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Effects of vibration frequency and velocity parameters on Doppler frequency shift in laser Doppler vibrometer systems

Lazer Doppler vibrometre sistemlerinde titreşim frekansı ve hız parametrelerinin Doppler frekans kayması üzerindeki etkileri

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Abstract
In this article, the effects of maximum velocity, vibration frequency and vibration amplitude parameters of objects on Doppler frequency shift (DFS) in Laser Doppler Vibrometer (LDV) systems using lasers at 1064 nm and 1550 nm wavelengths have been examined. In this context, while the velocity change of the object has been obtained in the range of 0 – 1200 µm/s with the laser at 1064 nm wavelength, the DFS varied between 0 and 2255.64 Hz. On the other hand, for 1550 nm wavelength, DFS have taken the values in the range of 0 – 1548.39 Hz. Moreover, for the 1064 nm wavelength, the maximum DFS and sampling time have been obtained in the range of 295.26 – 2066.84 Hz and 6.77 – 0.96 ms, respectively, in response to the change of vibration frequency from 50 to 350 Hz. For the same values of the vibration frequency, at the wavelength of 1550 nm, the maximum DFS and sampling time have changed in the range of 202.68 – 1418.78 Hz and 9.86 – 1.41 ms, respectively. Therefore, it is observed that as the vibration frequency increases, the maximum velocity and DFS increase linearly, while the sampling time decreases logarithmically. The results show that laser systems at 1064 nm wavelength respond faster but produce higher DFS values. On the other hand, LDV systems employing lasers at 1550 nm wavelength offer lower DFS and longer sampling times. Additionally, lasers that emit light at a wavelength of 1064 nm are more sensitive to velocity changes, whereas lasers at a wavelength of 1550 nm provide more stable measurement opportunities.

Keywords: Doppler frequency shift (DFS), Laser Doppler vibrometer (LDV), Vibration frequency, Vibration velocity

Öz
Bu makalede, 1064 nm ve 1550 nm dalgaboylarında lazerler kullanan Lazer Doppler Vibrometre (LDV) sistemlerinde, nesnelerin maksimum hız, titreşim frekansı ve titreşim genliği parametrelerinin Doppler frekans kayması (DFK) üzerindeki etkileri incelenmiştir. Bu kapsamda, 1064 nm dalgaboyundaki lazer ile nesnenin titreşim hızı değişimi 0 – 1200 µm/s aralığında elde edilirken, DFK, 0 ile 2255,64 Hz arasında değişim göstermiştir. Buna karşılık, 1550 nm dalgaboyu için DFK, 0 – 1548,39 Hz aralığında değerler almıştır. Ayrıca, 1064 nm dalgaboyu için titreşim frekansının 50 – 350 Hz aralığında değişimine karşılık, maksimum DFK ve örnekleme süresi, sırasıyla, 295,26 – 2066,84 Hz ve 6,77 – 0,96 ms aralığında elde edilmiştir. Aynı titreşim frekans değerleri için 1550 nm dalgaboyunda, maksimum DFK ve örnekleme süresi, sırasıyla, 202,68 – 1418,78 Hz ve 9,86 – 1,41 ms aralığında değişmiştir. Dolayısla, titreşim frekansının artışıyla, maksimum hızın ve DFK'nın lineer olarak arttığı, örnekleme süresinin ise logaritmik olarak azaldığı gözlemlenmektedir. Sonuçlar, 1064 nm dalgaboyundaki lazer sistemlerinin daha hızlı tepki verdiğini, ancak daha yüksek DFK değeri ürettiğini göstermektedir. Buna karşılık, 1550 nm dalgaboyunda lazer kullanan LDV sistemleri daha düşük DFK ve daha uzun örnekleme süresi sunmaktadır. Bunun yanı sıra, 1064 nm dalgaboyunda ışıma yapan lazerler, hız değişikliklerine daha duyarlı olmasına karşılık, 1550 nm dalgaboyunda ışıma yapan lazerler daha kararlı ölçüm imkânı sağlamaktadır.

Anahtar kelimeler: *Doppler frekans kayması (DFK), Lazer Doppler vibrometre (LDV), Titreşim frekansı, Titreşim hızı*

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1. Introduction

LIDAR (Light Detection and Ranging) sensor is an imaging device that accurately measures the distance and surface structure of an object without contact and remotely by using a laser beam. In LIDAR systems, laser pulses are directed to the object's surface whose distance is to be measured, and the reflected light photons are detected by the photodetector and the distance is computed. LIDAR systems generally consist of a laser, detector, IMU (Inertial Measurement Unit) and GPS (Global Positioning System) components. In these systems, in principle, a three-dimensional point cloud is created using the IMU and GPS data obtained. Each point represents a reflection signal at a specific location (Cartesian coordinates (x, y, z)). In this way, high-resolution and detailed three-dimensional maps are acquired. The obtained three-dimensional (3-D) mapping data is widely used, especially in topography systems, autonomous vehicles and geographic information systems (Allahverdi et al., 2009; Çelik et al., 2014; Karaman, 2019).

LDV is a measuring device that remotely and non-contactly detects the vibration velocity of the target or object based on the DFS of laser light. These devices are also used to precisely measure waveforms of elastic waves or particle motion in the ultrasonic frequency range (Nishizawa et al., 1997; Nishizawa et al., 1998; Lei & Nishizawa, 1998; Scales & Wijk, 1999; Sivaji et al., 2002; Fukushima et al., 2003; Boudet et al., 2005; Campman et al., 2005). Imaging cameras are also used for such measurements. However, since these cameras operate at low frame rates in the range of a few hundred hertz, they are not preferred over LDVs (Blackmon & Antonelli, 2006; Ma et al., 2008).

The operation of an LDV is principally based on reflecting a laser beam onto a moving surface and measuring changes in the velocity of the surface through a photodetector (Drain, 1980). The light beam produced by the laser light source in the LDV focuses on a specific point on the surface, and as this point moves, a frequency shift occurs on the laser beam. This frequency shift is called DFS. Depending on the DFS, the velocity and direction of movement of the object's surface are determined. LDV is considered an important technological device as it measures the surface vibrations of an object with high accuracy and precision using DFS data (Adrian, 1993).

Figure 1 shows the working principle of an LDV system. The LDV system includes a laser source that produces laser beam at a specific frequency (f_o), a reflector, splitters, a Bragg cell, and a photodedector in general. The first splitter used in the LDV illustration shown in Figure 1 allows the light coming from the laser source to be divided into two: light beam and test beam (Oldengram et al., 1973; Buchhave, 1975; Halliwell, 1979).

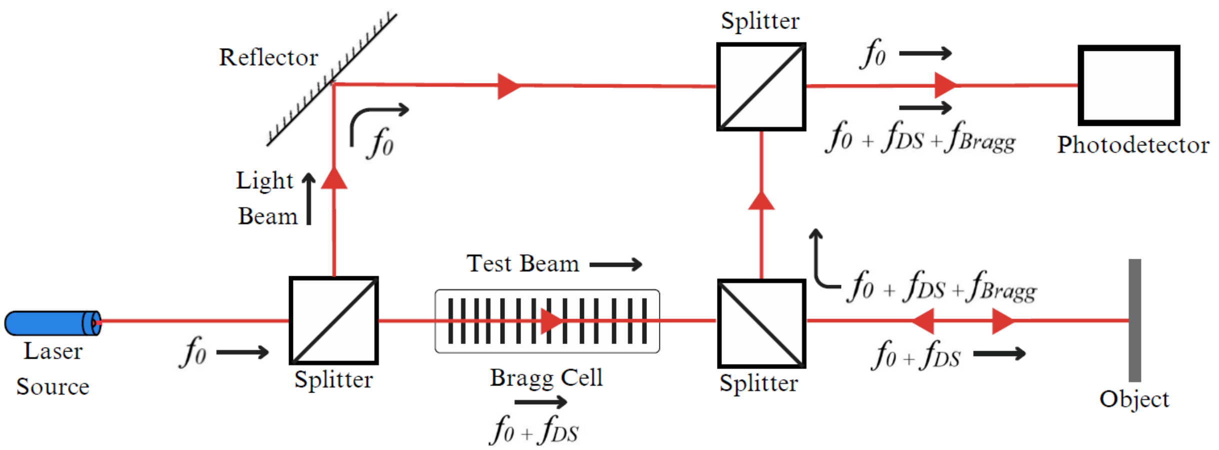

Figure 1. Principle scheme of an LDV system

In the LDV systems, splitters play a crucial role in creating separate paths for the light and test beams and directing them to the appropriate parts of the system. In this LDV scheme, the light beam is reflected from the reflector and reaches the photodetector through another beam splitter. The reflector employed in the LDV system acts as a fixed surface that reflects the light beam back to the photodetector. Afterwards, the test beam is passed through a Bragg cell where its frequency is changed by f_{Bragg}, i.e. frequency of Bragg, and then directed to a second splitter. The Bragg cell used in the system, i.e. acousto-optic modulator, is used to shift the frequency of the test beam by a certain amount (f_{Bragg}). This frequency shift is crucial for separating the signals of the reference and test beams and facilitating precise Doppler shift measurements. When the Bragg cell is not used in the LDV system, DFS can only be measured depending on the speed of the test beam, but the direction of motion cannot be distinguished and stationary objects cannot be detected. Furthermore, small frequency differences at low speeds become difficult to measure without the constant frequency shift provided by the Bragg shift, significantly reducing the overall sensitivity and accuracy of the system (Watson et al.,1992; Hardie et al., 1998; Kraczek, 2017).

The second beam splitter employed in the LDV configuration combines the light beam and the test beam after the test beam passes through the Bragg cell and reflects off the target object and sends it to the photodetector. The photodetector detects the interferometric pattern between the light beam and the test beam reflecting back. This interferometric pattern changes depending on the velocity and vibration frequency of the target object, and the velocity and vibration frequency of the surface are computed using signal processing techniques. In this way, the LDV system measures surface vibrations and velocities of the target object with high precision and high accuracy in a non-contact method (Stanbridge et al., 1999; Choi et al., 2003; Stanbridge et al., 2004).

The schematic illustration of DFS is shown in Figure 2. For the object moving towards the LIDAR sensor, the frequency change due to Doppler shift is clearly shown in Figure 1. As obviously in this figure, a shift in Doppler frequency occurs as the object moves forward and backward. Consequently, the forward and backward movement of the object causes a change in the Doppler frequency, in other words, a DFS.

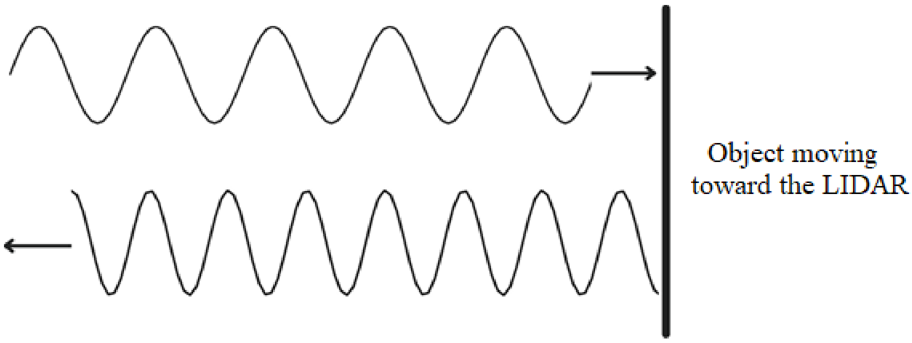

Figure 2. Schematic illustration of DFS (McManamon, 2015)

Numerous studies are reported in the literature addressing the basic principles and applications of laser vibration and the Doppler effect (Romaniuk & Gajda, 2012; Tabatabaiet al., 2013). However, studies on performance comparisons of laser systems at different wavelengths and the responses of these systems to different vibration frequencies are limited. Therefore, this research article focuses on the response of laser systems using different wavelengths to vibration frequency and their relationship with parameters such as DFS and sampling time. The article is a theoretical study and includes simulations performed at different vibration frequencies with a fixed vibration amplitude and the dependencies of these parameters. In this context, by using laser beams with wavelengths of 1064 nm and 1550 nm, changes in parameters such as maximum vibration velocity, DFS, and sampling time are observed. In other words, the study aims to determine to what extent the changing frequency depending on the constant vibration amplitude affects the maximum vibration velocity, Doppler shift and sampling time. The reason why 1064 nm and 1550 nm wavelength lasers are the focus of this study is that these wavelength lasers are widely used in LDV systems.

2. Material and method

The precise measurements of the Doppler effect and laser vibration are critical for understanding the dynamic behavior of materials and objects and for use in various industrial applications. The laser vibration is a widely used technique to properly detect vibration frequencies and amplitudes of material surfaces (Lutzmann et al., 2016). In addition, using the Doppler effect to determine the velocity of moving objects directly affects the performance and accuracy of laser systems in some cases (Chen et al., 2006).

LDV systems used in vibration measurements detect the response at only one point at a time. In these systems, the laser beam is directed at a point on the test structure and a measurement is taken over a time frame long enough to ensure that the impact response of the structure fades. The laser is then directed to a new point of the structure and the process is repeated. In this manner, several measurements are made at each location to reduce noise effects (Allen & Sracic, 2010).

DFS refers to a change in frequency relative to a moving source or receiver. As the object moves, the frequency of the reflected light changes due to Doppler shift, and this change is used to measure the vibration velocity of the object.

In the LIDAR systems, when the pulse returns, its frequency will have shifted based on the Doppler shift of the return light. DFS is expressed as a function of velocity and wavelength of the laser source as given in equation (1) (Fukushima et al., 2009).

$$\Delta f = \frac{2v}{\lambda} \tag{1}$$

where Δf is the DFS, v is the velocity and λ is the wavelength of laser source.

As can be seen from equation (1), the higher the velocity towards or away from the sensor, the higher the frequency shift. Due to the fact that the two-way path, to the object and returned from the object of the light, the factor 2 is included in the equation. The relationship in (1) is often used to measure small reciprocating velocities resulting from vibrations. Therefore, the measured Doppler frequency helps determine the vibration velocity of the object.

DFS values of the moving object at various velocities for the wavelengths of 1064 nm and 1550 nm are given in Table 1.

Table 1. DFS at specific velocities for the wavelength of 1064 nm and 1550 nm

Velocity (µm/s)	DFS (1064 nm) (Hz)	DFS (1550 nm) (Hz)
1	1.88	1.29
10	18.80	12.90
100	187.97	129.03
1000	1879.70	1290.32

As can be seen from Table 1, the vibration velocity of an object and the DFS caused by vibration vary linearly. The relatively small changes in vibration velocity cause significant changes in the DFS. Using the LDV systems, the DFS caused by the difference in wavelength can be measured precisely even in a very small temporal period. From this perspective, LDV systems are considered as devices that provide high performance and accurate measurements.

As an object vibrates, velocities occur towards and away from the LIDAR systems. Equation (2) shows the position change due to vibration (McManamon, 2019).

$$x = Asin(2\pi f t) \tag{2}$$

In equation (2), A and f denote the vibration amplitude and the frequency, respectively.

The Doppler effect is used by devices such as LDV, allowing the vibration velocity of the objects to be measured. In this context, since the velocity is derived from dx/dt, it is obtained from the derivative of the surface position of a vibrating object as given in equation (3) (McManamon, 2019).

$$v = \frac{dx}{dt} = 2\pi f Acos(2\pi f t) \tag{3}$$

The sampling time is written as given in equation (4), depending on the Doppler frequency (McManamon, 2019)

$$T_S = \frac{2}{F_D} \tag{4}$$

where T_S is the sampling time and F_D is the Doppler frequency.

3. Simulations and findings

Simulations related to the effectes of maximum velocity, vibration frequency and vibration amplitude parameters on DFS have been carried out using Matlab. Equations (1), (3) and (4) have been used to obtain the simulations.

Figure 3 shows the relationship between velocity and DFS for lasers emitting at wavelengths of 1064 nm and 1550 nm. As seen in Figure 3, there is a linear relationship between velocity and DFS for both wavelengths.

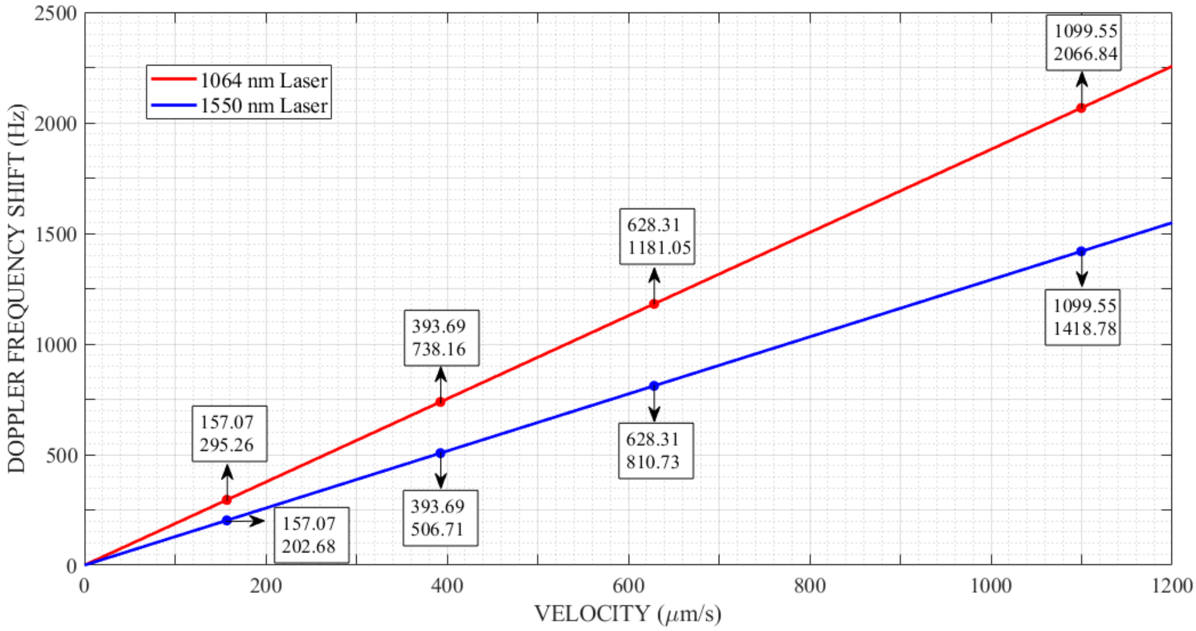

Figure 3. Varition of DFS with velocity for wavelengths of 1064 nm and 1550 nm

For the laser with a wavelength of 1064 nm, the object's velocity limits are between 0 and 1200 μm/s, while DFS is between 0 and 2255.64 Hz. DFS for the 1550 nm wavelength laser ranges from 0 to 1548.39 Hz for the same velocity limit values. Hence, the sensitivity to velocity change of DFS for laser systems operating at 1064 nm is higher than that of laser systems operating at 1550 nm. This is because both the photon energy and therefore the photon frequency at 1064 nm are greater than the photon energy and photon frequency at 1550 nm. In other words, a higher photon frequency causes a higher DFS per unit velocity change, thus higher sensitivity to velocity change.

As can be clearly seen from Figure 3, for a wavelength of 1064 nm, at a vibration frequency of 50 Hz, the maximum velocity, maximum DFS and sampling time have been found to be 157.07 μm/s, 295.26 Hz and 6.77 ms, respectively. When the vibration frequency has been increased to 200 Hz, the maximum velocity has increased to 628.31 μm/s, the maximum DFS has risen to 1181.05 Hz, while sampling time has decreased to 1.69 ms. The data obtained from this simulation show that as the vibration frequency increases, the maximum velocity and DFS increase linearly, whereas sampling time decreases logarithmically. This is considered to be an indication that high-frequency vibrations in laser systems require more precise sampling and vibration control is important.

For the 1550 nm wavelength laser, at 50 Hz vibration frequency, the maximum velocity, maximum DFS and the sampling time have been obtained as 157.07 μm/s, 202.68 Hz and 9.86 ms, respectively. As the vibration frequency has been increased to 200 Hz, the maximum velocity and the maximum DFS has reached to the values of 628.31 μm/s and 810.73 Hz, respectively. In this manner, the sampling time has risen to the value of 2.46 ms. Similar to the simulation performed at 1064 nm wavelength, the maximum velocity and DFS increase linearly with the increment of vibration frequency, while the sampling time decreases logarithmically.

Using the simulation data in Figure 3, mathematical formulas related to the relationships between velocity (v) and DFS (F_{DS}) for wavelengths of 1064 and 1550 nm are obtained as given in equations (5) and (6), respectively.

$$F_{DS} = 1.87970.v + 1.54637 \text{ x } 10^{-2} \quad (5)$$

$$F_{DS} = 1.29032.v + 9.56986 \text{ x } 10^{-3} \quad (6)$$

As can be seen from the equations, the DFS increases linearly as the velocity increases. The velocity change rate of DFS, i.e. sensitivity to velocity change is 1.88 Hz(μm/s)$^{-1}$ for 1064 nm and 1.29 Hz(μm/s)$^{-1}$ for 1550 nm, respectively. This conclusion confirms that the 1064 nm wavelength shows higher sensitivity to velocity changes and produces a larger DFS. This means that the sensitivity to velocity change of photons at 1064 nm is higher compared to the sensitivity to velocity change of photons at 1550 nm wavelength.

Simulation regarding the vibration frequency dependence of the Doppler frequency is shown in Figure 4. As obviously seen in Figure 4, DFS changes linearly with vibration frequency for both 1064 nm and 1550 nm.

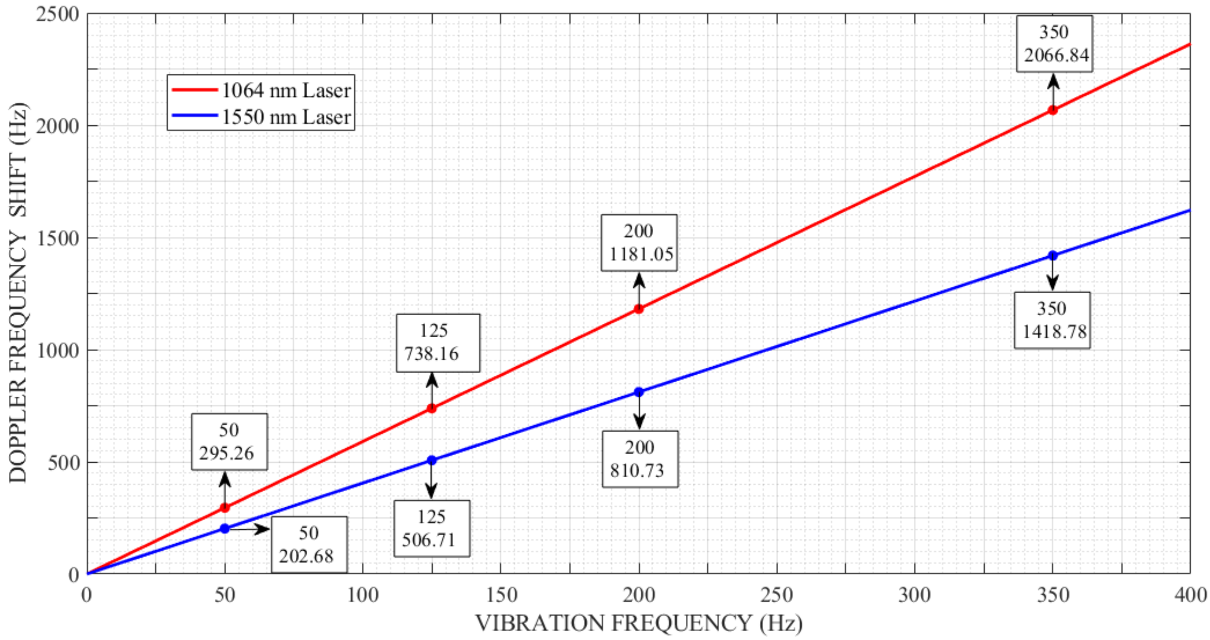

Figure 4. Varition of DFS with vibration frequency for wavelengths of 1064 nm and 1550 nm

It can be seen in Figure 4 that, while the vibration frequency varies between 0 and 400 Hz, the DFS varies between 0 and 2362.1 Hz at 1064 nm. For the laser used at a wavelength of 1550 nm, the DFS for the same vibration frequency limits is between 0 and 1621.47 Hz.

Applying the interpolation method to the simulation data obtained from Figure 4, equations expressing the relationships between vibration frequency (F_V) and DFS for 1064 nm and 1550 nm are stated as in equations (7) and (8), respectively.

$$F_{DS} = 5.90527.F_V - 3.33330 \text{ x } 10^{-3} \quad (7)$$

$$F_{DS} = 4.05364.F_V + 4.44440 \text{ x } 10^{-3} \quad (8)$$

The vibration frequency dependencies of DFS for both wavelengths are found to be 5.90 and 4.05, respectively. Therefore, the dependency value is larger for 1064 nm than for 1550 nm. This indicates that laser systems with a wavelength of 1064 nm provide more sensitive and faster responses than laser systems with a wavelength of 1550 nm.

The simulation of the variation of sampling time with DFS at wavelengths of 1064 nm and 1550 nm is shown in Figure 5. As can be seen in Figure 5, the sampling time decreases logarithmically as the DFS increases. For the 1064 nm wavelength laser, the DFS varies between 295.26 Hz and 2066.84 Hz, while the corresponding sampling times decrease from 6.77 ms to 0.96 ms. On the other hand, for the laser used at 1550 nm wavelength, the DFS values have varied between 202.68 Hz – 1418.78 Hz, while the sampling time has taken values between 9.86 – 1.41 ms.

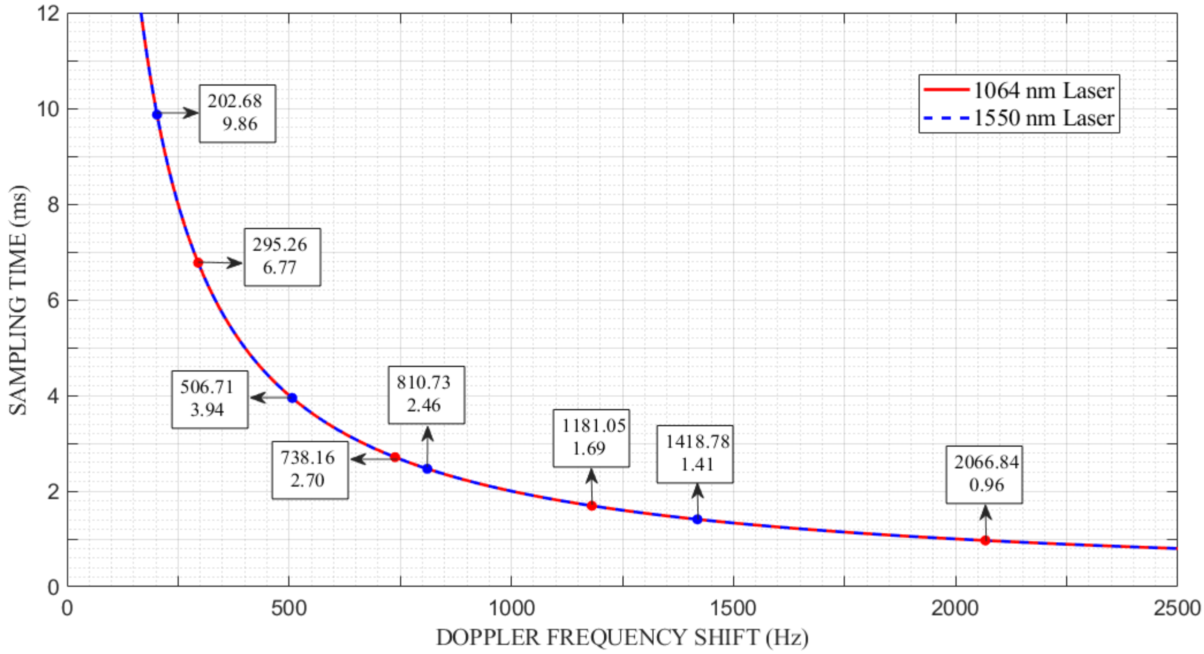

Figure 5. Varition of DFS with sampling time for wavelengths of 1064 nm and 1550 nm

Applying the curve fitting method to the data obtained in the simulation shown in Figure 5, the mathematical relations representing the relationship between DFS and sampling time (S_T) are obtained for 1064 nm and 1550 nm wavelengths as in equations (9) and (10), respectively.

$$S_T = 3.229\ x\ 10^{-6}. {F_{DS}}^2 - 0.01075. F_{DS} + 9.446 \tag{9}$$

$$S_T = 9.990\ x\ 10^{-6}. {F_{DS}}^2 - 0.02281. F_{DS} + 13.76 \tag{10}$$

As is obviously understood from the equations (9) and (10) there are quadratic relationship between DFS and sampling time. As DFS increases, sampling time decreases. The larger the sampling time, the shorter the response time of the system. Therefore, the smaller the sampling time, the faster the response time of the system. Therefore, knowing the sampling time is an important parameter for the evaluation of LVD systems. Therefore, the response time of the LDV system with 1064 nm wavelength is higher than that of the system with 1550 nm wavelength.

For wavelengths of 1064 nm and 1550 nm, vibration frequency, vibration amplitude, maximum velocity, maximum DFS and sampling time parameters are given in Table 2 and Table 3, respectively.

Table 2. DFS and corresponding parameters due to surface vibrations at 1064 nm

Vibration frequency (Hz)	Vibration amplitude (µm)	Maximum velocity (µm/s)	Maximum DFS (Hz)	Sampling time (ms)
50	0.5	157.07	295.26	6.77
125	0.5	393.69	738.16	2.70
200	0.5	628.31	1181.05	1.69
350	0.5	1099.55	2066.84	0.96

Table 3. DFS and corresponding parameters due to surface vibrations at 1550 nm

Vibration frequency (Hz)	Vibration amplitude (µm)	Maximum velocity (µm/s)	Maximum DFS (Hz)	Sampling time (ms)
50	0.5	157.07	202.68	9.86
125	0.5	393.69	506.71	3.94
200	0.5	628.31	810.73	2.46
350	0.5	1099.55	1418.78	1.41

4. Conclusion

In this study, the relationship between DFS, vibration frequency and maximum velocity in LDV systems is investigated. In this context, changes in performance parameters such as vibration frequency, vibration amplitude, maximum velocity, maximum DFS and sampling time for 1064 nm and 1550 nm radiation wavelengths have been analyzed through simulations performed in Matlab environment.

For the wavelength of 1064 nm, where the vibration frequency is 200 Hz, the maximum DFS has been found to be 1181.05 Hz at the sampling time of 1.69 ms. On the other hand, for 1550 nm, at the same value of the vibration frequency and the sampling time of 2.46 ms, the maximum DFS has been obtained as 810.73 Hz. According to the simulation results and findings, it has been concluded that the maximum velocity and DFS have increased linearly with the increase in vibration frequency, while the sampling time has decreased logarithmically. This reveals that high-frequency vibrations in laser systems require more precise sampling and jitter control is critical. This difference has shown that laser systems at 1064 nm wavelength have responded faster, but produced higher DFS.

On the other hand, laser systems, i.e. LDV systems at 1550 nm wavelength exhibit more stable performance because they offer lower DFS. In other words, lasers in LDV systems emitting at 1064 nm wavelength are more sensitive to velocity changes, whereas lasers emitting at 1550 nm wavelength provide a more stable measurement opportunity. As a result, the findings obtained in this research article can be considered to be of critical importance and value in terms of the design and optimization of these systems, as well as providing useful data in the precise measurement of the vibration frequency and vibration velocity of the target or object with LDV systems. In addition, it will be possible to design and optimize LDV systems in which the vibration velocity of object is measured more precisely and accurately, and to analyze the data theoretically.

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Author contribution

The contribution role of A. Günday includes conceptualization, data curation, checking simulations, methodology, investigation, project administration, supervision, validation, visualization, writing – original draft and writing – review & editing. The contribution role of T. Sipahi includes methodology, project administration, supervision process, review & editing and the contribution roles of A. Balabey, C. Utar, M. Demir, M.M. Yılmaz include investigation, theoretical analysis, simulation, data curation, methodology, and draft writing of the article.

Declaration of ethical code

The authors declare that this study does not require ethical committee approval or any legal permission.

Conflicts of interest

The authors declare no competing interests.

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