IRAQI JOURNAL OF APPLIED PHYSICS Vol. 21, No. 3, July-September 2025, pp. 376-379

Ragheed M. Ibrahim
Musab S. Mohammed

Department of Physics,
College of Education for
Pure Science,
Mosul University,
Mosul, IRAQ

Measurement of Mechanical Vibrations Using a Semiconductor Laser

In this research, a system for detection and measuring micromechanical vibrations resulting from electric motors using a diode-pumped solid state (DPSS) laser was designed and implemented. The operating principle of this technology is based on directly modulating the semiconductor laser with the electrical signals generated by the mechanical vibrations and then detecting the light beam carrying these information signals, represented by the frequencies of the mechanical vibrations. Using an electrical signal analyzer these signals are displayed and their frequencies are calculated. Both the vibration frequency and amplitude variations with rotor speed are included in the measurements. The data clearly show that 1.5 I_{th} was the optimal operating current value, and the waveform of vibration underwent noticeable alterations that allowing the detection of subtle vibration details.

Keywords: Laser vibration sensor; Piezoelectric; Mechanical vibrations; Direct modulation
Received: 6 March 2025; **Revised:** 8 April 2025; **Accepted:** 15 April 2025

1. Introduction

Vibration is common phenomena in everyday life, which is known as the movement of a particle, device, or system of connected devices spread around an equilibrium position [1]. Mechanical vibrations, whether caused by humans or nature, reveal a great of information deal about the structural health of the status of dynamically changing systems [2,3]. There are two measurable factors in every vibration, namely the amplitude of the vibration and the frequency with which the object moves. Four parameters are used to describe this motion, namely displacement, frequency, amplitude and acceleration [4]. A wide range of machinery may suffer damage from undesired vibrations which cause wear and energy loss, increase loads, and drain energy from the system. Alternatively, structural vibration patterns can be utilized for early or preventative maintenance as they are associated with changes in the structure [1,5]. Thus, for many systems as well as the environment around them, vibration monitoring and detection are essential particularly for predictive maintenance, in systems functioning in challenging and/or electromagnetically sensitive environments, such as space applications, or simply for machines exposed to lightning or drastically and quickly changing weather conditions, such as wind turbine blades, where malfunctions can have disastrous effects. Beyond equipment, there are a plethora of instances and circumstances where accurate vibration monitoring is crucial, such as seismic activity and structural health monitoring [6,7].

The investigation of vibrations produced by electrical and mechanical devices is still a highly favored area of study as numerous application domains needing vibration analysis have emerged as a result of more complicated machinery and processes, as well as rising exploration and production expenses [2,8]. These application domains include quality control [9], environment testing [10], modal analysis [11], and machine monitoring [12].

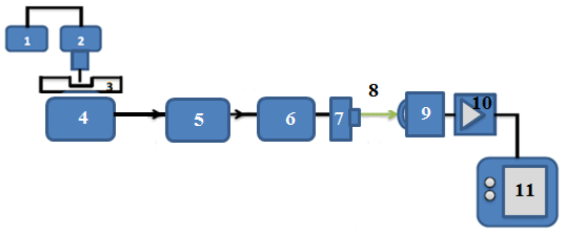
Numerous techniques have been developed to measure vibration using mechanical, electrical, or optical instruments. Irrespective of the operational principle, these techniques may be classified into two main groups depending on whether or not physical contact with the vibrating item is required [2,3,13]. There are a variety of contact techniques for measuring mechanical vibrations, the most important of which are accelerometers such as: Piezoelectric, Linear Variable Differential Transformer (LVDT), potentiometric, variable reluctance and Piezoresistive [3,12]. Furthermore, several non-contact techniques have also been developed, like optical sensor [14], Eddy current sensor [15], laser Doppler vibrometer [16]. This paper describes the design and implementation of a semiconductor laser system for monitoring micromechanical vibrations. This technique's operation is based on the direct modulation of electrical signals produced by mechanical vibrations into a semiconductor laser.

2. Experimental Part

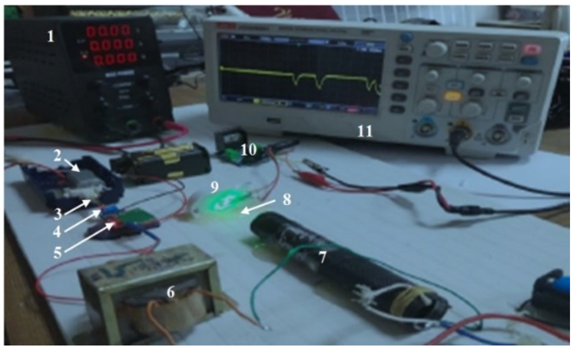
Figure (1) depicts the experimental setup, which included a power supply with a change accuracy up to 0.1 V was utilized to operate the vibration element, which is a small electric motor connected to the vibration arm that produces vibrations according to a pre-set arrangement and at different frequencies depending on the voltage applied to it. To monitor the vibrations, a piezoelectric-based vibration sensor was used; this sensor is coupled to a high-gain, wide-gain pulse amplification circuit. A DPSS semiconductor laser with a wavelength of 532 nm and a maximum output power of 10 mW was used in this experiment

Vol. 21, No. 3, July-September 2025, pp. 376-379

work. The electrical pulses generated by the vibrations are loaded into the DC driving current of the semiconductor laser through the intensity modulation circuit. The light coming out of the laser is amplitude modulated, where the intensity changes according to the intensity of the pulses entering the laser current. The resulting intensity modulations signal is detected by the PIN photodetector coupled with an amplification circuit. Finally, a demodulation circuit was used to separate the transmitted signal from the loaded signal and then displayed using a digital oscilloscope for subsequent analysis.



(a)



(b)

Fig. (1) (a) Schematic diagram of experimental setup, (b) Photograph of the experimental setup: (1) Motor Driver Module, (2) Electric motor, (3) vibrato arm, (4) sensor, (5) pulse amplifier, (6) modulation circuit, (7) laser diode, (8) modulated Laser beam, (9) photodiode, (10) Demodulation circuit, (11) Digital Oscilloscope

3. Results and Discussion

The system's basic working concept represent by the direct modulation of laser light by the vibration element's signal, meaning it can be made to alter in response to modifications inside the laser cavity. In this case the dc bias of the laser diode needs to be set above the lasing threshold level, where the output power varies linearly with the bias current, to avoid a sudden break in the output curve at the threshold.

The process of amplitude modulation can be clarified using a set of nonlinear rate equations and can by written as [17]

$$\frac{dN_e}{dt} = \frac{I}{eV} - \frac{N_e}{\tau_{sp}} - GN_{ph} \quad (1)$$

$$\frac{dN_{ph}}{dt} = \left(G - \frac{1}{\tau_{ph}}\right) N_{ph} \quad (2)$$

where N_e and N_{ph} denotes the electron and photon number, respectively, τ_{ph} the photon lifetime, τ_{sp} the spontaneous lifetime, V the active layer volume, I the current and G is the stimulated emission rate

The greatest modulation depth at which a linear response is achievable is provided by

$$M_m = \frac{P_m - P_t}{P_m} \quad (3)$$

where P_m is the maximum optical power and P_m is the output power at threshold. Since the output power at threshold is often about ten percent, the greatest modulation depth can exceed ninety percent [17,18]

Figure (2) shows the P/I curve characteristics at room temperature, which plots the output optical power of a green laser diode against the injected electrical current. From this figure, the threshold current value can be extracted by extending the linear region of the characteristics, the stimulated emission region, and it was found to be equal to 50 mA, while it is noted that the maximum optical power emitted is equal to 10 mW.

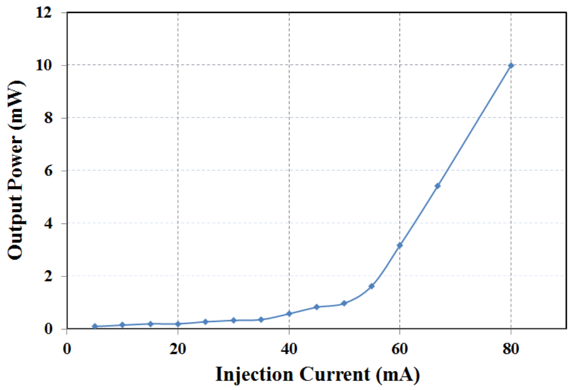


Fig. (2) Power-current characteristics of DPSS laser

The experimental data were gathered from a vibrating arm connected to a DC electric motor of an experimental system a. Figure (3) represents the vibration waveform resulting from the vibration of a vibrating element at different injection current of 0, 50, 65, 75, 80 and 90 mA, and at fixed vibration speed. Image (3a) shows the case where the vibration element is vibrating but the laser current is zero, and some slight noise is observed resulting from the signal transmission elements and amplifiers used in the electronic circuit after the photodetector. Image (3b) shows the vibration waveform of the vibrating element when the laser is operated with a current equal to the threshold current. It is found that the vibration frequency of the vibrating element is equal to 35 Hz with a slight variation in the duration of the pulses due to the instability of the vibration of the element. Image (3c) shows the vibration waveform of the vibrating element when the laser is operated with a current equal to 1.3 I_{th}. It is noted that the frequency of vibration has not changed, but the amplitude of the pulses increased slightly. Image (3d) shows the vibration waveform of the vibrating element when the laser is operated with a current equal to 1.5 I_{th}. It is noted that the pulses are almost noise-free, clear and of large amplitude

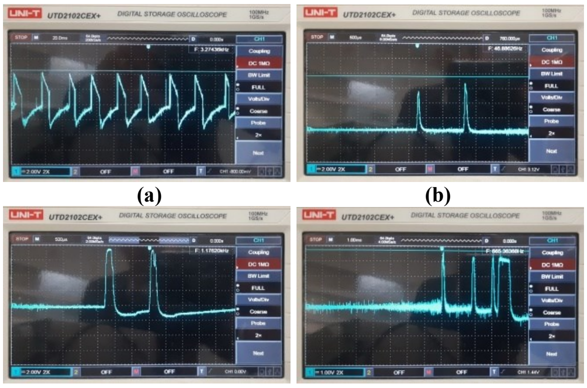
ISSN (print) 1813-2065, (online) 2309-1673

compared to the previous image. Image (3e) shows the case of operating the laser with a current 1.6 I_{th}. It is noted from it that the pulses do not differ much from the previous image but the amplitude of the pulses decreased slightly, which indicates that the laser works well within these limits of currents. Finally, image (3f) represents the laser operating condition with current 1.8 I. It is noted that the pulses have become irregular and their amplitude has decreased significantly with the appearance of noise with the pulse signal, which indicates that the laser's operating area has become beyond the stimulated emission area due to the pulses loaded on it, and the laser should not be used at this operating point.

(a) (b) (c) (d) (e) (f)

Fig. (3) Waveform of vibration at laser injection current of (a) 0mA, (b) 50mA, (c) 65mA, (d) 75mA, (e) 80mA, (f) 90 mA, motor voltage of 0.8 V

Figure (4) shows the vibration Waveform images of the vibrating element at different vibration speed and fixed operating current of 1.5 I_{th}. The vibration speed was changed according to the applied voltage to the vibrating element. Image (4a) shows the vibration waveform of the vibrating element at applied voltage of 0.8 V. It is noted that the vibration frequency of the element is 35 Hz and a pulse duration of 8 ms. Image (4b) shows the vibration waveform at applied voltage of 1 V. It is noted that the vibration frequency of the element is 714 Hz with a pulse duration of less than 100 ms. Image (4c) shows the vibration waveform at applied voltage of 1.2 V. It is noted that the vibration frequency of the element is 769 Hz and regular pulses. Image (4d) shows the vibration waveform at applied voltage of 1.3 V. It is noted that the vibration frequency of the element is 1 kHz and irregular pulse duration that can be measured for each pulse separately.



(a) (b) (c) (d)

Fig. (4) Waveform of vibration at motor voltage of (a) 0.8V, (b) 1V, (c) 1.2V, (d) 1.3V, laser injection current of 75mA

4. Conclusions

In this study, we have effectively proved a direct amplitude modulated method to the DPSS laser, which greatly improves the vibration detecting system's capabilities. The semiconductor laser was operated with different currents and the waveform of vibration element were record. The results showed that the best value for operating current was 1.5 I_{th} and when reaching at high operating currents the laser did not work normally, and distortion and noise occurred in the output signal. By operating the laser with a suitable current, different frequencies of the vibrating body (35, 714, 769, 1000 Hz), the waveform of vibration underwent noticeable alterations that allowing the detection of subtle vibration details. Therefore, The direct amplitude-modulated DPPs laser system exhibited high stability and accuracy, even while examining low-amplitude vibrations. The improved quality of the signal, made possible by this method, coupled with amplification circuits, enabled to measure the vibrations of different bodies with high accuracy. finally, through the obtained vibration data, the status of various mechanical equipment can be determine, and its analysis helps detect abnormal operating conditions and early faults that can eventually become severe and impair machine performance.

References

[1] B. Yaghootkar et al., "A High-Performance Piezoelectric Vibration Sensor", *IEEE Sens. J.*, 17(13) (2017) 4005-4012.

[2] E. Casamenti et al., "Vibration monitoring based on optical sensing of mechanical nonlinearities in glass suspended waveguides", *Opt. Exp.*, 29(7) (2021) 10853-10862.

[3] G. Perrone et al., "A Low Cost Optical Sensor for Non-Contact Vibration Measurements", *IEEE Trans. Instrum. Measure.*, 58(5) (2009) 1650-1656.

[4] M.H.M. Ghazali et al., "Vibration Analysis for Machine Monitoring and Diagnosis: A Systematic Review", *Shock & Vibration*, 2021(2) (2021)1-25.

[5] N.K. Verma et al., "Laser based optical sensor for vibration measurements", *NDT&E Int.*, 39 (2006) 106-108.
[6] S. Xu et al., "Vibration sensor for the health monitoring of the large rotating machinery: Review and outlook", *Sens. Rev.*, 38(1) (2018) 44-64.
[7] A. Khadka et al., "Non-contact vibration monitoring of rotating wind turbines using a semi-autonomous UAV", *Mech. Syst. Signal Process.*, 138 (2020) 106446.
[8] D.H.C.De Sá Martins et al., "Diagnostic and severity analysis of combined failures composed by imbalance and misalignment in rotating machines", *Int. J. Adv. Manufact. Technol.*, 114(9) (2021) 3077-3092.
[9] M.C. Carnero et al., "Statistical quality control through overall vibration analysis", *Mech. Syst. Signal Process.*, 24(4) (2010) 1138-1160.
[10] T. Chu et al., "A review of vibration analysis and its applications", *Heliyon*, 10 (2024) e26282.
[11] B. Samimy et al., "Mechanical signature analysis using time-frequency signal processing application to internal combustion engine knock detection", *Proc. IEEE*, 84(9) (1996) 1330-1343.
[12] M. Romanssini et al., "A Review on Vibration Monitoring Techniques for Predictive Maintenance of Rotating Machinery", *Information*, 4 (2023) 1797-1817.
[13] R. M. Ibrahim et al., "Effect of Material Irradiated Type and Spot Size on Spot Center Temperature of a Diode-Pumped Solid State Laser", *Iraqi J. Appl. Phys.*, 20(3) (2024) 540-544.
[14] D. Goyal et al., "The Vibration Monitoring Methods and Signal Processing Techniques for Structural Health Monitoring: A Review", *Archiv. Comput. Methods Eng.*, 23 (2016) 585-594.
[15] Z. Xu et al., "Single-Ended Eddy Current Micro-Displacement Sensor with High Precision Based on Temperature Compensation", *Micromachines*, 15 (2024) 366-382.
[16] Y. Li "Miniaturization of Laser Doppler Vibrometers - A Review", *Sensors*, 22(13) (2022), 1-25.
[17] N.H. Zhu et al., "Directly Modulated Semiconductor Lasers", *IEEE J. Sel. Topics Quantum Electron.*, 24(1) (2018) 1-19.
[18] R.S. Tucker, "High-speed modulation of semiconductor lasers", *J. Lightwave Technol.*, 3(2) (2003) 1180-1192.

ISSN (print) 1813-2065, (online) 2309-1673