Development of Laser Vibrometer

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In this article, development of a noncontact vibration measuring instrument based on optical triangulation principle has been discussed. The design aspects of the sensor, consisting of low power diode laser in visible range, focusing optics, one dimensional position sensing detector and processing electronics has been elaborated in detail. The sensor measures vibration amplitude in the range of ±5 mm and vibration frequency in the range of 0.1 Hz - 1 kHz from a distance of 200mm and generates proportional analog output voltage. The output of sensor is fed to PC through ADC card where in-house developed software program perform calculation on received data to find vibration amplitude and frequency and then display it graphically. The calibration of sensor in terms of vibration frequency and amplitude is done against accelerometer and commercial laser sensor in the vibration test laboratory of RED, BARC.

Introduction:

Vibration is the motion of a particle or a body or a system of connected bodies displaced from its position of equilibrium[1]. The system tends to return to its equilibrium position under the action of restoring force. The back and forth movement of the system about its position of equilibrium results in vibration. The vibration of an object is expressed in terms of its amplitude and frequency. The detection of vibration plays an important role in the different areas of structural health monitoring and industrial engineering. In general, vibration detection can be divided into two categories: contact type and non-contact type. Usually in the contact type vibration sensing, the sensor is attached to the machines or instruments in order to detect the vibration amplitude and frequency. In some applications where precise vibration measurement is required or in toxic and hazardous environment, addition of contact sensor becomes impractical due to inaccessibility or since this attachment adds a mass on the instrument or the machine and might alter its vibration characteristics. The other category of vibration sensors are non-contact type. Measurement of vibration through optical technique has gained importance due to its non-contact, non-destructive nature and high speed. Optical methods are more useful generally for remote measurement in hazardous & toxic environment, where human/operator intervention is very difficult.

In this article, development of a high-resolution, simple in operation and low cost optical triangulation based instrument namely Laser Vibrometer (Fig. 1) for non-contact vibration measurement is explained which can measure vibration from a distance of 200 mm in the frequency range of 0.1 Hz to 1 kHz with an accuracy of 1% of the measured frequency value and amplitude range of 2 μm to 5 mm with maximum error of 2.5% of measured value and a resolution of 1 μm.

Working Principle:

In optical triangulation principle, the laser source, target and the detection system form three vertices of a triangle. Laser beam falls on the target and the back-scattered light is collected by the detection system. A pair of symmetric triangles is formed by the point of laser beam falling on the target, optical center of the lens and focused spot on the detector as shown in Fig. 2. Any movement of the target, results in the movement of focused light spot from the back scattered light on the photo-detector. Thus by measuring the movement of focused spot on the detector and using formula of symmetric triangles, the displacement of the target is calculated. This displacement of the target with respect to time constitutes the vibration signal.

The measuring system consist of two parts

i) Sensor part

ii) PC based software

In general, there are two types of optical triangulation configuration. The first one is a perpendicular configuration, in which the incident beam is aligned with the normal to the surface and another is an oblique configuration, in which the incident beam is inclined to normal to the surface. We have used inclined configuration here, as it gives better linearity and resolution.

The sensor consists of laser source, focusing optics (plano-convex lens), position sensitive photo-detector (PSD) and signal processing electronics. When the target surface is at the stand-off distance (reference position) from the sensor, laser beam emitting from the sensor falls on the target and the back scattered light is focused on the optical axis by the lens in its image plane as shown in Fig. 1. PSD is kept aligned with the image plane of the lens. When the target surface is displaced from its reference position by Δ, the corresponding image of

Fig. 1: Photograph of laser Vibrometer sensor with PC interface

digital converter) and software on PC for vibration calculation. In the sensor, laser diode (Make: Lasiris) with 5 mW output power and wavelength (λ) equal to 635 nm is used as the light source as shown in Fig. 2.

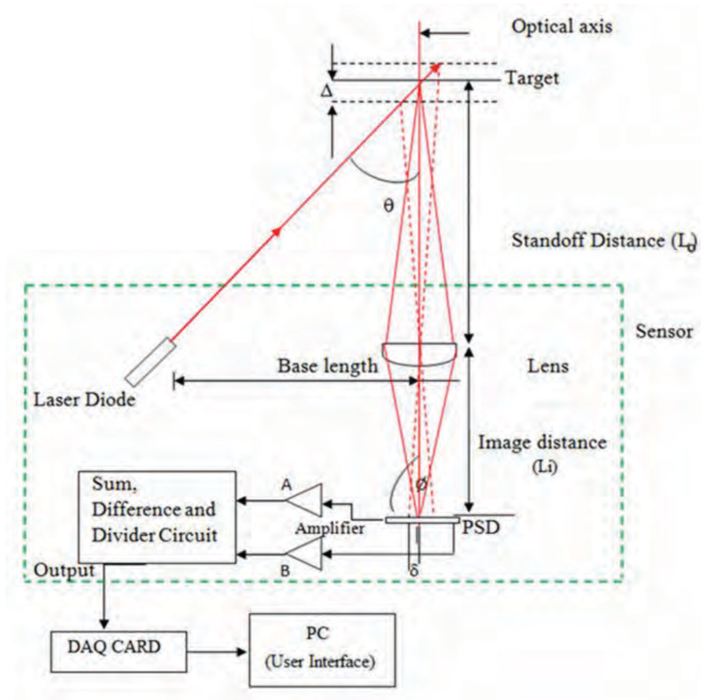


Fig. 2: Schematic diagram of Laser Vibrometer

the laser spot is displaced at the detector by δ. The PSD converts optical displacement signal into electrical signal. The electrical signal is processed by the electronic circuit to generate the output voltage which is proportional to the displacement of focused spot (δ). In Optical triangulation sensors, the amount of laser spot displaced on the detector for a given displacement of the target depends on the geometrical parameters chosen in sensor configuration. The geometrical parameters are focal length of lens (f), angle between the laser beam and lens optical axis (θ), and the distance between the laser beam and the optical axis of lens in the plane of the lens also called as base-length (d). For chosen above parameters of sensor, the distance between lens optical center and target or stand-off distance L_o is given by

$$L_o = d/\tan\theta \quad (1)$$

And distance between lens optical center and PSD is given by

$$\frac{1}{L_i} = \frac{1}{f} - \frac{1}{L_o} \quad (2)$$

Thus the relation between the target displacement Δ and displacement of centroid of the image spot (δ) at the detector is calculated using the laws of symmetric triangles and is given as[2]

$$\Delta = \frac{L_o \delta \cos\theta}{L_i \sin\theta + \delta \cos\theta} \quad (3)$$

The output voltage of sensor is proportional to δ which is fed to the PC after digitisation. For known values of L_o , L_i ,θ and measured value of δ ,the target displacement Δ is calculated by the PC based software using (3) above. The FFT of the time domain displacement signal gives frequency content of the vibration and peak-to-peak amplitude of the displacement signal gives amplitude of vibration. The calculated values are then graphically displayed on monitor for user interface.

System description:

The laser vibrometer instrument consists of a sensor, interfaced to PC through a data acquisition card (Analog to digital converter) and software on PC for vibration calculation.

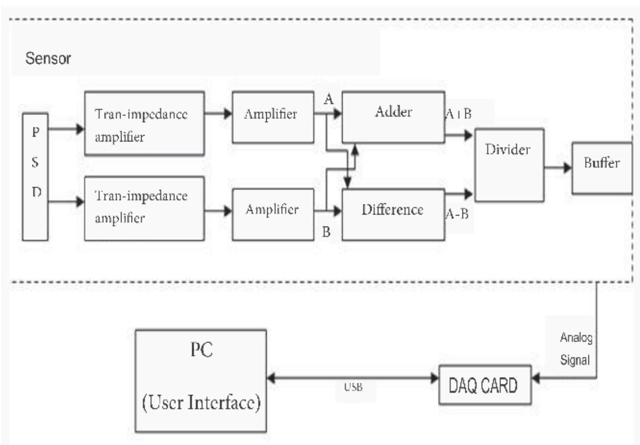
The laser is selected in visible wavelength range for ease of alignment. Laser beam falls on the surface of the target at an inclined angle of 45° to its normal and back scatters. A portion of the backscattered light is collected by the focusing optics via Plano-convex lens of focal length f = 100 mm, Diameter = 50 mm and is focused on a PSD, SL-15 (Make: UDT) having active area of length 15 mm and width 1 mm. For proper alignment, it is necessary to have laser beam, lens optical axis and normal to the target surface in the same plane. This ensures that the focused spot falls within active area of PSD. The photo-detector converts optical signal into electrical signal. The PSD selected has a common cathode and two anode pins, which are at the two ends of its length. The PSD has the characteristic that if the focused spot falls at its center, then the output currents at its two anodes are equal. But if the focused spot is falling away from the center, then the current through the anode which is nearer to the spot will be proportionately more than the anode which is relatively further from the spot. The PSD is biased in reverse mode with cathode connected to +15V. The two current outputs from PSD are amplified and are converted to voltage using trans-impedance amplifiers to give two output voltages A and B as shown in Fig. 3(a). The sum (A+B) and difference (B-A) are determined using Op-Amp based adder and difference circuit and division is implemented using multiplier IC AD734. Then spot movement on PSD (δ) is calculated using relation,

$$\text{Spot Position displacement}(\delta) = \frac{X}{2}\frac{(B-A)}{(A+B)} \quad (4)$$

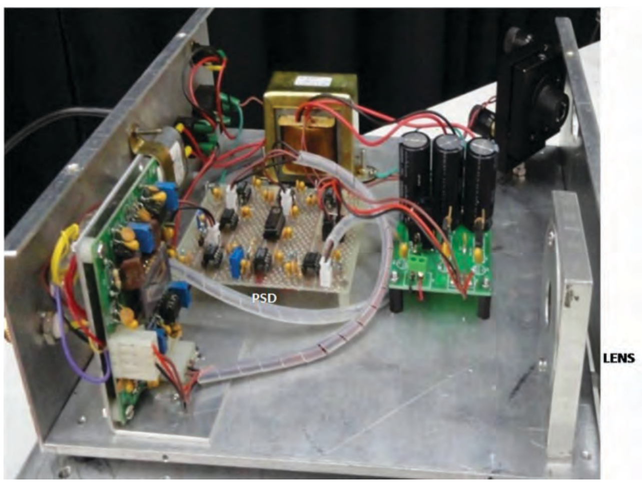
where, X is Effective Length of PSD. Here X is 15 mm.

For obtaining the linear relationship between Δ and δ and to keep the size of the sensor optimum, following dimensions have been selected in the developed sensor

Base length d= 200 mm



(a)



(b)

Fig. 3: (a) Block diagram of Vibrometer circuit (b) inside view of sensor

Standoff distance, L_o= 200 mm, this gives $= 45^\circ$ from (1).

PSD is kept perpendicular to optical axis

For, L_o = 200 mm, f = 100mm we get L_i = 200 mm (PSD distance from lens) using (2).

Substituting, above values in (3), the relationship becomes:

$$200\Delta + \Delta\delta = 200\delta \quad (5)$$

As, the product Δδ<<200Δ, if we neglect Δδ I (5), we get the linear relationship between Δ and δ, as Δ=δ. This approximation introduces a maximum error of 2.5% of measured value for displacement of ±5 mm and less than 0.5% for amplitude less than 1 mm. As the vibration amplitudes are normally much less than 1 mm, we have taken this approximation for calculation. After approximation of (5), the sensitivity of output voltage of the sensor is 1 mV/ μm. However if higher accuracy at higher amplitudes is required, the appropriate corrections in the software can be made.

The output of the sensor is fed to Analog to Digital converter in USB based ADC module USB4716, which is interfaced with PC using USB. The block diagram of the complete instrument and inside view of sensor circuit is shown in Fig. 3(a) and 3(b) respectively. The SAR type ADC with maximum sample data rate of 200 kilo-samples/sec and 16-bit resolution has been selected in order to cover amplitude range and resolution. Sensor unit generates the analog signal in the range ±5 V, which is acquired using the ADC module and is analyzed using application software.

Signal Analysis

The basic objective of the signal analysis is to extract vibration information from electrical signal output from the sensor. The displacement of the target is reflected as change in position of laser spot on detector. This change in laser spot position is represented in terms of voltage change. The amplitude and frequency of vibration can be obtained by analyzing this voltage signal. The peak to peak voltage change represents the displacement and FFT analysis of the signal is used to find the frequency of vibration. For analysis purpose and for better SNR, frequency measurement has been divided in two different ranges i.e. 0-100Hz, 0-1 kHz. The range of frequency is selectable by user through GUI. The sampling rate is depends on frequency range. The data acquired by application software 'KAMPAN 1.0' is analyzed to calculate the frequency of vibration and displacement.

At each instance 2048 samples are recorded using DAQ. The data is process using anti-aliasing low pass filter.

The raw data is further processed to find the DFT using Danielson-Lanczos algorithm. The output data of DFT contains the frequency and amplitude information. The two such consecutive instances of the spectrums are multiplied to reduce the random noise in spectrum. This improves the signal to noise ratio. The output of DFT is converted to represent frequency and displacement. The peak frequencies are identified and processed further to derive velocity and acceleration information. The frequency spectrum is displayed on screen. The provision is made to record the background spectrum and also to subtract it from the current spectrum.

The application software is developed using "C++" language. The user interface displays the signal, frequency spectrum, vibration frequencies and displacement. The snapshot of the user interface is as shown in Fig.4.

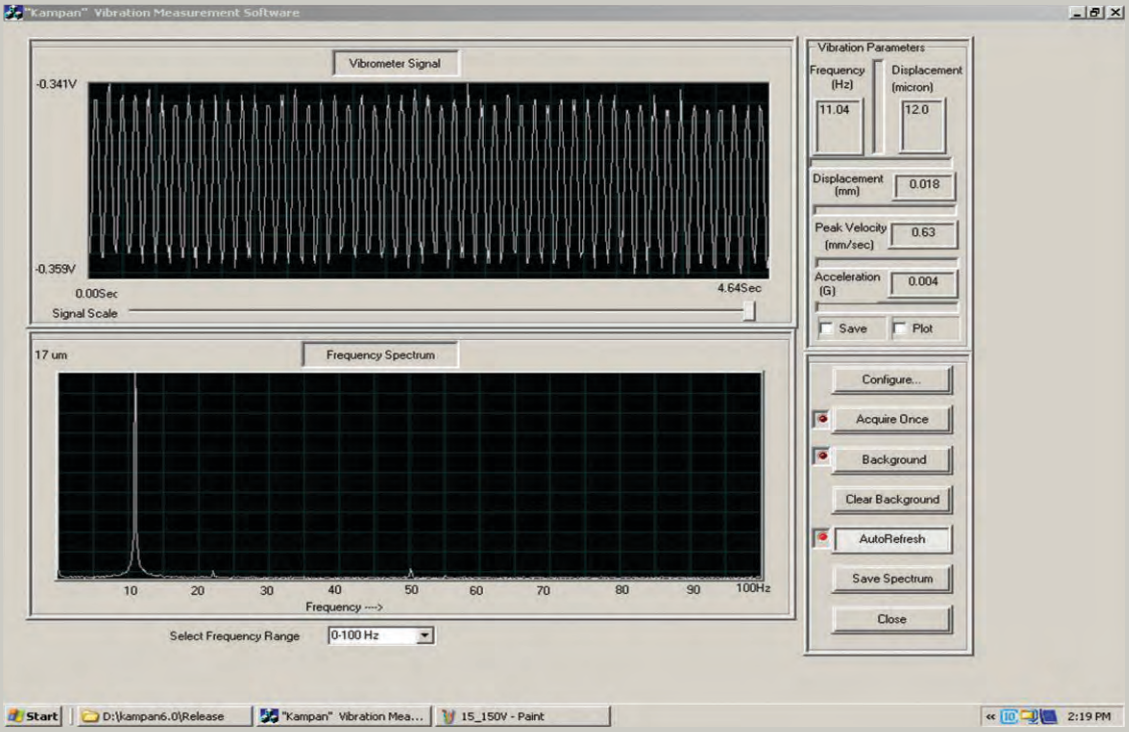


Fig. 4: Snapshot of the user interface at PC

Experimental results and discussion :

Laser vibrometer Sensor is tested against the accelerometer (model no. BNK 4396) and commercial laser sensor (μepsilon make : model no OPTO NCDT 1700) for measurement of vibration of shaker at RED vibration lab and the results obtained are summarized as follows:

1) Test have been carried out on shaker for vibration frequency range of 0 to 1 kHz and amplitude range of 2 μm to 10 mm.

2) The sigma(σ) value calculated for 5 readings by different sensors at 10 Hz vibration frequency are as follows:

a) Accelerometer: Average=4.0616 mm, σ=0.046 mm

b) Laser Vibrometer: Average=4.0098 mm, σ=0.007mm

c) μEpsilon laser sensor: Average=4.0756 mm, σ=0.003 mm

3) Frequency values obtained from all the three sensor for complete range of measurement are identical and equal to the set frequency value.

4) Laser Vibrometer can measure highest vibration amplitude of 10 mm

5) At lower value of Vibration amplitude (less than 2 μm), the percentage error increases and the amplitude information becomes unreliable although it shows correct frequency.

6) The readings of laser Vibrometer are more closer to Accelerometer readings than readings of μepsilon Laser sensor.

7) The maximum difference in the amplitude measurement reading between laser Vibrometer and accelerometer is less than 5 %.

8) Thus in the present set of readings , frequency range 0- 1 kHz could be verified and amplitude range 2 μm – 10 mm. For testing of instrument at higher frequencies (> 1 kHz) with higher amplitude (> 2 μm) a different shaker should be available.

Conclusion:

A vibration measuring instrument Laser Vibrometer has been developed by designing a vibration sensor based on optical triangulation technique and it is interfaced with the PC where a software program developed in C++ language computes the frequency and amplitude components of vibration from the signal received. The sensor measures vibration in the frequency range of 0.1 Hz to 1 kHz with an accuracy of 1% of measured value and displacement range of ±5 mm with a resolution of 1 micron.

Acknowledgment:

The authors are thankful to Head, LPTD for his support and encouragement in carrying out this work. For calibration of laser vibrometer, help extended by Shri S K Sinha,SO/H and Shri Anil kumar Narayan of Vibration lab, RED,BARC is thankfully acknowledged. For assembly and skilfully testing of the instrument, the authors are thankful to Shri Ramdas Gangurde, Tech (F), LPTD

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