# APPLICATION OF LASER DOPPLER VIBROMETERS IN DAMAGE DETECTION


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## 1. INTRODUCTION

Laser Doppler Vibrometers (LDVs) provide an excellent tool to measure structural vibration, and so offer a fast, accurate and cheap routine in damage detection upon examining the change in structural modal parameters. In this paper, a modal parameter identification technique employing the Eigensystem Realization Algorithm (ERA) is developed. The ERA is a general formulation for modal analysis identification for multi-input-multi-output cases. It is capable to detect close-coupled modes from a damped structure and does not depend on frequency resolution in data acquisition. Using the output of the ERA, a damage identification technique can be developed. Damage can be modeled as changes in mass, stiffness and damping matrices. By solving an inverse eigenvalue problem as an optimization problem, locations and size of damage can be determined.

## 2. LASER DOPPLER VIBROMETERS AND DATA ACQUISITION SYSTEM

The LDV is capable to scan at 35kHz, at a maximum distance of 30m. Detailed specifications of the LDVs can be found in [3]. A data acquisition is set up as in Fig. 1 and its specifications are shown in Table 1.

**Table 1**: Specifications of the Data Acquisition System

| | Scanning Laser | Reference Laser |
|---|---|---|
| Anti-alias filters | Bessel 3rd order | Butterworth 3rd order |
| Signal Amplifier | 8-channel simultaneous sampling, switchable gains of 1, 10, 100, 200, 500 | |
| AD/DA Converter | 16-bit, 100 kS/s, 16 analog inputs, 2 analog outputs | |

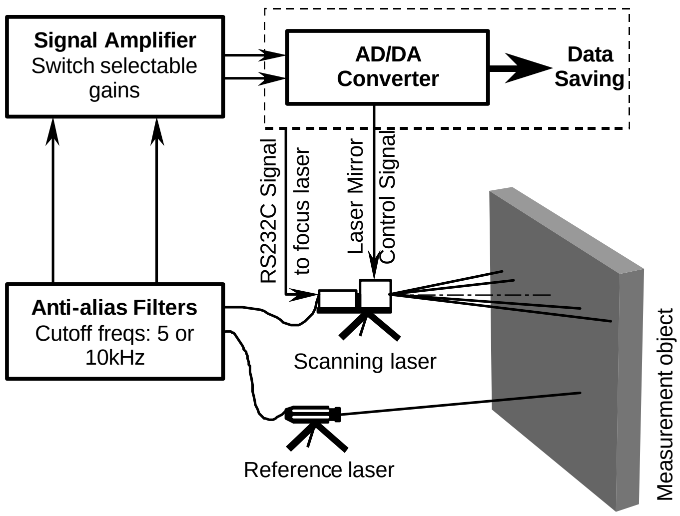


**Fig.1**: The LDV and Data Acquisition System

## 3. SYSTEM IDENTIFICATION USING THE ERA

A viscously damped system with N DOF can be modeled in a continuous state-space equation:

$$\{\dot{y}(t)\} = [A']\{y(t)\} + [B']\{u(t)\}$$
$$\{x(t)\} = [R]\{y(t)\}$$

This continuous state-space can be written in discrete form. By using the free-response synthesized from the ambient vibration measurement, system transition matrix can be “realized”. Eigenvalue decomposition of this matrix will provide modal parameters of the system. Detailed formulation of the ERA can be found in [2].

Ambient vibration measurements can be used to synthesize the system’s free response. Farrar and James [1] has pointed out that cross-correlation functions between a designated reference measurement and other measurements will have the same form of system’s impulse response function, provided that the unknown ambient source is assumed to be white-noise random process. It should be pointed out that the ERA requires synchronous measurement at all points, hence, data obtained from the scanning laser at each single point needs to be synchronized. The reference laser measurement will provide the global information for this synchronization process.

Furthermore, for a noise reduction scheme by averaging, averaged cross-spectral density functions should be evaluated in the frequency domain, then Inverse Fourier Transform to give the averaged cross-correlation functions. To average the cross-spectra in that way, synchronized cross-spectra should be used. It has been shown that [4]:

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$$G_{x_{Rij}x_{Sij}} = \frac{P_{x_{Rij}}}{P_{x_{Ro}}} G_{x_{R0}x_{S0}}$$ where $P_x$ and $G_{xy}$ are power spectral and cross-spectral density functions, respectively.

That means that by dividing each cross-spectrum by a factor of $\frac{P_{x_{Rij}}}{P_{x_{R0}}}$, a synchronized cross-spectrum can be obtained.

Fig.2 summaries steps in modal analysis identification technique for ambient vibration measurement from the LDV.

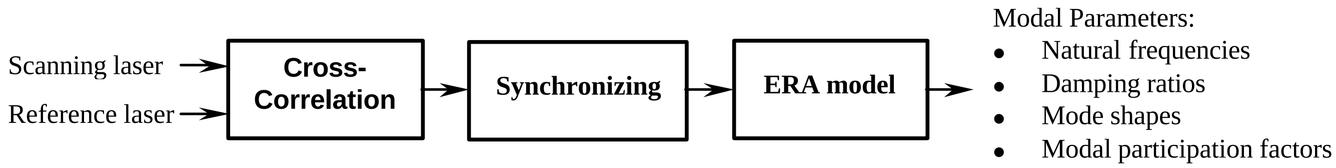


**Fig. 2**: Modal Analysis Identification Technique using ambient vibration measurement from the LDV

## 4. DAMAGE DETECTION TECHNIQUE

An inverse eigenvalue problem to model damage in a mechanical system is expressed in the followings:

$$\left(\left[{}^{\backslash}a_{\backslash}\right] + \left[\Phi^{u}\right]^{T}[dA]\left[\Phi^{u}\right]\right)\{\dot{q}\} + \left(-\left[{}^{\backslash}a_{\backslash}\right]\left[{}^{\backslash}\Lambda^{u}_{\backslash}\right] + \left[\Phi^{u}\right]^{T}[dB]\left[\Phi^{u}\right]\right)\{q\} = \{0\}$$

Diagonal matrix $\left[{}^{\backslash}a_{\backslash}\right]$ can be determined from the ERA by assuming a mass matrix. By iterating to search for matrices $[dA]$ and $[dB]$ so that the following objective function is minimized, damage locations and magnitude can be determined.

$$F = \sum_{i=1}^{Ne}\left(\left(1 - MAC\left(\{j\}_i, \{y^{d}\}_i\right)\right)^2 + \left|\Omega_i - l_i^{d}\right|^2\right)$$

Matrices $[dA]$ and $[dB]$ are sparse matrices that should maintain the connectivity of structural elements, hence the number of variables used in the search algorithm is much smaller than the matrix size. With some knowledge of structure's damage, a considerable number of variables can be further reduced leading to an accurate and fast convergence of the search algorithm. Minimization using this search technique has utilized the downhill simplex method to deal with multi-variable search. Details of formulation and results can be found more in [4].

## 5. CONCLUSIONS

This research has developed a synchronization and free-response synthesis techniques to use with the ERA to determine modal parameters of a damped structure, that can be implemented for Laser Doppler Vibrometer measurement in ambient vibration. Measurement of structural modal parameters before and after damage can be used as an input to a Damage Detection Program in which an inverse eigenvalue problem is solved by minimizing an objective function. Upon the minimization, damage locations and damage size can be found. It is worth noting that this damage identification technique maintains the structural connectivity and does not requires the knowledge of stiffness and damping matrices.

**References:**


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