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CONTROL OF FLEXIBLE STRUCTURES WITH DISTRIBUTED SENSING AND PROCESSING

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p. 20

ABSTRACT

Technology is being developed to process signals from distributed sensors using distributed computations. These distributed sensors provide a new feedback capability for vibration control that has not been exploited. Additionally, the sensors proposed are of an optical and distributed nature and could be employed with known techniques of distributed optical computation (Fourier optics, etc.) to accomplish the control system functions of filtering and regulation in a distributed computer. This paper extends the traditional digital, optimal estimation and control theory to include distributed sensing and processing for this application. The design model assumes a finite number of modes which make it amenable to empirical determination of the design model via familiar modal-test techniques. The sensors are assumed to be distributed, but a finite number of point actuators are used. The design process is illustrated by application to a Euler beam. A simulation of the beam is used to design an optimal vibration control system that uses a distributed deflection sensor and nine linear force actuators. Simulations are also used to study the influence of design and processing errors on the performance.

PRESENTATION OUTLINE

- MOTIVATION
- OPTICAL SENSING AND PROCESSING
- DESIGN PHILOSOPHY
- OVERVIEW OF THEORY
- EXAMPLE AND SENSITIVITY STUDIES
- CONCLUSIONS AND FUTURE PLANS

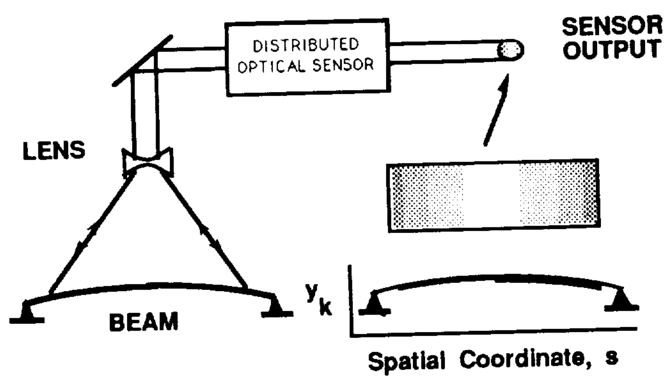
Technology is being developed for optical sensing and processing of images that can represent distributed deflections of space structures. The motivation for this is summarized below.

MOTIVATION

- ADVANTAGES OF OPTICAL DISTRIBUTED SENSING AND PROCESSING
  - Non-contacting, high precision distributed position and velocity measurements
  - Parallel computations
  - Immunity to Electromagnetic Interference
- COMBINE TRADITIONAL, EMPIRICAL, MODEL-BASED CONTROLLER DESIGN WITH OPTICAL DISTRIBUTED SENSING AND PROCESSING

A portion of the BEAM is illuminated by a coherent laser source which is gathered by LENS optics and optically input to a DISTRIBUTED OPTICAL SENSOR which produces as its SENSOR OUTPUT a coherent light wherein position or velocity information over the illuminated portion of the simply-supported beam is represented by spatial intensity variations.

OPTICAL SENSOR



Images from the sensor output are then processed by a distributed optical processor the features of which are listed below.

OPTICAL PROCESSING

- SAMPLED-DATA IMAGE PROCESSING
- SIGNALS REPRESENTED BY IMAGES WITH SPATIAL INTENSITY VARIATIONS
- ADDITION AND SUBTRACTION USING COHERENT BEAMS
- INTEGRAL AND DIFFERENTIAL OPERATORS VIA FOURIER OPTICS

Distributed sensing is combined with traditional Kalman filtering and optimal control techniques for control system design. The technique is model-based and uses a finite number of modes. Also, the number of actuators considered is finite. Implementation is performed by distributed processing.

DESIGN PHILOSOPHY

- DESIGN MODEL -- EMPIRICALLY DERIVED
  - FINITE NUMBER OF MODES
  - DISTRIBUTED SENSOR
  - FINITE NUMBER OF ACTUATORS
- CONTROL LAW DESIGN -- DISCRETE KALMAN FILTER AND REGULATOR THEORY

$$x = \begin{bmatrix} \text{Modal Amplitude} \\ \text{Modal Velocity} \end{bmatrix}$$

- IMPLEMENTATION VIA DISTRIBUTED PROCESSING

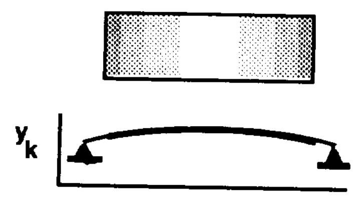
The form of measurement is shown below. It is similar to the form used for point sensors except that the finite dimensional vector representing locations of point sensors in traditional formulation is replaced by a spatial coordinate, s, which is defined over the segment that lies in the sensors "field of view". The sensor noise characteristics at any point are assumed to be independent of any other point as shown by the last equation on this page.

MEASUREMENT MODEL -- FINITE MODES with DISTRIBUTED SENSING

FORM OF MEASUREMENT

$$y_k = y(s, t_k) = H'(s)x_k + n_k(s)$$

$$s \in \Omega_M$$



SENSOR NOISE

$$E\{n_k(s)\, n_k'(s_1)\} = R(s)\, \delta(s - s_1)$$

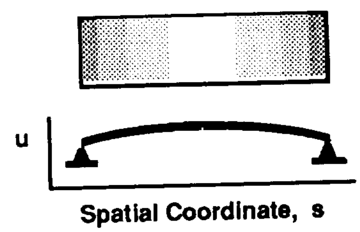
The state is assumed to be distributed and defined over the entire structure and can be expressed in terms of mode-shapes and corresponding modal amplitudes. The modal amplitude can be recovered from the modal state by integrating over the domain of the structure as shown by the last equation on this page.

DISTRIBUTED PROCESSING SIGNAL REPRESENTATION

$$u = u(s,t_k) = \phi'(s)\,[I \mid 0]\,x(t_k)$$

$$v = \frac{\partial u}{\partial t}(s,t_k) = \phi'(s)\,[0 \mid I]\,x(t_k)$$

$$s \in \Omega$$



$$[I \mid 0]\,x(t_k) = \int_{\Omega} \phi(\sigma)\,u(\sigma,t_k)\,d\sigma$$

With the assumption of finite modes, an appropriate model for the evolution of the modal state as a sampled data system is shown below. The noise term is added to account for process noise.

DYNAMICS MODEL -- FINITE MODES with DISTRIBUTED SENSING

MODAL STATE $x_k = x(t_k) = \begin{bmatrix} \text{Amplitude} \\ \text{Velocity} \end{bmatrix}$

DYNAMICS $x_{k+1} = \Phi x_k + \Gamma f_k + w_k$

PROCESS NOISE $E(w_j w'_k) = Q \delta_{jk}$

Noise is introduced during distributed processing. The noise terms W, N and M appearing in the prediction, update and regulator equations, respectively, are modeled as white Gaussian noise.

OPTICAL PROCESSING WITH NOISE

PREDICTOR $u_{k+1}^{(-)}(s) = \mathbb{F}\, u_k^{(+)}(s) + \phi'(s)\,\Gamma f_k + W$

where $\mathbb{F} = \{ \phi'(s)\,\Phi \int_\Omega \phi(\sigma)\,(\,\bullet\,)\,d\sigma \}$

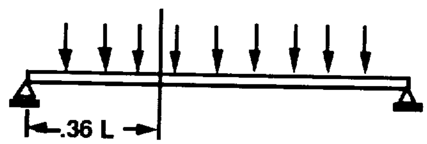
UPDATE $u_k^{(+)}(s) = u_k^{(-)}(s)$

$$+ \int_{\Omega_M} \phi'(s)\,K(\sigma)\,[y_k(\sigma) - H'(\sigma) \int_\Omega \phi(\eta)\,u_k^{(-)}(\eta)\,d\eta]\,d\sigma + N$$

REGULATOR $f_k = \int_\Omega G\,\phi(\eta)\,u_k^{(+)}(\eta)\,d\eta + M$

The method was applied to a simply supported beam with nine linear force actuators and a distributed deflection sensor. Distributed processing was simulated on a digital computer.

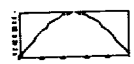
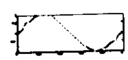
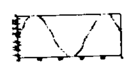
SIMULATION STUDIED



- SIMPLY SUPPORTED BEAM
- 9 LINEAR FORCE ACTUATORS
- DISTRIBUTED DEFLECTION SENSOR
- DIGITAL SIMULATION OF DISTRIBUTED PROCESSING

For simulation only the first three modes were used. The characteristics of the first three modes of the beam are summarized below.

MODAL CHARACTERISTICS OF THE BEAM

MODE	FREQ. (HZ)	DAMPING	MODE-SHAPE
1	0.600	0.0100	
2	2.400	0.0050	
3	5.400	0.0045	

In empirically derived models, errors can be introduced from different sources in the identification process. The model errors can be found in frequency, damping and mode-shape.

MODEL-ERRORS AND NOISE

- **MODEL- ERRORS**

  Frequency
  Damping
  Mode-shape

- **NOISE**

  Sensor noise : included in K-Filter Design

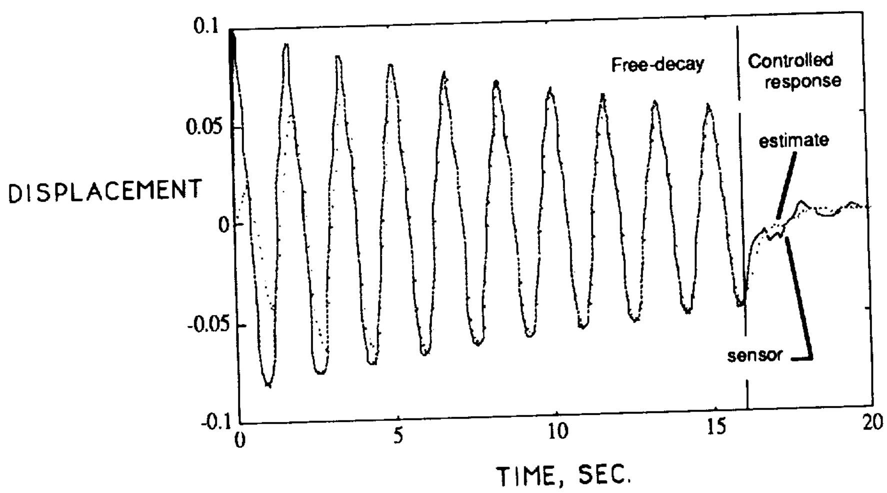
  Process noise : included in K-Filter Design

  Distributed processing noise: W, M, N -cannot be included Kalman Filter Design

The beam was allowed to vibrate freely from an initial displacement (0.1^n, n=1,2,3). After ten seconds of free vibration an LQG based controller designed for the first mode was activated. The response below shows the measurements obtained at one point (.36L from the left end) and the corresponding estimations. It takes about five seconds for the estimations to converge to the measurements. The closed-loop segment of the response shows that the vibrations are effectively damped out.

CONTROLLER PERFORMANCE
NOMINAL DESIGN

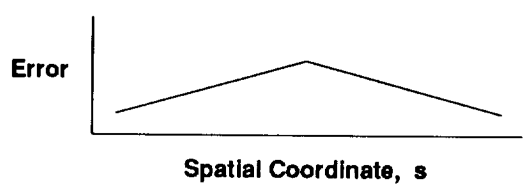
DISPLACEMENT AT .36L FROM LEFT END



Parameters of the model were varied to study its effect on the performance of the estimator and controller. The verified ranges in which the variation of frequency, damping-ratio and mode-shape of the first mode did not produce instability during closed-loop simulations is listed below. The first mode shape was varied by superposing a triangle shaped error on the mode shape with the height of the error triangle represented as a percentage of the amplitude of the nominal mode shape.

VERIFIED STABILITY RANGE
Mode 1

FREQUENCY	**-50 %**	**to**	**100 %**
DAMPING RATIO	**-80 %**	**to**	**100 %**
MODE SHAPE	**-5 %***	**to**	**100 %**

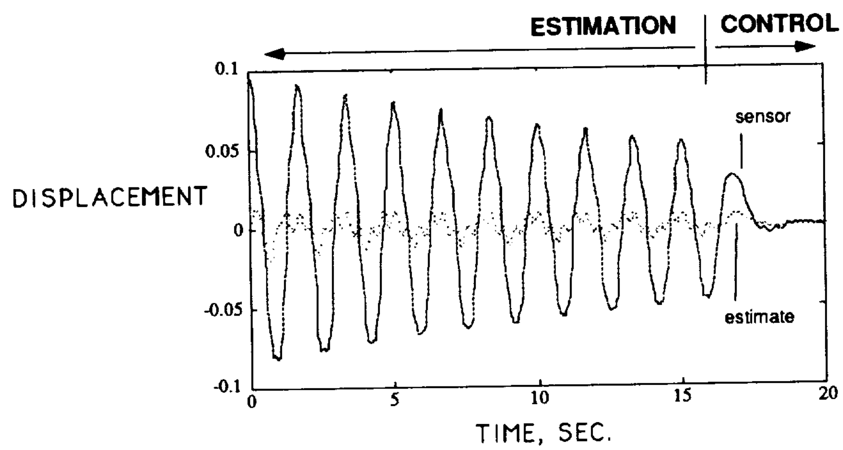


* Unstable < -5 %

The reponse below shows the controller perfromance with 100% mode-1 frequency error. In the open-loop segment the estimations are erroneous as expected but after the controller is activated, the frequency errors observed in the open-loop estimations are eliminated and the vibrations are controlled effectively.

CONTROLLER PERFORMANCE
100% MODE 1 FREQUENCY ERROR

DISPLACEMENT AT .36L FROM LEFT END

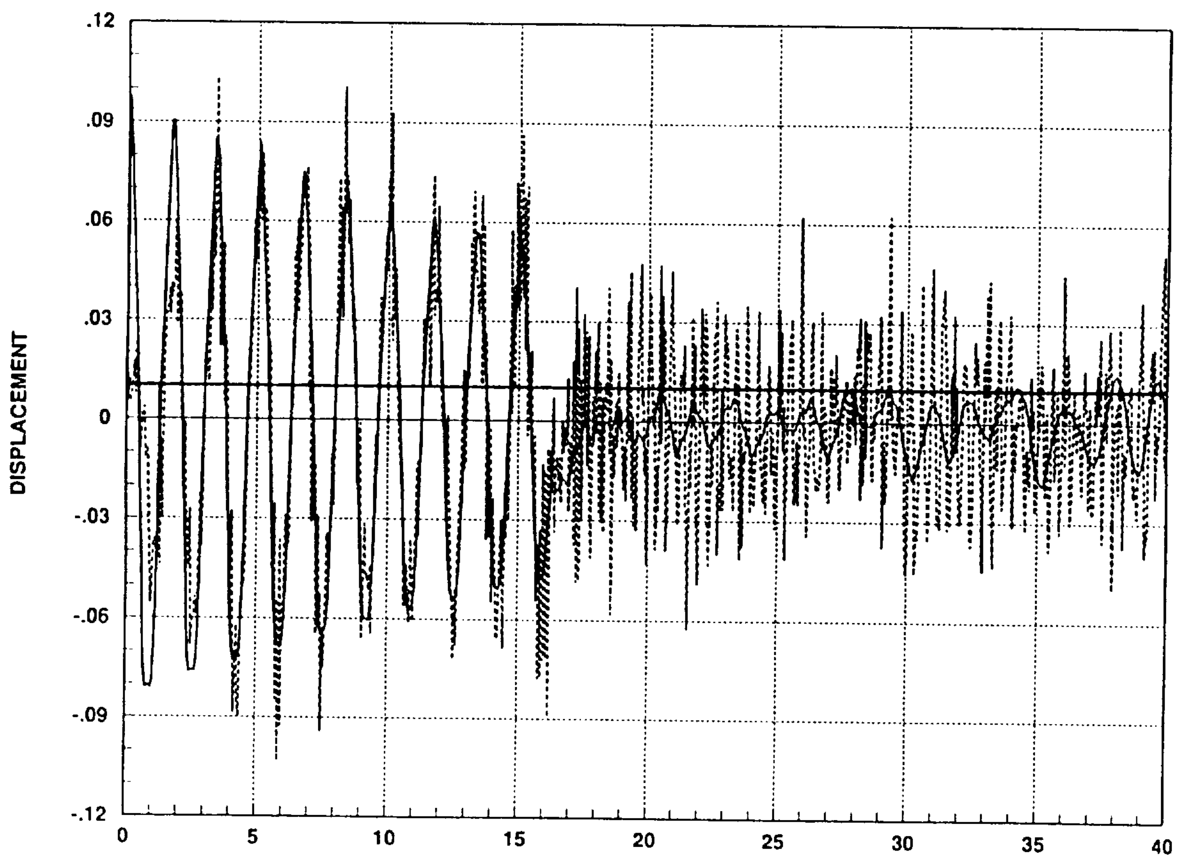


The response below shows the effect of optical prediction noise with RMS noise intensity of 0.01 which is 10 percent of the initial displacement of .1 units. The noise intensity level is indicated as a thick horizontal line. The solid line represents the measurement and the broken line, its estimation. Both the open-loop and the closed -loop estimations are noisy because the filter does not take into account the optical processing noise. In the closed-loop segment the response does not show any unbounded growth, thus demonstrating the robustness of the system to optical processing noise.

RESPONSE WITH PREDICTION NOISE

DISPLACEMENT AT .36L FROM LEFT END

RMS Noise Intensity : 0.01



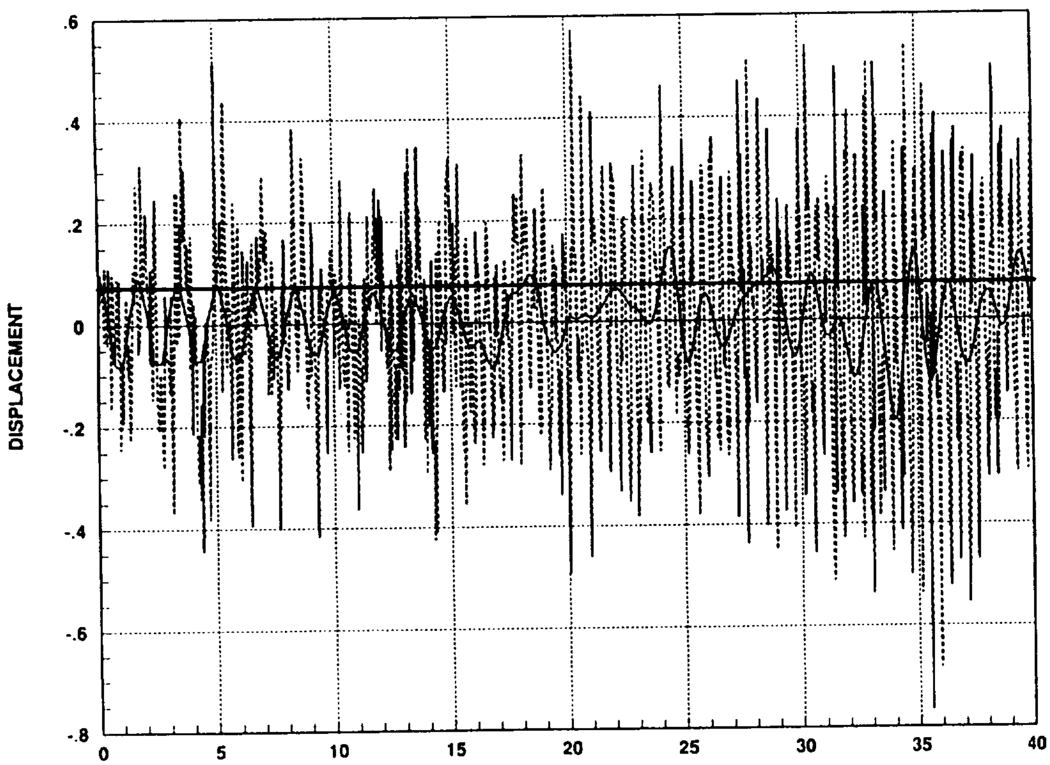
RESPONSE AND ITS ESTIMATE AT S=.36

A simulation study was also made with RMS noise intensity of 0.08, an eight-fold increase over the previous study. As before, the noise intensity level is indicated as a thick horizontal line. The solid line represents the measurement and the broken line, its estimation. The estimations are noisy and do not bear any similarity with the measurements. In the closed-loop segment the plant responds to the actuator noise only and does not show any unbounded growth, thereby demonstrating again the robustness of the system to optical prediction noise.

RESPONSE WITH PREDICTION NOISE

DISPLACEMENT AT .36L FROM LEFT END

RMS Noise Intensity : 0.08



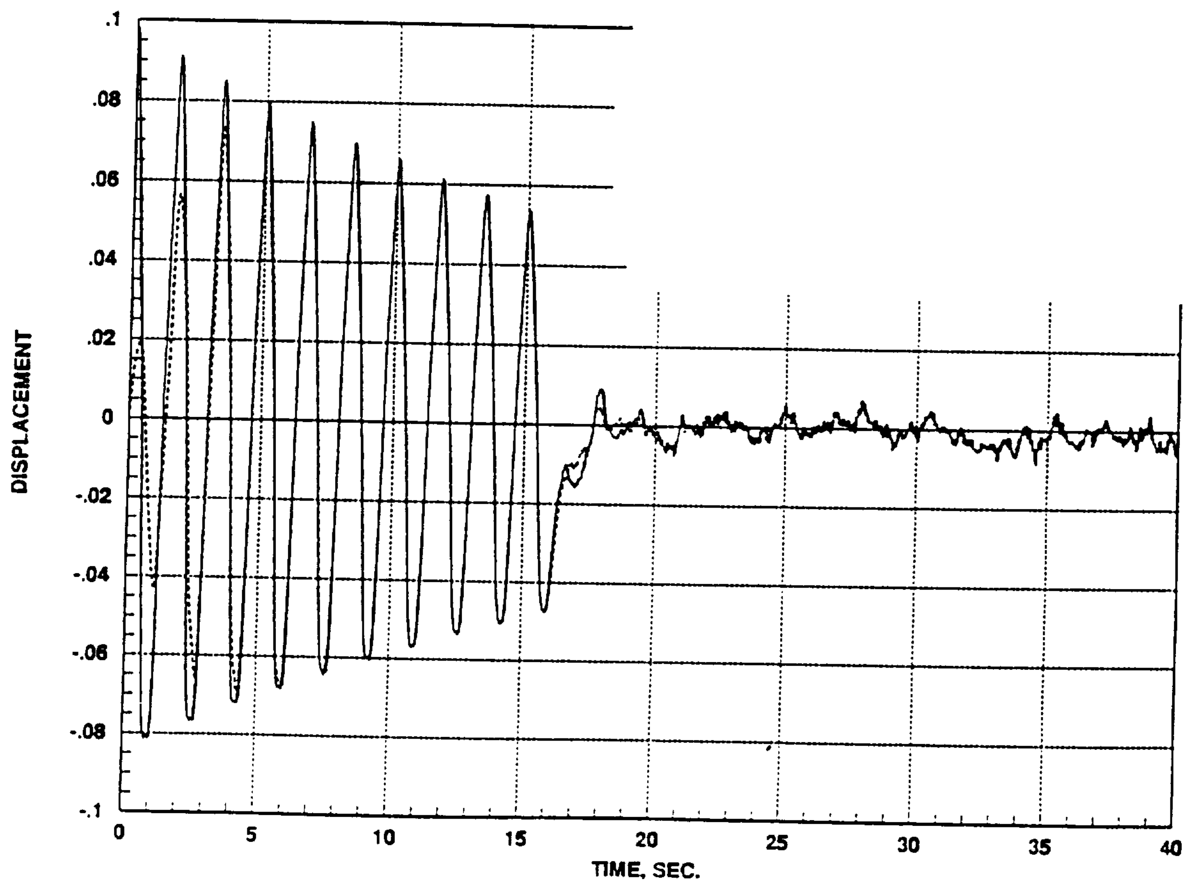
RESPONSE AND ITS ESTIMATE AT S=.36

The response below shows the effect of actuator command generation noise with RMS noise intensity of 0.1. After the controller is activated the response amplitudes are reduced, albeit noisy because of the command generation noise. The closed -loop estimations are also noisy because the filter does not take into account the actuator command generation noise.

RESPONSE WITH ACTUATOR COMMAND GENERATION NOISE

DISPLACEMENT AT .36L FROM LEFT END

RMS Noise Intensity : 0.10



RESPONSE AND ITS ESTIMATE AT S=.36

In this presentation a design process for distributed sensing and processing was developed and demonstrated using a distributed processing simulator. It was shown that the process is robust to modelling errors and distributed processing noise. Future plans include experimental verification of the concepts outlined.

CONCLUSIONS AND FUTURE PLANS

- DEVELOPED DESIGN PROCESS FOR DISTRIBUTED SENSING AND PROCESSING
- TESTED USING A DISTRIBUTED PROCESSING SIMULATOR
- PROCESS IS ROBUST TO MODELLIING ERRORS IN FREQUENCY, DAMPING, AND MODE-SHAPE AND DISTRIBUTED PROCESSING NOISE
- EXPERIMENTAL VERIFICATION OF THE CONCEPTS