Full-field laser vibrometry – a novel approach
for vibration mode studies and non-destructive inspection

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Abstract

This presentation reports a full-field matrix laser vibrometer (MLV) that was developed in an effort to expedite full field vibration measurement, based on implementation of a 2D array comprising $16 \times 16$ heterodyne laser vibrometers. The MLV is conceptually simple in design and robust in implementation, due to the flexibility afforded by fiber optic component integration. The system integrates the MLV measurement probe, linked by a bi-directional fiber optic umbilical, to a remote electronics unit, which houses a fiber laser, a multi-channel fiber-coupled Indium Gallium Arsenide (InGaAs) receiver array, and a multi-channel A-to-D digitizer/processor array. The MLV measurement probe is thus largely passive and of sufficiently low-weight and size to facilitate its deployment in inaccessible areas or around large structures. The paper reviews aspects of the MLV system design and implementation, and presents example of applications, which include dynamic modal imaging and non-destructive testing.

Keywords: Laser Doppler velocimetry, vibration studies, non-destructive testing

1. Introduction

The practical application of optical non-contact vibration measurements techniques for structural damage detection continues to expand in-line with ongoing development of optical sensors and digital data processing technology which enhance system speed, sensitivity, and robustness. Methods such as electronic speckle pattern interferometry (ESPI) and laser Doppler vibrometry (LDV) are frequently applied to steady state or transient vibration mode analysis for structural health monitoring of engineering components. Dynamic full-field ESPI, for example, currently allows structural vibration modal patterns to be captured up to a maximum frequency dictated by the framing rates of specialized high-speed conventional, CCD or CMOS cameras [1]. In digital systems, efforts to overcome the inevitable space-bandwidth limits imposed by serial multiplexed detector readout have led several groups to explore the possibilities offered by [2] ESPI with high-speed linear CCD arrays [3] or CMOS detector arrays [4]. In addition to limited temporal bandwidth, sensitivity to out-of-plane displacement may also be too low for reliable detection of nanometer scale vibration modes.

Unlike ESPI, the LDV technique provides high sensitivity and temporal bandwidth for single point surface velocity measurements. However, acquisition of full-field (2D) images by opto-mechanical beam scanning necessitates multiple independent measurements, making the method slow and thus suited to steady-state or well characterized vibrations, generated under controlled conditions. Multi-beam LDVs, including 96 channels pseudo-linear [5] and 16 channel linear arrays [6] have been developed and demonstrated, providing full-field data with concomitantly fewer sequential measurements. Nevertheless, these systems remain slow and therefore susceptible to error in uncontrolled conditions. This presentation discusses development of $16 \times 16$ array MLV capable of instantaneous full-field vibration measurement and gives examples of its operational capabilities.
2. Configuration of the MLV system

Figure 1 illustrates the optical layout of the MLV system which employs a varied of fiber-optics components for system integration to make the design compact and robust. A fiber optic umbilical, for example, carries laser light into the measurement probe and the 2D array of detected optical signals back from the probe to a separate electronics unit which houses the major electronic subsystems (laser source, detectors and digitizers). The remote probe is thus largely EM neutral and comparatively small, which facilitates its deployment in inaccessible areas or around large structures.

![Fig. 1. Matrix laser vibrometer system configuration, comprising remote measurement probe linked by fiber optic umbilical to electronics unit comprising fiber laser, receiver and digitizer/processor array.](image)

In the MLV design, the output from a narrow linewidth Er-Yb fiber laser operating at 1550 nm is split into two channels by a polarization maintaining fiber-optics splitter to form the reference and signal arms of the interferometer. The reference channel is fiber guided via a waveguide phase modulator (PM) and through the microlens array (MLA) is launched to the focal plane array. The signal beam is collimated by a fiber pigtailed telescope to illuminate a diffractive optical element. The latter serves to generate a 16x16 beam array which is transmitted by an adjustable zoom F-theta objective lens and brought to a focus on the measurement surface. The current configuration supports a (x 4) zoom range to achieve working distances from 0.5 m up to 2.0 m with beam coverage from 75 x 75 mm up to 300 x 300 mm (beam spacing 4.3 mm through 20 mm). The mixed optical signals collected by each fiber are conveyed by a fiber ribbon array to a remote detector. The fiber ribbons terminate into a bank of fiber connectors which mate via bulkhead connectors to 4 detector modules. Each module houses a 64-channel InGaAs pin diode receiver. The analog outputs from the detector array are supplied to an array of PCI 16-channel 0.625 MS/s/channel A-to-D converters with 8 MB/channel on board RAM and a 400 MHz on-board processor. Each processor executes an identical digital phase demodulation sequence locally and hands off the processed base-band data in 16-channel blocks to a central processor where the signals are collated and displayed as full-field displacement or velocity images.

3. Dynamic modal imaging

The prototype MLV was designed and built to support 16x16 beam array generation, detection and processing, although in the tests described here were conducted with the 12x12 prototype MLV system. In these tests, we examined the dynamic behaviour of a center pinned
metal plate. The data obtained are sufficient to illustrate the principal strength of the MLV, namely (i) its capacity for rapid 2D capture of steady-state vibrations or (ii) continuous full-field capture of transient (non-steady state) vibrations. For these tests, the beam array illuminated the central portion of a high-stiffness circular disk, of diameter 90 mm and thickness 6.0 mm, as illustrated in Fig. 2(a). A small circular piezo-element was glued to the rear face of the plate to excite the vibration (Fig. 2(b)).

Fig. 2. (a) Spatial distribution of the 12 x 12 beam array generated on the aluminium test plate (imaged by Spiricon SP155 CCD) (b) Image of the test plate with measurement grid overlaid on data showing operational deflection shape indicating the resonant vibration mode at 23.7 kHz.

The purpose of this test was to simulate burst mode capture of a transient vibration, for which the piezo was driven with a sinusoidal frequency chirp from 1.0 kHz through 50 kHz of duration 109 ms, while the plate response was measured with the MLV. The array data were processed to determine the relative surface velocity. One selected frame of the processed velocity images, corresponding to the $m_{1,2}$ mode at 23.7 kHz, are shown in Fig. 2(b), overlaid on an image of the disk, with the locations of the measuring beam array indicated in white.

The data of Fig. 3 show the time domain velocity profile (Channel No. 67 of 144) from 0 to 109 ms comprising 65536 data points.

Fig. 3. a) Temporal velocity profile of channel #58/144 of center pinned aluminum plate excited by a 1-50 kHz frequency chirp of 109ms duration; b) 2D velocity images at principal resonant peaks of 14.4 kHz, 23.7 kHz, 33.8 kHz, and 44.7 kHz from the complete 65536 frame sequence.

The recorded data represent a complete record showing the temporal evolution of the plate operational modes driven by the piezo from 1 through 50 kHz and the evolution of the operational deflection profile as the excitation approaches and passes through the various
resonant modes of the plate. The data of Fig. 3 also show the 2D velocity profile of the plate selected at several (4) of the most prominent velocity peaks corresponding to the m_{1,1}, m_{1,2}, m_{1,3} and m_{1,4} vibration modes.

4. Rapid non-destructive testing of composite materials with MLV

A substantial body of research has established the diagnostic value of structural vibration analysis in providing information concerning both global structural integrity and local damage assessment in aerospace structures, including composite built systems [7]. Many different analyses have been applied to composite structural health monitoring, including evaluation of natural frequencies [8], mode shapes [9], frequency response functions [10], curvature strain [11] and matrix update methods. The ability of these methods to detect the presence and location of defects based on global measurements is attractive from an application perspective, but remains contingent upon the sensitivity of these parameters to the local stiffness reductions caused by specific defects based on their type, size, shape (with respect to the composite lay-up) and depth within the structure. In addition, the success of many such methods is further contingent on the validity of baseline data sets for the undamaged structure, derived from finite element analysis or measurements performed prior to the damage. Non-contact methods employing laser vibrometry, by comparison, provide good sensitivity for defect detection and location, based on measurement of the local stiffness reduction or higher mobility directly over the defect, and have similarly been widely investigated for this purpose.

Figure 4 shows the inspection of a composite specimen in which a portion of the Nomex honeycomb core has been removed while the upper composite ply layers remain intact leaving a 1 inch unsupported circular membrane. Suspended below the MLV probe is a Motorola 80W compression driver which is used to generate an airborne acoustic chirp directed towards the test sample. Since the membrane resonance frequency of the defect is unknown, the acoustic chirp covers a broad range from 1 through 10 kHz. In a typical blind test where the location and presence of defects is unknown, an XY gantry is employed to perform a sweep of the complete test sample with the defect location identified by subsequent analysis of the data. Figure 4(a) shows the MLV probe positioned over the test sample and a 2D grid whose vertices represent the locations of the measurement beams.

![Figure 4](image)

**Fig. 4.** (a) The MLV probe is aligned over an area with the simulated defect on the test sample; (b) The vibration response of the defect in Fig 2 (a) measured in a 1-10 kHz sweep; (c) Resonant response of the U-shaped defect as acoustic excitation is increased from 8.1 kHz to 13.8 kHz, indicating excitation of higher order resonant modes.

Figure 4(b) shows the spatial distribution of peak velocity across the 2D array at a frequency of 2.7 kHz where the RMS velocity of channels around the defect area show a prominent FFT peak. At this frequency, the defect is accordingly highlighted due to the
comparatively low background vibration amplitude of the undamaged material compared to the prominent defect response. In this case, the defect location is clearly identified in addition to the approximate size and shape of the affected area. Some caution is, however, warranted when inferring the defect shape and size from the modal response, in much the same way as a circular membrane supports multiple resonant modes. We note that whereas low order modes may indeed look circular, many higher order resonant modes may be more complex and thus less representative of the membrane shape. In the meantime, we note that the resonant response clearly identifies the presence, location and approximate size of the simulated core debond defect.

Figure 4(c) shows the case of a defect having a more convoluted spatial profile for which we observe that the correspondence of the measured modal response to the (known) defect shape depends upon the specific selected frequency peak. With this U-shaped defect we note that the true defect shape is more or less well represented according to the modal order, with the higher order mode excited in the vertical and horizontal branches more clearly delineating the U-shape, in addition to the stronger energy confinement, and hence signal-to-noise, which accompanies the modal response at higher frequencies.

5. Summary
In conclusion, this paper reviews development and potential applications of the MLV, including it’s use for rapid acquisition of full-field vibration deflection shapes and modes of the vibrating plate. The same capability is employed in rapid detection of the vibrational signatures associated with sub-surface defects in a range of composite-based aerospace engineering structures. For this application the specimen is excited by a non-contact acoustic transducer while the MLV measures the resulting full-field surface vibration response. Spectral analysis of rms velocity maps is employed to image the membrane resonant response and thus identify the location of damage in the structure.

References