- not only detects the movement but also gives us an estimate of the DIRECTION and the SPEED of the movement.



a) a frame from an image sequence



b) the next frame from the sequence



d) optical flow for some image points (lines present displacements)

KLT: The aim is to find the displacement d that minimizes the dissimilarity.

The displacement d is chosen to minimize the dissimilarity between two feature windows, one in image I and one in image J:

$$\varepsilon = \iint_W [J(x+d) - I(x)]^2 \, w(x) dx$$

where *w* is the given feature window,
$x = [x, y]^T$ are coordinates in the image and $d = [dx, dy]^T$ is the displacement.
The weighting function *w(x)* is usually set to the constant 1

Differentiating

$$\frac{\partial \varepsilon}{\partial d} = 2 \iint_W [J(x+d) - I(x)] \frac{\partial J(x+d)}{\partial d} w(x) dx = 0$$

Approximating

$$J(x+d) \approx J(x) + d_x \frac{\partial}{\partial x} J(x) + d_y \frac{\partial}{\partial y} J(x)$$

$$\frac{\partial \varepsilon}{\partial d} = 2 \iint_W [J(x) - I(x) + g(x)^T d] \; g(x) w(x) dx = 0$$

Where $g(x) = \begin{bmatrix} \frac{\partial}{\partial x} J \\ \frac{\partial}{\partial y} J \end{bmatrix}$

Rearranging terms yields a linear 2 × 2 system:

$$Zd = e \qquad Z = \iint_W \mathrm{g(x)g(x)^T w(x)dx} \qquad e = \iint_W [I(x) - J(x)] g(x) w(x) dx$$

Displacement d is obtained by solving this equation using a Newton-Raphson algorithm

processing method for dynamic parameter extraction

Technical assumptions

- High vertical resolution to obtain sufficient deformation
- Plan of study is perpendicular to the structure (small angular errors)
- Camera stability, image not fuzzy
- Good contrast

High speed camera to obtain a frequency bandwidth of several hundred of Hz

If we assume global motion with constant velocity vx and vy (in pixels per standard-speed frame) and spatially band limited image with Bx and By as the horizontal and vertical spatial bandwidths (in cycles per pixel),

the minimum temporal sampling frequency fs (in cycles per speed frame) to avoid motion aliasing is given by:

$f_s = 2Bt = 2B\ vx + 2By\ vy$

Microsoft Development Environment [design] - lkdemoresonance2.cpp

Fichier Edition Affichage Déboguer Outils Fenêtre ?

lkdemoresonance2.cpp

```
            IplImage* eig = cvCreateImage( cvGetSize(grey), 32, 1 );
            IplImage* temp = cvCreateImage( cvGetSize(grey), 32, 1 );
            double quality = 0.01;
            double min_distance = 10;

            count = MAX_COUNT;
            cvGoodFeaturesToTrack( grey, eig, temp, points[1], &count,
                                   quality, min_distance, 0, 3, 0, 0.04 );
            cvFindCornerSubPix( grey, points[1], count,
                cvSize(win_size,win_size), cvSize(-1,-1),
                cvTermCriteria(CV_TERMCRIT_ITER|CV_TERMCRIT_EPS,20,0.03));
            cvReleaseImage( &eig );
            cvReleaseImage( &temp );

            add_remove_pt = 40;
        }
        else if( count > 0 )
        {
            cvCalcOpticalFlowPyrLK( prev_grey, grey, prev_pyramid, pyramid,
                points[0], points[1], count, cvSize(win_size,win_size), 3, status, 0,
                cvTermCriteria(CV_TERMCRIT_ITER|CV_TERMCRIT_EPS,20,0.03), flags );
            flags |= CV_LKFLOW_PYR_A_READY;
            for( i = k = 0; i < count; i++ )
            {
                if( add_remove_pt )
                {
                    double dx = pt.x - points[1][i].x;
                    double dy = pt.y - points[1][i].y;

                    if( dx*dx + dy*dy <= 25 )
                    {
                        add_remove_pt = 0;
                        continue;
                    }

                }

                if( !status[i] )
                    continue;

                points[1][k++] = points[1][i];
                cvCircle( image, cvPointFrom32f(points[1][i]), 3, CV_RGB(0,200,0), -1, 4,0);
```

3. Software validation

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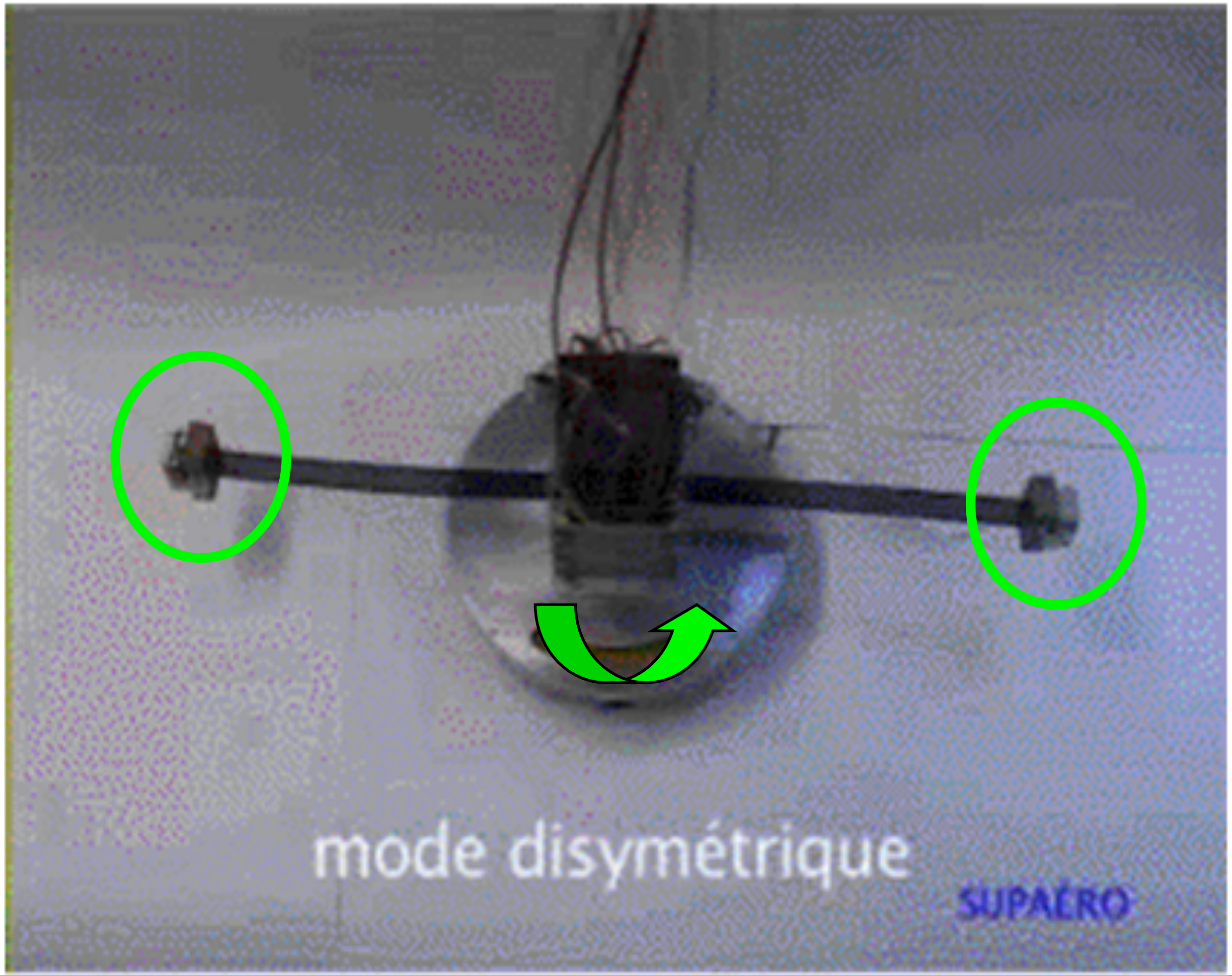
Software Validation, normal camera

Satellite Model, Flexible structure

key points
- to choose



Helicopter Blade, Flexible structure

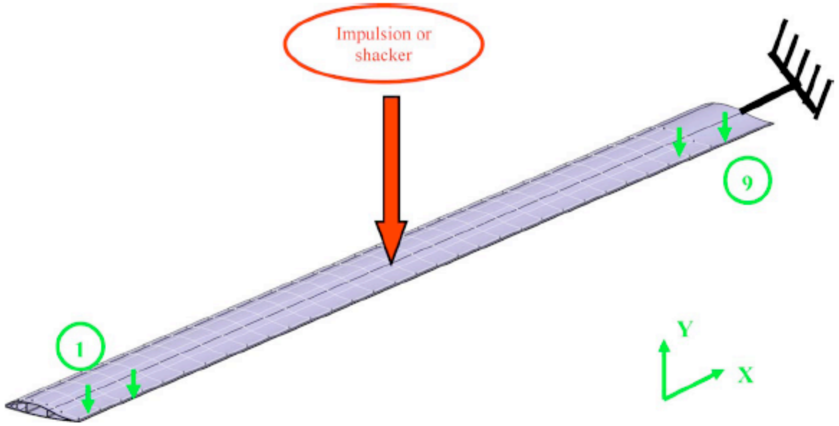


Fig. 6 Helicopter blade example: KLT trackers are used to follow nine targets in bending (Y displacement). The targets are numbered from 1 to 9, and the blade is excited at its center.

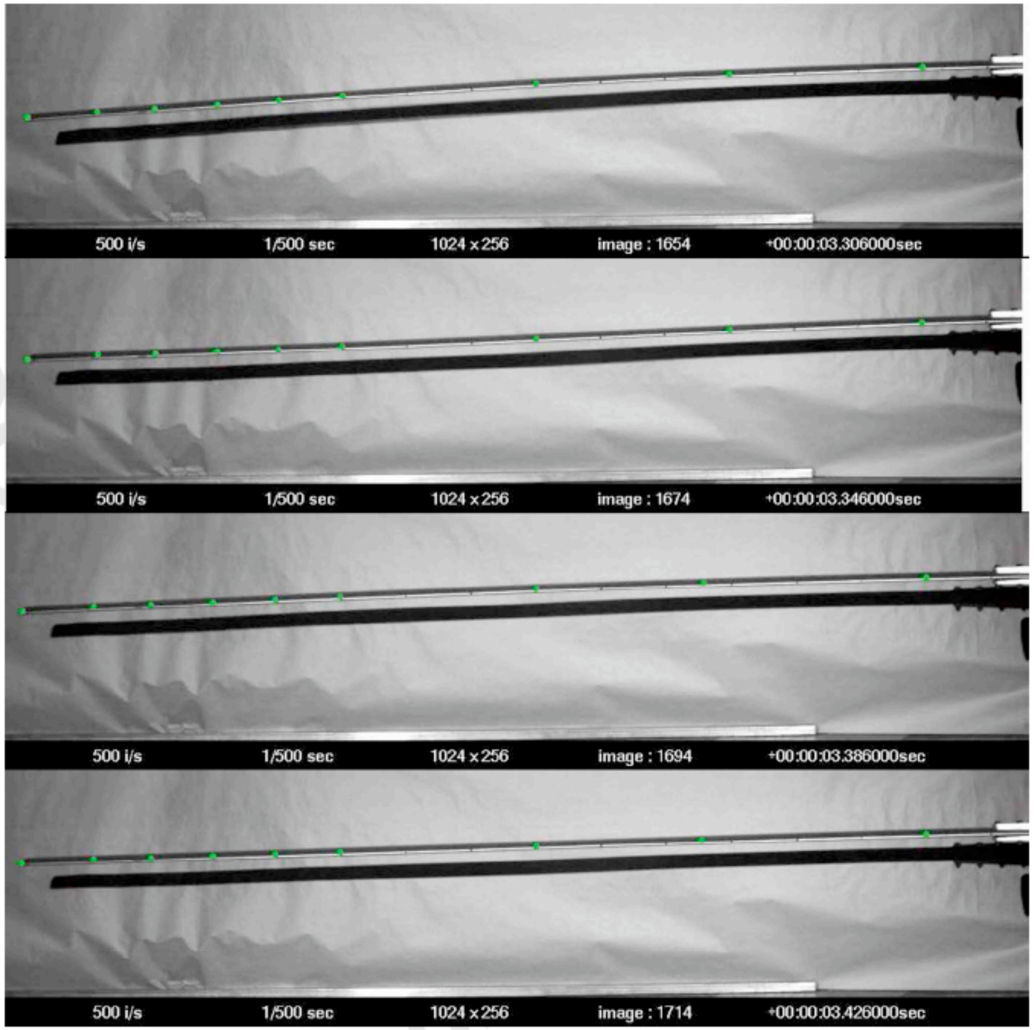


Fig. 10 Half-period is visualized from several successive frames. Virtual sensors are visualized with a small green dot; displacement is measured in the Y direction (green dots).

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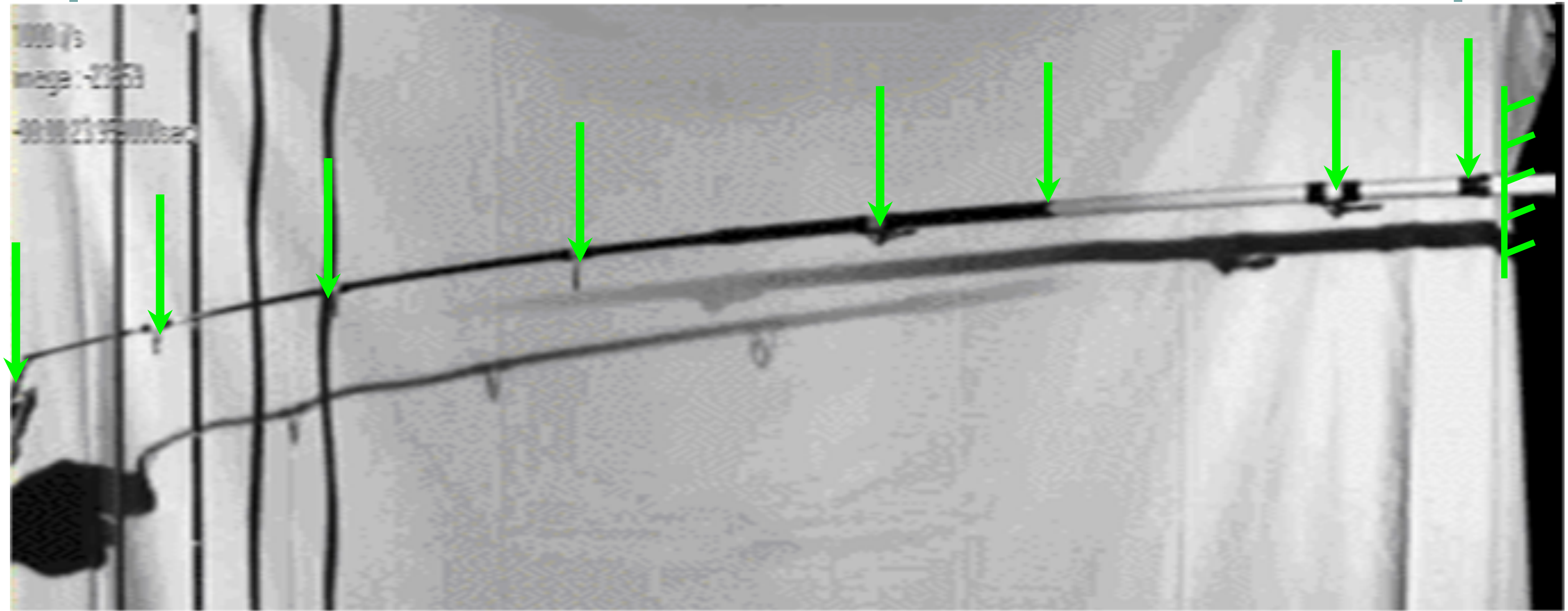
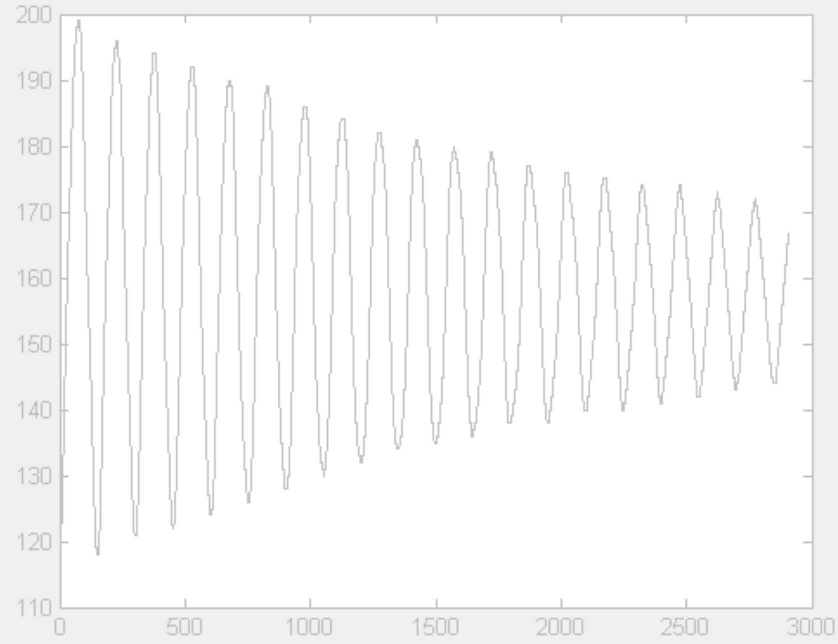
Pedagogical practice using High Speed Camera

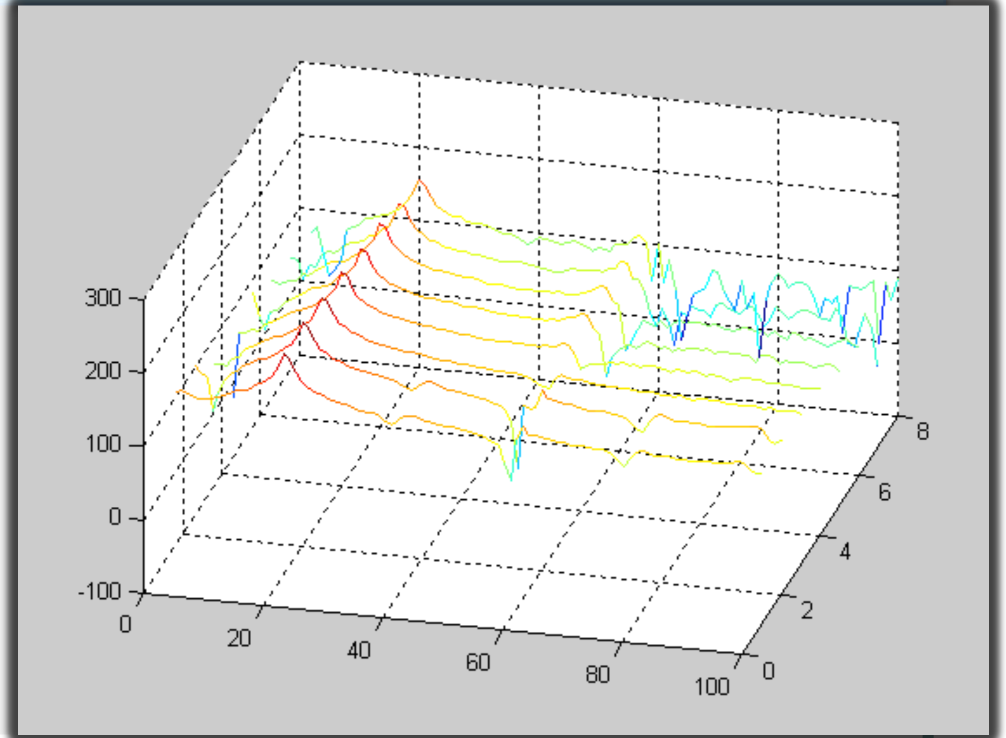
Fishing rod Test rig (blocked in XY plane)



Analysis of software results

(High Speed Camera) Fishing rod Free Vibration response





Displacement at the free edge

(pixels vs frame)

Amplitude of the FRF

(dB vs Frequency Vs points under study)

Smoothed temporal data: moving average

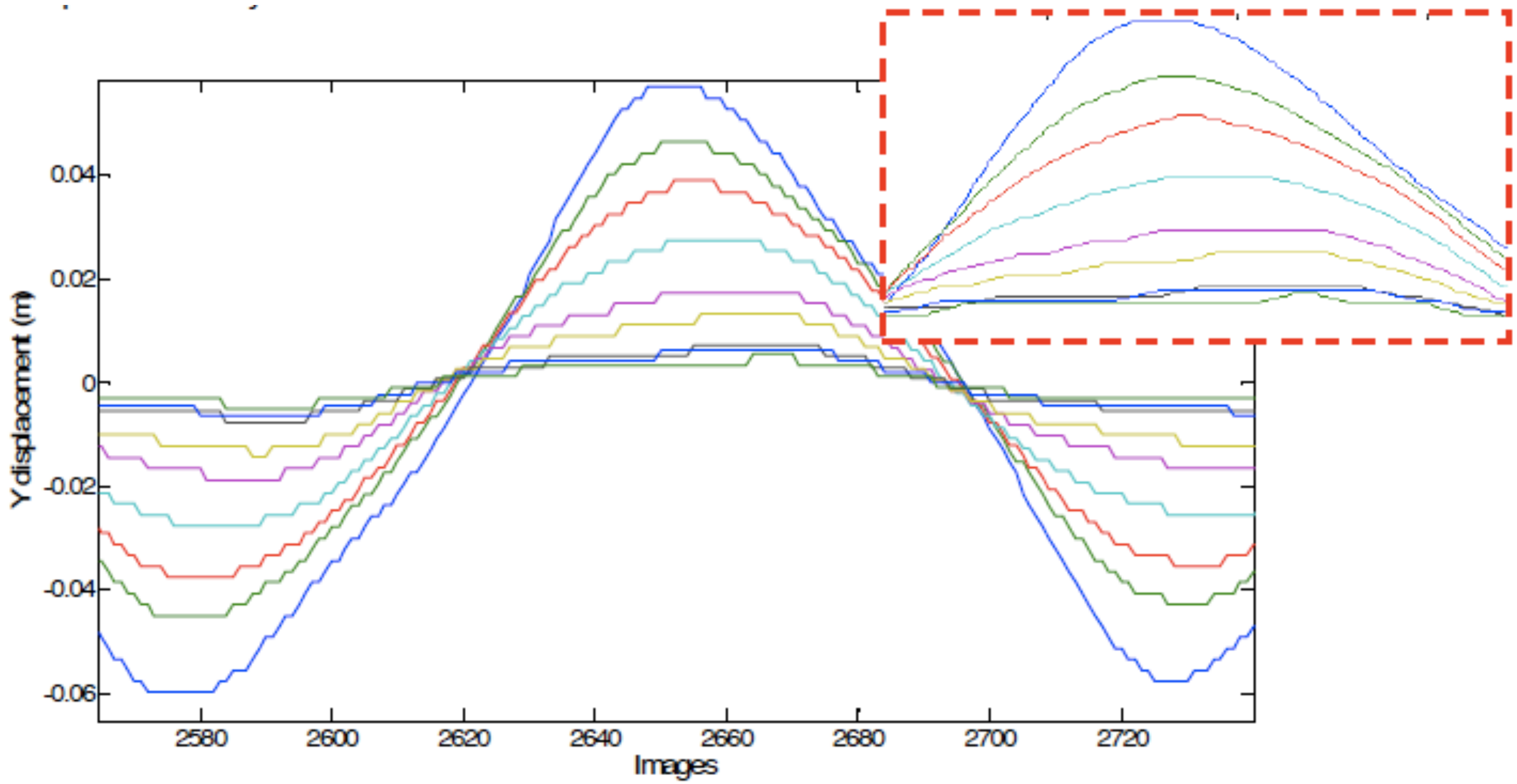
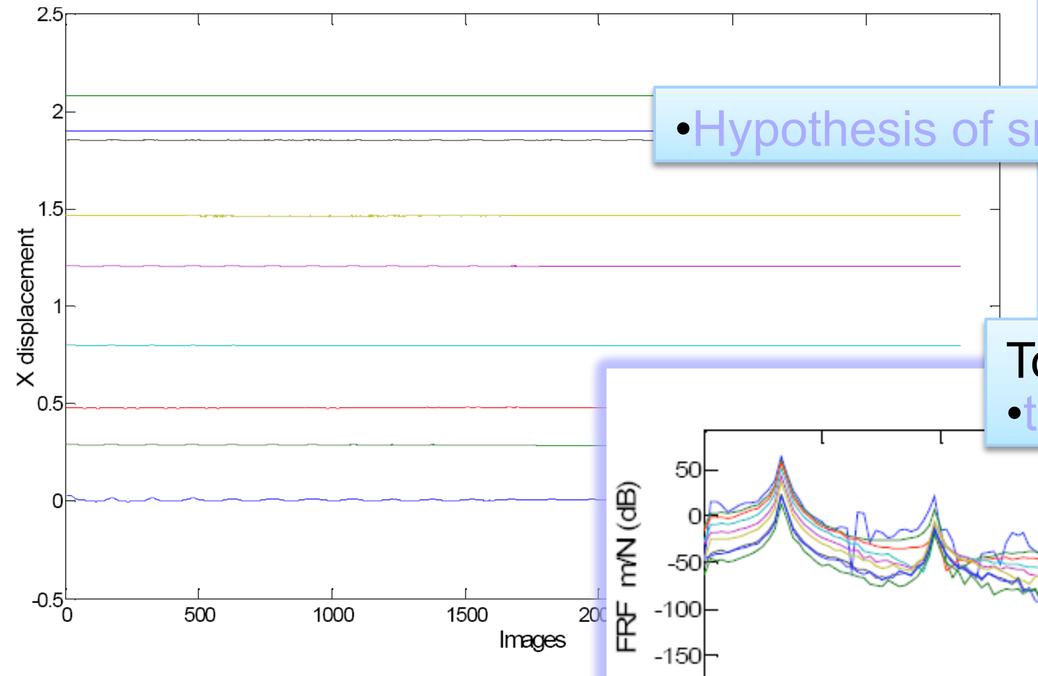


Figure 4: Effect of the moving average function on the temporal signal. This pre-processing aims at obtaining smooth FRFs.

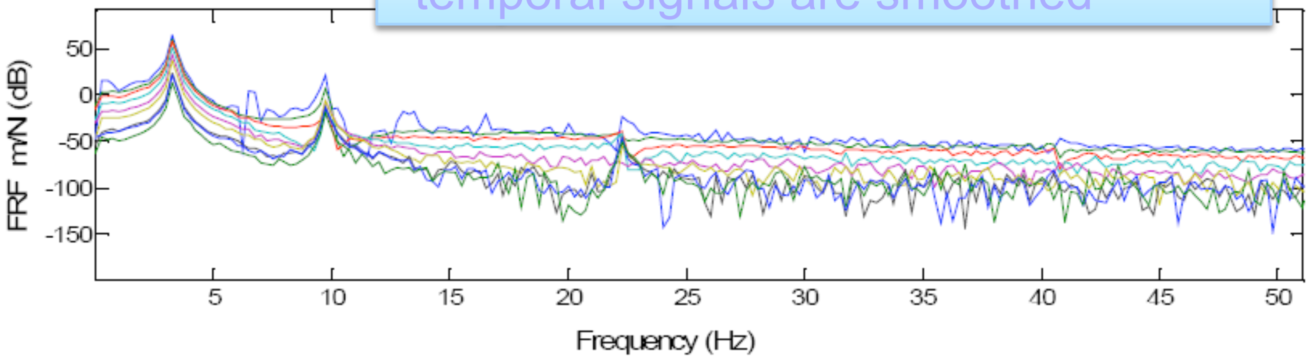
From video motion estimation to dynamic monitoring



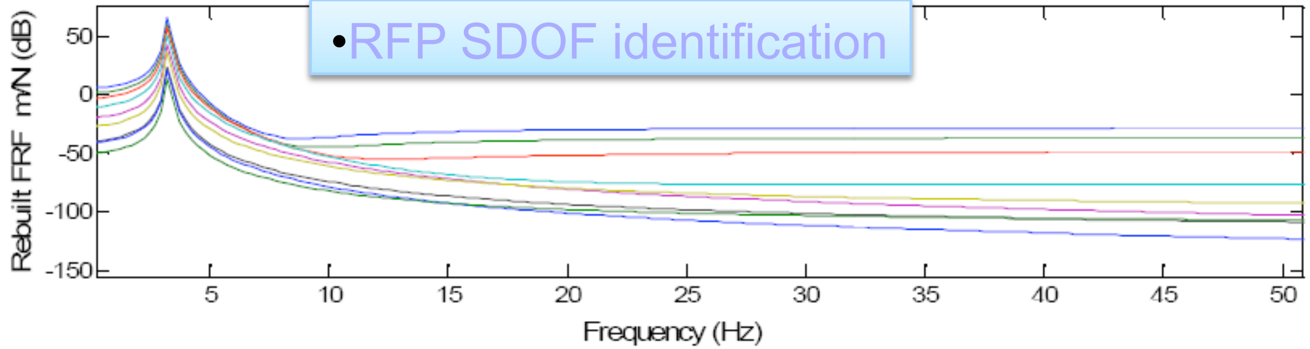
- Hypothesis of small linear displacement

To enhance the spectral resolution :

- temporal signals are smoothed



- RFP SDOF identification



Results of the motion tracking monitoring

$E(f)$	$\sigma(f)$	$E(\xi)$	$\sigma(\xi)$
3.32 (Hz)	6E-4	0.93 (%)	3E-4
9.78 (Hz)	8E-2	0.96 (%)	3E-3
21.69 (Hz)	3E-2	0.73 (%)	3E-3

High Correlation with previous accelerometers data

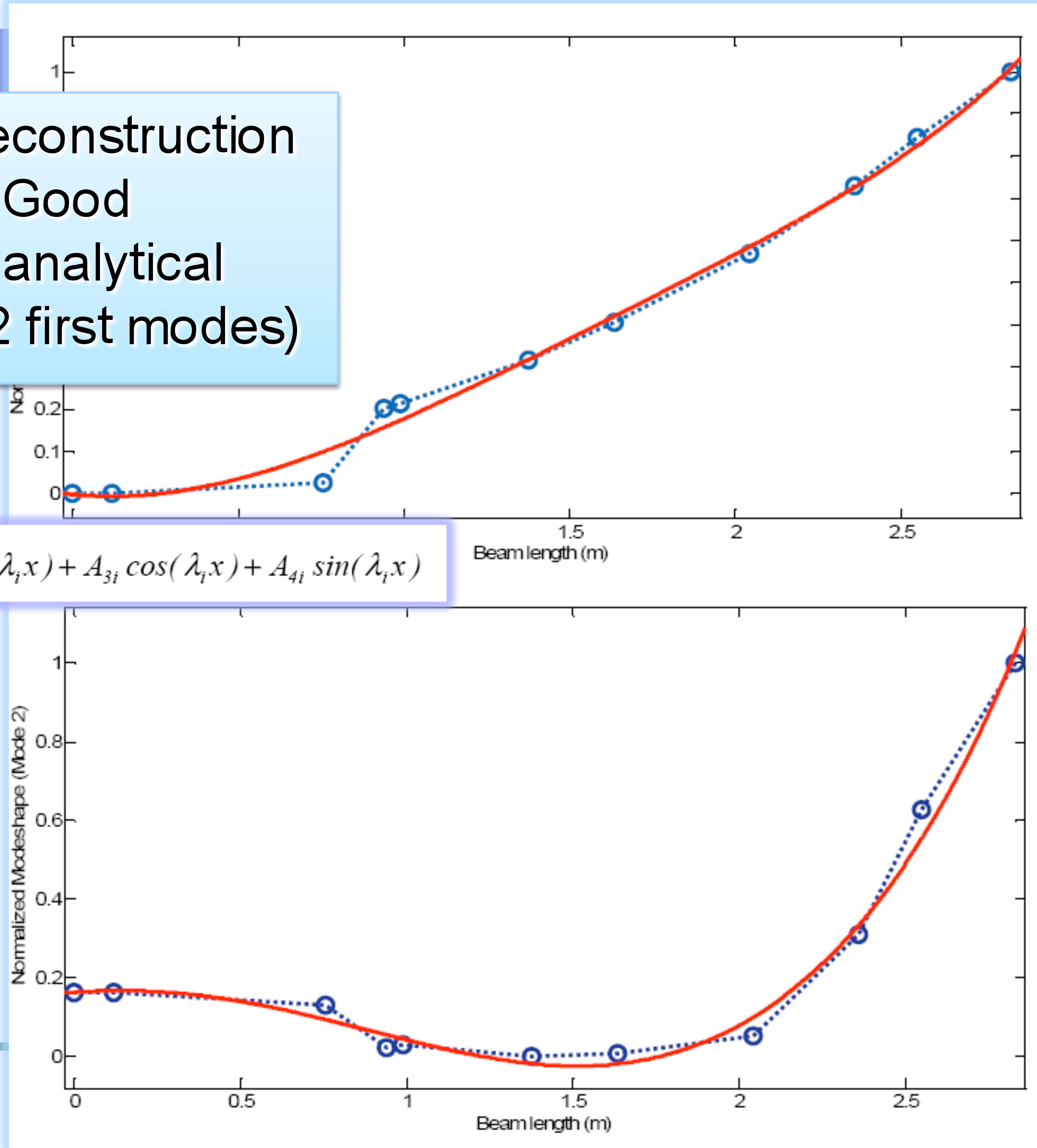
Frequency ratio	Tapered theory	Experimental	Error
$\frac{\omega_2}{\omega_1} = \left(\frac{\beta_2}{\beta_1}\right)^2$	2.61	2.945	12%
$\frac{\omega_3}{\omega_2} = \left(\frac{\beta_3}{\beta_2}\right)^2$	1.81	2.21	22%

Good correlation with theory

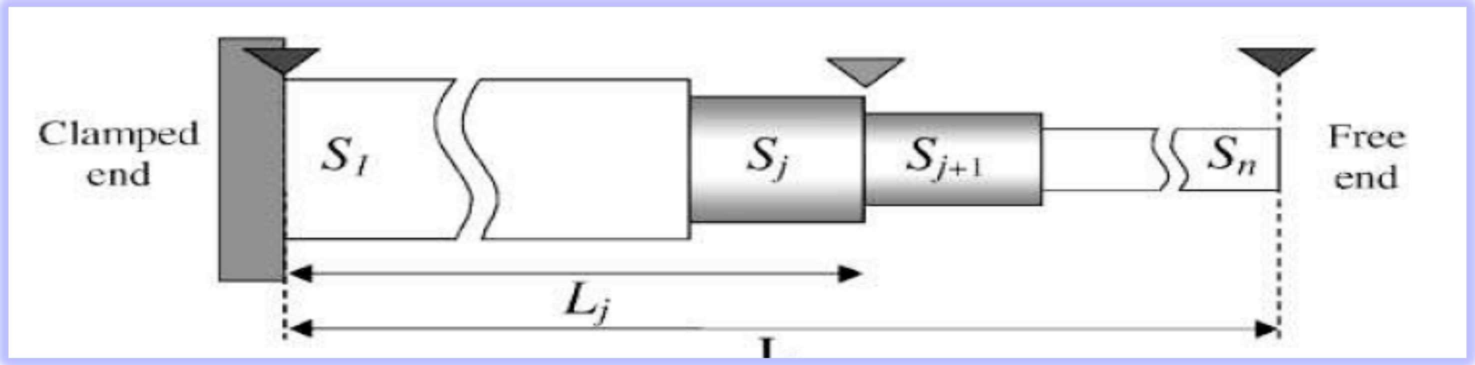
H. Wang and W.J. Worley, Tables of natural frequencies and nodes for transverse vibration of tapered beams, NASA CR443, 1966.

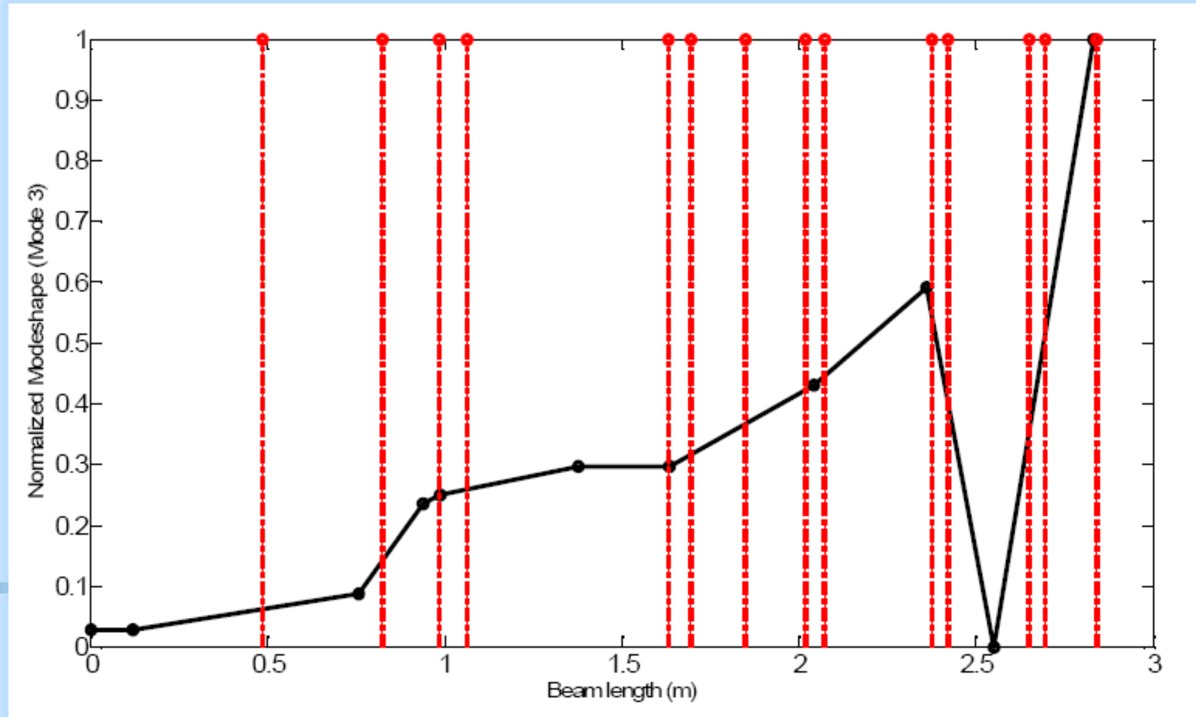
Mode shapes reconstruction from FRF data: Good regression with analytical mode shapes (2 first modes)

$$Y_i(x) = A_{1i}\cosh(\lambda_i x) + A_{2i}\sinh(\lambda_i x) + A_{3i}\cos(\lambda_i x) + A_{4i}\sin(\lambda_i x)$$



3rd Mode shape identification: Influence of tapered beam





Conclusions

- Computer vision methods are able using Lukas-Kanade optical flow algorithm to extract reliable dynamic parameters
- Several validations of the software from simple case to the worst case: Now we know the limitations !
- If small linear displacement hypothesis not checked:

→ Sparse signal reconstruction (Random Sampling)

- Making some important assumptions our method coupled with operational modal analysis could also be used to :

→ Monitor real structure under ambient excitation

→ Check structural integrity

Future Works

- Multiple camera for 3D dynamic reconstruction (markerless)