VIBROMET™ 500V: SINGLE POINT LASER DOPPLER VIBROMETER

INTRODUCTION

This paper discusses a Single Beam LDV product offered by MetroLaser; specifically it discusses the VibroMet™ 500V single point laser Doppler vibrometer (LDV). A discussion of the single point LDV system is presented including its principles, hardware, software, capabilities and specifications, applications and examples. To avoid confusion the single point system is referred to as the 500V but references to the 500 and an earlier VibroMet™ 100 are made throughout since they have been around longer and some of the data presented here were collected with these earlier versions. All of the single point VibroMet™ share numerous similarities; a major difference is the visible pointer laser included in the new VibroMet™ 500V.

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Principles

The VibroMet™ 500V (and its predecessors the VibroMet™ 500 and the VibroMet™ 100) is a heterodyne laser Doppler vibrometer that employs self-mixing[1,2] to mix the object beam with the reference beam (also known as local oscillator) on the face of the photodetector. The system employs a diode laser at a wavelength of 780 nm to produce both the object beam (to illuminate target) and the reference beam (local oscillator) and a Bragg cell acousto-optic modulator (AOM) to impress a carrier frequency. The photodetector is an integral part of the diode laser module commonly used to monitor laser power. The LDV system is based on a patented electro-optical configuration[3] and is schematically illustrated in **Figure 1**. Most of the light from the laser diode comes out of the laser and is collimated by a custom lens. The collimated beam goes through the AOM where part of the beam is diffracted and frequency shifted (typically 35 to 40 MHz); this is the object beam. Part of the collimated beam (the zero order) goes through the Bragg cell undiffracted and it is blocked by a beam stop. The object beam illuminates the target and part of the light scattered by the target goes back into the AOM where it is diffracted and frequency shifted again (for a total now of 70 to 80 MHz). This effect is known as double frequency shift and has the beneficial effect of creating a carrier frequency at double the RF drive thus helping to separate the signal from any possible RF noise. The frequency shifted object beam enters the diode laser where it experiences gain and it is mixed with the reference beam (a small portion of the diode laser beam normally employed to monitor laser power). Details of this process are shown on **Figure 2**. An optional focusing lens is shown on **Figure 1**. It is employed to create a small focused beam that may be needed for some applications. The standard VibroMet™ 500V does not include a focusing lens but instead uses a collimated object beam. The collimated beam allows the VibroMet™ 500V to work at variable distances from a few cm to several meters without the need to adjust or align any optical components.

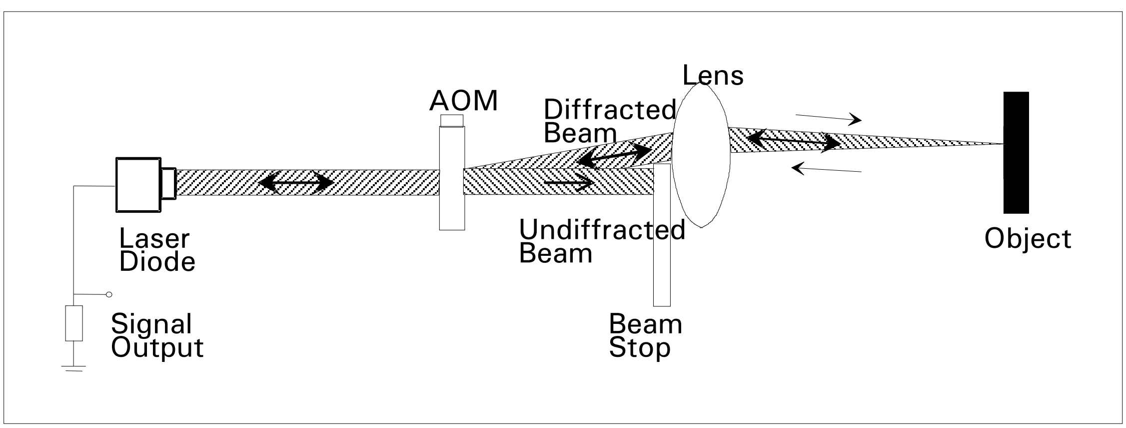


Figure 1. Schematic Diagram of MetroLaser VibroMet™.

Figure 2 illustrates the principles of the self-mixing effect in the VibroMet 500V. As the returned object beam (beam D) gets into the laser diode, it will mix with the laser beam inside the cavity to generate a beat signal with a frequency of $2f_B+f_D$. Here f_B refers to the frequency shift added to the beam by each pass though the Bragg cell and f_D is the Doppler shift that is due to the vibrational velocity of the target. The optical beat signal is then detected by a built-in photodiode inside the laser diode package, giving a corresponding electrical signal output. Similar to conventional LDVs, this signal can be processed by FM-demodulation electronic circuits to decode the target vibration frequency and amplitude. The mathematical expressions are shown below.

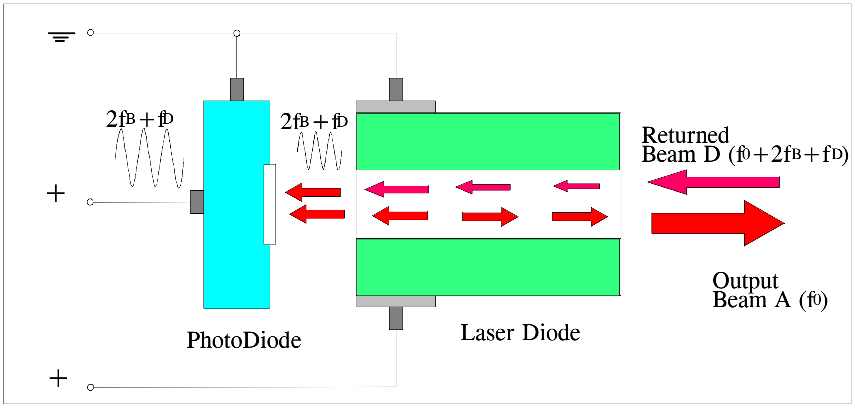


Figure 2. Self-Mixing Effect.

For a vibrating object the optical frequency of the scattered object beam will be Doppler shifted due to the object vibration velocity. This Doppler frequency shift f_D is given by the Doppler equation:

$$f_D = 2\, v \cos \alpha / \lambda\,, \tag{1}$$

where v is the target vibrational velocity, λ is the optical wavelength of the laser, and α is the intersection angle between the object beam and the target velocity direction. For vibrating targets, the equations relating photodetector signal to vibration are given below. For a target position given by

$$X = X_m \cos(\omega_a\, t), \tag{2}$$

where X_m is the maximum displacement, and ω_a is the vibration rotational frequency, the vibration velocity v is computed to be:

$$v = -\, X_m \omega_a \sin(\omega_a\, t). \tag{3}$$

Substituting **Equation (3)** into **Equation (1),** the Doppler frequency shift f_D of the scattered light beam is given by:

$$f_D = -\,2\, X_m\, \omega_a \sin(\omega_a\, t) \cos \alpha / \lambda. \tag{4}$$

Then, the electric field of the scattered object beam at the receiver can be written as:

$$E_s(t) = E_S \cos\,[2\pi\,(f_0 + f_D)t + \phi_1]$$

$$= E_S \cos\,[2\pi\,(f_0 - 2X_m\omega_a \sin(\omega_a\, t) \cos \alpha / \lambda) + \phi_1], \tag{5}$$

where f_0 is the optical frequency of the laser and ϕ is the phase. To increase the signal-to-noise (S/N) ratio and detector sensitivity, a carrier frequency, f_B is typically impressed on the system by frequency shifting either the object or reference beam with a Bragg cell. In the case of frequency shifting the reference beam the electric field of the reference beam is found to be:

$$E_r(t) = E_r \cos [2\pi (f_0 + f_B)t + \phi_2]. \tag{6}$$

Mixing the scattered light with the reference beam will produce a beat signal at the detector. The optical intensity on the detector is given by:

$$I(t) = 2\, E_s\, E_r \cos (2\pi\, (f_B + f_D) + \Delta\phi)$$

$$= I \cos (2\pi\, f(t) + \Delta\phi), \tag{7a}$$

and

$$f(t) = f_B + f_D = f_B - 2\, X_m\, \omega_a \cos \alpha \sin (\omega_a\, t)\, /\lambda, \tag{7b}$$

and $\Delta\phi = \phi_2 - \phi_1$. **Equation (7b)** shows that the detected LDV signal is a typical FM signal. Generally, $f_B >> f_D$, and the carrier frequency, f_B, is modulated by the vibration with a frequency of ω_a and an amplitude of $2\, X_m \omega_a \cos \alpha / \lambda$. Using an FM-demodulation technique (e.g., phase-locked loop, I&Q, etc.), f_B is subtracted out by the circuit and the output signal is given by:

$$A(t) = (2\, X_m\, \omega_a \cos \alpha / \lambda\,) \sin (\omega_a\, t). \tag{8}$$

Equation (8) shows that after FM-demodulation, the output signal contains only the vibration frequency ω_a.

Description of hardware

The VibroMet™ 500V consists of a laser sensor head and an electronic controller. The laser sensor head contains the diode laser, Bragg cell, photodetector, and front-end electronics. The optical head also includes an electronic circuit to band-pass the signal by 4 MHz and to mix it down to an intermediate frequency (IF) of 10.7 MHz. Its output is an electric signal with a carrier frequency mixed down to 10.7 MHz that serves as input to the electronic controller. The VibroMet™ 500V also includes a red (650 nm) diode pointing laser to ease the visualization of the measurement spot on the target. A photograph of the VibroMet™ 500 (same appearance as the VibroMet™ 500V but without the red pointer laser) system is shown in **Figure 3**.

Figure 3. Photograph of VibroMet™ 500: laser sensor head and electronic controller.

The electronic controller contains the power supply, RF power to the Bragg cell, and PLL analog demodulator to process the IF signal and output an analog vibrational velocity signal in real time. Another output of the electronic controller is the 10.7 MHz frequency modulated signal, which may be digitized and analyzed in software. The electronic controller contains a signal strength indicator, an out-of-range velocity indicator, two selectable velocity ranges and five selectable low pass filters (1, 2, 5, 10, and 20 kHz), which may be used to enhance S/N of certain spectral bands. Also included is a safety interlock for remotely turning the system on or off if needed.

Description of software

The VibroMet™ 500V outputs an analog velocity signal that may be recorded and analyzed with any spectrum analyzer or simply viewed on an oscilloscope. MetroLaser has developed software that enables the user to acquire and analyze the velocity signal using data acquisition boards from National Instruments (e.g., PCI 6220). **Figure 4** shows a typical computer screen with labels highlighting the various functions of the software.

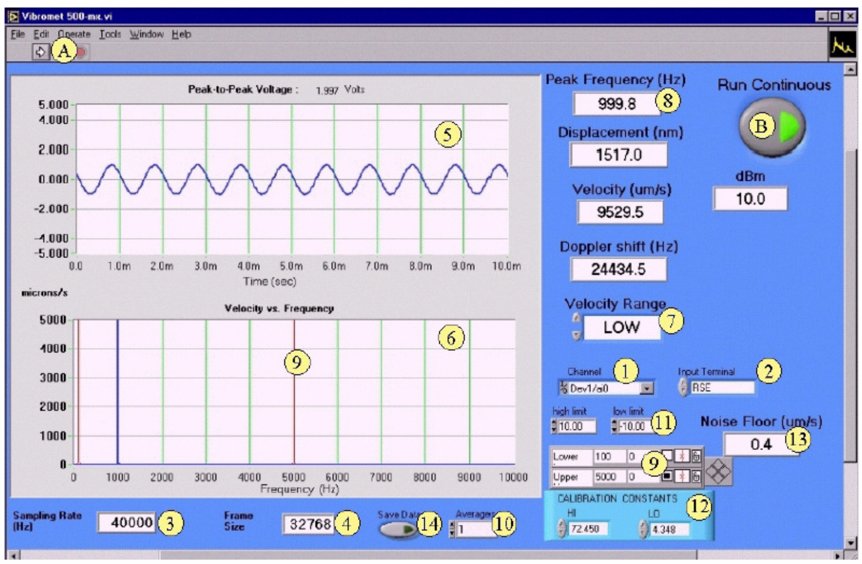


Figure 4. Typical computer screen displayed by software.

The arrow labeled 'A' is used to run the program. The program may be run continuously or in a single shot mode by selecting this function in button B. The software assumes by default that the VibroMet velocity output is on Channel 0 of the data acquisition board. This can be changed by entering a different number in the 'Channel' field (1). The default input configuration for the channel is 'Referenced Single-Ended.' (2) In the above example, the Sampling Rate (3) is 40000 Hz and the Frame Size (4) is 32768 points. With these settings, the VibroMet software would acquire a block of data from the vibrometer for a time of 0.8192 seconds (= 32768 / 40000), which will be displayed on the upper graph (5) (Velocity vs. Time). In **Figure 4**, the time scale has been set to 10 ms, so only part of the entire block of acquired data is displayed. The lower graph (6) is a Fourier transform of the time domain data shown in the upper graph (Velocity vs. Frequency).

The software enables setting the filter bandwidth (7) to match that set on the VibroMet (either LOW or HIGH). For each graph, the 'Autoscaling' can be turned On or Off by right-clicking on the graph. When 'Auto-scaling' is Off, the x and y axes limits can be changed by the user.

The software finds the peak in the FFT plot (lower graph), and computes the peak frequency, velocity, displacement, and Doppler Shift (8). The red vertical cursors (9) can be moved to look at different parts of the frequency spectrum. The displayed values for the velocity, frequency, etc. are always based on the largest peak between the two cursors. The cursor positions can be dragged to different positions, or can be moved by entering numbers directly into the box (9). The software can average several FFTs by increasing the number of Averages (10) from the default value of '1'.

By default, the upper and lower limits of the data acquisition board are set to +10 and –10 Volts (11). For looking at very small signals, it may be beneficial to reduce these values to something smaller, such as +1 to –1 Volts. This will increase the bit resolution of the acquisition.

The calibration constants (12) are provided for each VibroMet 500. The data sheet provided with each system ensure that the calibration constants are correct.

The average noise floor between the two cursors is shown in Box (13). This calculated noise floor is an average of the values between the two red cursors; moving the cursors will change the displayed result.

When running the software, the user has the option to Save the Time and Frequency Data. To save the data, click 'Save Data' (14), and choose an appropriate Folder and File Name, such as 'data1.dat'. The saved data can be viewed with the 'Read Stored Waveforms' program, or even in a spreadsheet such as Excel. The data is stored in text format, in four columns. Column 1 only stores the time step between data points in the upper graph. Column 2 is the array of time domain values. Column 3 is the frequency step between points in the FFT graph, and Column 4 is the array of FFT values.

To view the saved data, use the 'Read Stored VibroMet Files' program. When this program is run (by clicking on the arrow in the upper left), it will prompt the user to find the stored data file. After that, the program works like the 'VibroMet 500.exe' program. An added feature is that the user can choose to display either Velocity (in mm/sec), Displacement (in microns), or Acceleration (in m/s^2) on the lower graph. In addition to the vertical cursors on the lower graph, the user can also use cursors on the time domain graph to window different parts of the data in time.

Instrument capabilities and measurement specifications

The VibroMet™ 500V measures vibrational velocity as a function of time as the primary parameter. Simple integration or differentiation (available in the software) would yield displacement or acceleration as a function of time. The following are typical specifications for the instrument:

- Velocity Range: A total of 2 μm/s to 1 m/s in two ranges. The low velocity range is from 2 μm/s to 50 mm/s and the high velocity range is from 50 μm/s to 1 m/s. The noise floor at the low velocity setting is about 2 μm/s and the noise floor at the high velocity setting is about 10 μm/s.
- Vibration Frequency Range: DC to 70 kHz. The lowest noise floor is obtained in the range of DC to 20 kHz; however, users that require the higher frequency can achieve it with a small increase in noise floor.
- Working Distance: From about 1 cm to 5 m; longer distances are possible, depending on the surface. The diode laser has a long coherence length and the working distance may be varied continuously without worrying about losing signal due to small coherence length limitations. The only requirement is to collect enough photons from the target, a requirement that is met by most realistic surfaces; however, surface treatment may be necessary for some "hard-to-see" targets.
- Environmental requirements: The VibroMet LDV systems have been used outdoors under near-freezing conditions and in desert, summer conditions. A temperature range of 3 to 45 C, as stated in the product literature can be easily met.

Applications and examples

The VibroMet™ 500V can be employed in most applications associated with measuring vibration and noise; especially those applications where non-contact measurements are particularly important. Applications may be divided into two broad categories: 1) those associated with objects that have an inherent vibrational signal and 2) those associated with objects that are stimulated with an external source (e.g., acoustic or shaker). Both kinds of objects are found in numerous industries including, but not limited to: Automotive, Computer, Medical, Military, Homeland Security, Musical Instruments, Sound Equipment, Industrial Machinery, Aerospace, Motors and Compressors. Below are just a few examples of these applications.

Automobile engine

Figure 5 shows the VibroMet™ 500 pointing at an automobile engine while the RPM was being ramped up from idle to about 6000 rpm. The corresponding engine vibration spectra are shown on **Figure 6**.

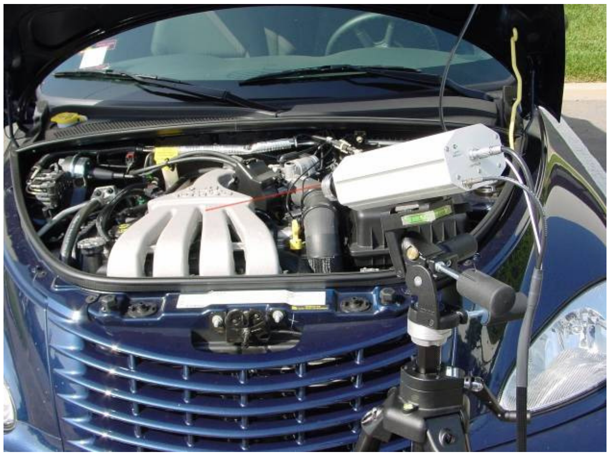


Figure 5. Measuring automobile engine vibration as a function of RPM.

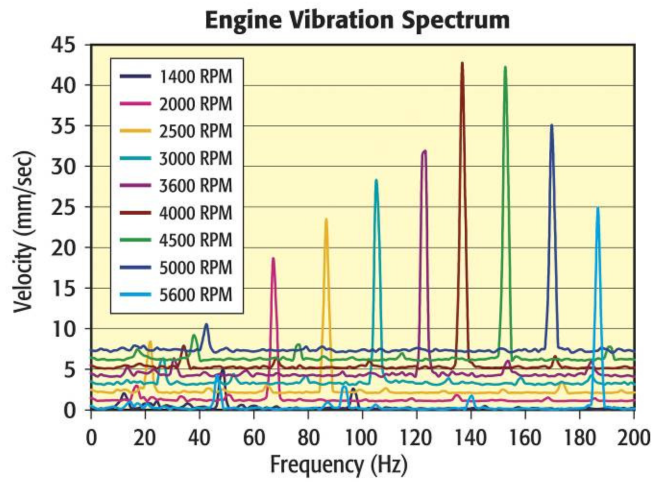


Figure 6. Velocity and frequency data of automobile engine as the RPMs are ramped up.

Homeland security

Preliminary experiments were conducted at MetroLaser to test how the vibrational characteristics of a small car change when the rear trunk is loaded with a simulated Improvised Explosive Device (IED) weighing approximately 500 lbs. The vehicle in case was a 2004 Toyota Matrix with an approximate vehicle weight when empty of 2778 lbs. The engine was idling while the car was parked on a level surface with the parking brake on. The load consisted of 14 bags of rocks, each weighing approximately 35 lbs, for a total load of about 490 lbs. The load was placed in the rear compartment of car. When the car was loaded, the rear end sunk about 6 cm, and the front end rose slightly. Two sets of experiments were conducted: 1) the laser vibrometer was pointed at four different locations (front side, middle side, rear side, and trunk) while the laser beam was nearly horizontal to the ground, thus measuring sideways motion; 2) the laser vibrometer was pointed at about 45 degrees and probed the hood and the trunk. In both sets of experiments, measurements were made while the car was empty and loaded. The experimental setup is shown in **Figure 7** for the 45-degree top-down measurements. The velocity vs. vibration frequency spectrum for one of the many conditions is shown in **Figure 8**. As indicated, there was a dominant component at about 23 Hz and secondary components at 17, 45, and 69 Hz.

Figure 7. Laser vibrometer pointing at the trunk for top-down measurements.

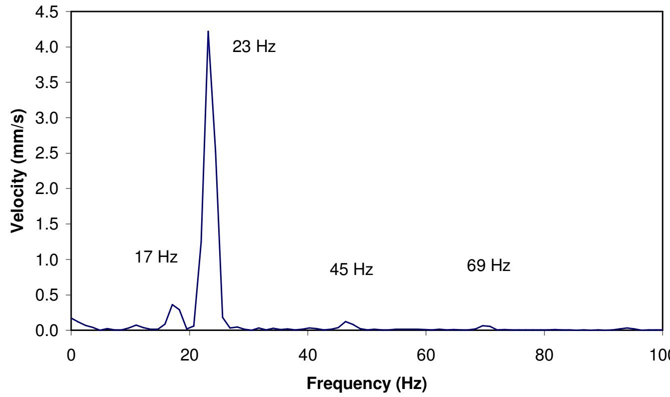


Figure 8. Plot of velocity vs. frequency for empty car, middle side test point.

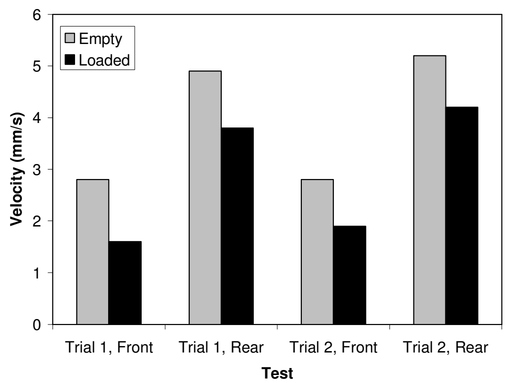


Figure 9. Results from top-down measurements of vibration at fundamental frequency (23 Hz)

The effect of load dampening on the vibrational velocity is illustrated in Figure 9.

Musical Instruments

Experiments with a VibroMet™ 500 were conducted at Taylor Guitars to evaluate the performance of guitars made of identical shape but with different woods. Some of the results of these experiments are shown on Figure 10 and Figure 11.

Figure 10. Measuring acoustic decay time of identical guitars made from different wood.

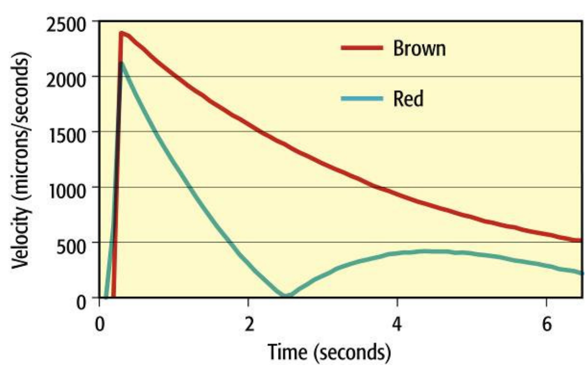


Figure 11. Vibrational velocity vs. time for two guitars after plucking the A note (110 Hz).

Military: Measurement of Buried Landmines with LDV and Acoustic Excitation

Changes to the mechanical stiffness of a medium can typically be measured by taping on the surface and listening to its acoustic response. This phenomenon is exploited by construction workers looking for studs behind drywalls and nondestructive testing engineers looking for delamination and water penetration in composite materials. In these types of applications the LDV would replace the human ear and become the listening device by probing the excited surface; and, instead of taping one could use a shaker or a non-contact acoustic wave from a speaker. Finding buried landmines is predicated on this principle.

Laser-acoustic techniques using low frequency acoustic waves have been successfully used for detecting buried landmines[4,5,6,7,8]. The method consists of exciting the ground with acoustic waves in the frequency range from about 50Hz to 300Hz, and employing a laser Doppler vibrometer (LDV) to obtain a vibrational velocity map of the ground surface. The interaction of a buried landmine with the acoustic waves causes the landmine to vibrate. The vibration amplitude of the ground surface above a mine is higher than the vibration amplitude of the surrounding area, due to the mechanical resonances of the mine and the higher mechanical compliance of the mine compared to the neighboring soil. Airborne sound created by loudspeakers, or seismic waves created by mechanical shakers, can be used to excite the ground vibration. Laser Doppler vibrometers are particularly well suited to this measurement application because of their high sensitivity, excellent spatial resolution, and long working distances.

MetroLaser has developed several LDV systems that are relevant to countermine technology. These instruments are used for the detection of buried anti-tank and anti-personnel landmines using the acoustic/seismic technique. An earlier version of the VibroMet, the VibroMet 100 used in landmine detection measurements is shown in **Figure 12**, while **Figure 13** shows a cart containing an array of LDVs at a test landmine field.

Figure 12. Commercial VibroMet™ 100 LDV used in landmine detection.

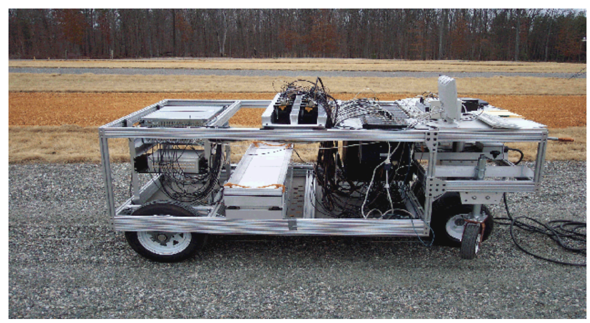


Figure 13. Cart built with Planning Systems Inc. and the University of Mississippi with 12 LDVs at a test landmine field.

The LDV cart, jointly developed by MetroLaser, Planning Systems, Inc. (PSI), and UM, includes an acoustic source to load the ground, 12 single-point LDVs to measure the ground velocity spectrum, electronics and computers to extract and store the ground velocity data, and a motor to move the cart at speeds up to 10 cm/sec. The 12 LDV beams are spread over a one-meter line, so the separation between beams is approximately 7 cm.

The cart has been fielded at several U.S. Army mine testing lanes around the United States, and has successfully found buried mines under a variety of conditions, such as gravel, dirt, and sandy surfaces. An example of the results with this system is shown in **Figure 14**. A VS 2.2 mine was buried approximately at a depth of one inch. This figure shows the velocity image of the ground surface as the cart was driven down the mine lane at a speed of 1 cm/second. The LDVs in Channels 7, 8, and 9 passed directly over the buried mine, while Channels 6 and 10 were just above the edges of the mine.

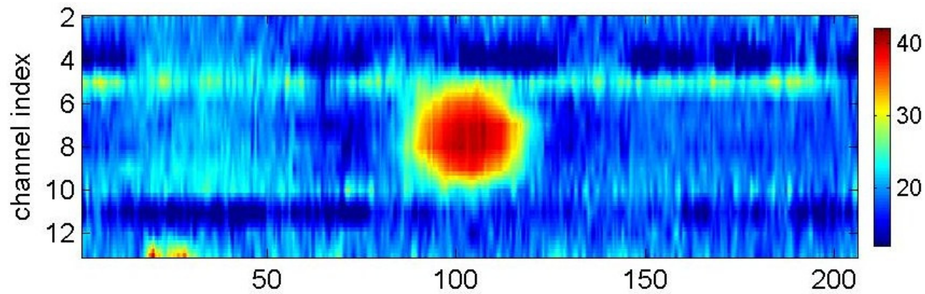


Figure 14. Velocity image above a VS 2.2 mine buried at a depth of 1 inch. The vertical axis corresponds to the LDV channel, and the horizontal axis corresponds to distance down the mine lane.

Aerospace

Vibrational patterns of turbine blades have been routinely measured with accelerometers on a shaker table. LDV provides a suitable alternative since it doesn't load the test object and measurements can be made from a standoff distance. **Figure 15** shows the VibroMet™ 500 making vibration measurements on a turbine blade.

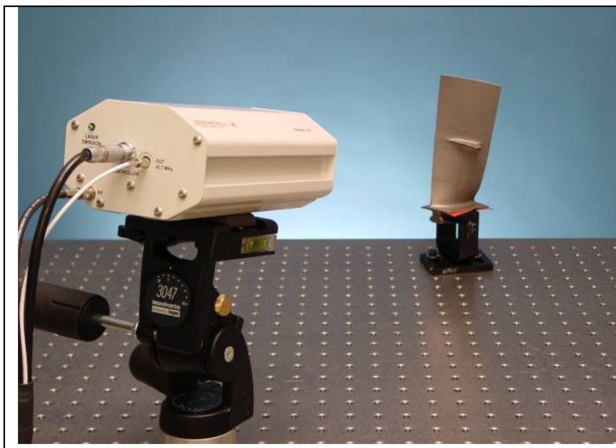


Figure 15. Measuring vibration of a turbine blade

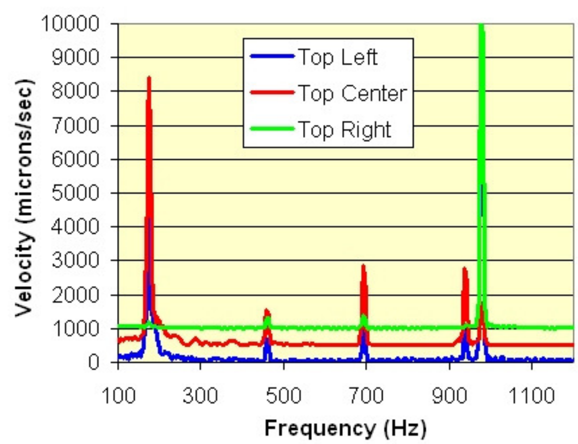
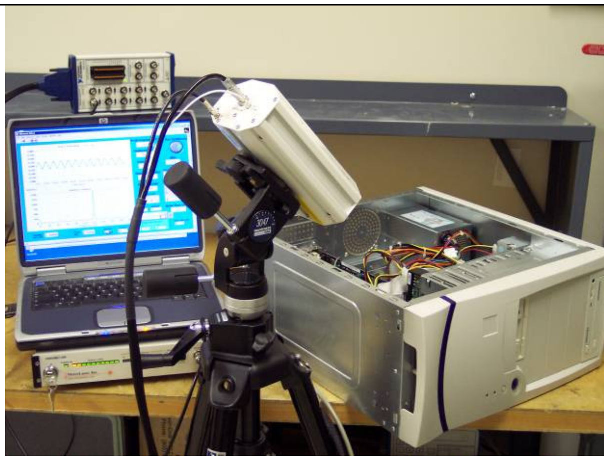


Figure 16. Measured velocity spectra at three locations across the top of the turbine blade.

Computer

Hard drives, fans, and other computer components are measured with LDV because of its non-contact capability and its high sensitivity.



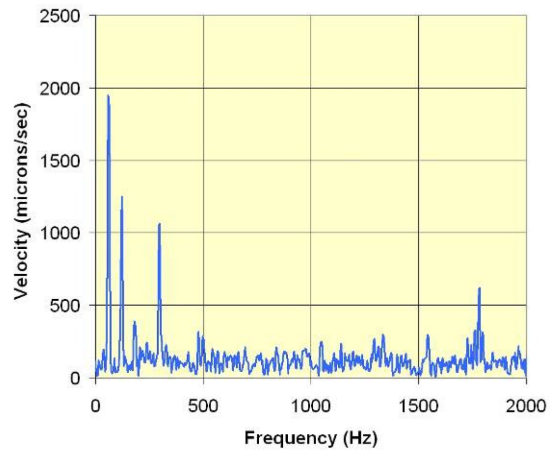
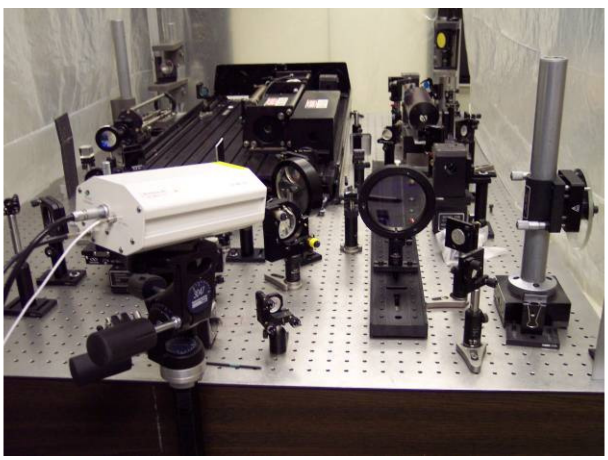


Figure 17. Measuring vibration of a computer drive

Figure 18. Vibration spectrum of the hard disk cantilever arm.

Characterizing optical mounts



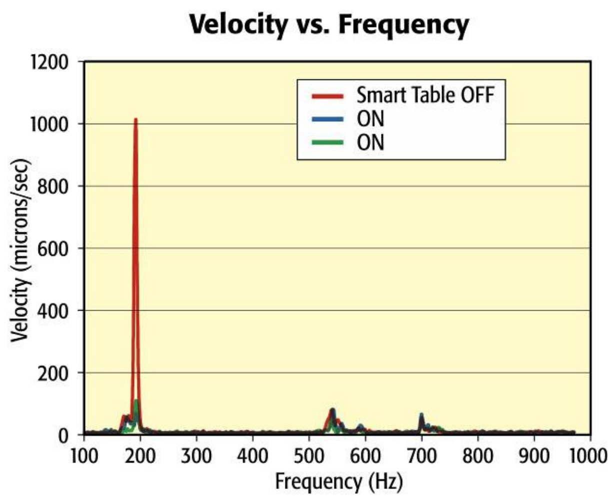


Figure 19. Quantifying vibrations in mounted optical components.

Figure 20. Velocity vs. frequency of optical mount on Newport Corporation's Smart Table with table ON and OFF. The vibrations on the table were induced with a mechanical shaker.

CONCLUSIONS

This paper has presented the principles and salient features of the VibroMet™ 500V single point laser Doppler vibrometer, a product developed by and available from MetroLaser. The VibroMet™ 500V is a compact system specifically designed for industrial and research applications where the distance to target may vary and surface preparation should not be required. For more information about MetroLaser's products and services, please visit www.metrolaserinc.com

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[2] Process and Device for Optically Measuring the Distance and the Velocity of a Target, US Patent 4,928,152, May 22, 1990.

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[5] Xiang, N. and Sabatier, J.M., “Land Mine Detection Measurements using Acoustic-to-Seismic Coupling”, Proceedings of the SPIE, Vol. 4038, p. 645, Orlando, April 2000.

[6] J.M. Sabatier and N. Xiang, “An Investigation of Acoustic-to-Seismic Coupling to Detect Buried Antitank Mines”, IEEE Transactions on Geoscience and Remote Sensing, 39(6), 1146-1154 (2001)

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[8] N. Xiang and J.M. Sabatier, “Laser DopplerVibrometer-Based Acoustic Landmine Detection Using the Fast M-Sequence Transform”, IEEE Geoscience and Remote Sensing Letters, 1(4), 292-294 (2004).