# Comparison between Laser Doppler and Sagnac-based vibrometers from the view of velocity noise density

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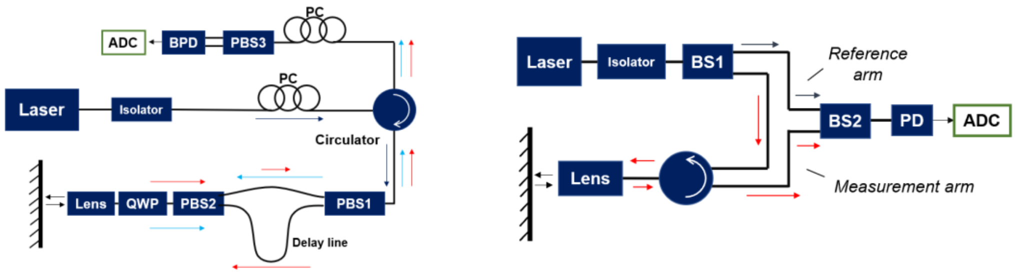
*Non-destructive testing is a group of analytic techniques widely used to evaluate and characterize the properties of a material, structure, or system. Conventional non-destructive testing often uses an ultrasound transducer in contact with the target, which is unsuitable for many applications. The non-contact testing methods, however, can provide more flexibility since they evaluate targets distantly. Laser Doppler vibrometry (LDV) and Sagnac-based vibrometry are two common non-contact testing methods utilizing the interferometer structure. In this paper, we compare the velocity noise density of the LDV and the Sagnac-based vibrometry, considering the shot noise limitation in simulation. We also review the advantages and disadvantages of both methods.*

## Introduction

Non-destructive testing (NDT) is a group of testing methods used in many realms, including material engineering, pipe and tube inspection, and defects characterization. Laser Doppler vibrometry (LDV) [1] is a well-recognized NDT technique widely used for defect characterization in evaluating composite materials. Sagnac-based vibrometry, which is widely used has been reported to show an outstanding performance in [2]. As shown in Fig. 1 (a) and (b), both Sagnac-based vibrometry and LDV are based on the principle of interference, which gives them great sensitivity and enables them to measure sub-nanometer or sub-picometer displacement in vibration.




(a) (b)

Figure 1: (a) The schematics of Sagnac-based vibrometer; (b) the schematics of laser Doppler vibrometer, QWP: quarter wave plate, PBS: polarization beam splitter, BPD: balanced photodiode, BS: beam splitter, PD: photodiode, ADC: analog-to-digital converter.

The LDV was first used to study fluid dynamics to measure the flow speed in high resolution without disturbing the liquid [3]. The light scattered by the particles in a flowing liquid undergoes the process of the Doppler effect. A laser beam is focused on a target to measure the vibration of a solid surface. By collecting the reflected or scattered light and mixing it with reference light, the frequency shift brought by the vibration of the target can be obtained after a demodulation process [4]. The Sagnac interferometer, first demonstrated for its potential in fiber-based gyroscopic sensing, is now utilized in vibration sensing, hydrophone, and many other domains [5]. The sameness of the clockwise and counterclockwise loop directions of Sagnac-based vibrometry makes it capable of operating using a low coherent light source [2, 5], which is not applicable for laser Doppler interferometer since its measurement beam needs a mutually coherent reference to beat with. In 2014, I. Pelivanov reported a balanced fiber-optic Sagnac interferometer to inspect the laser ultrasonic on a composite material with an excellent noise equivalent pressure of 400 Pa over 1 MHz to 10 MHz [2], which has attracted much attention from the NDT world. To further investigate the potential of Sagnac-based vibrometry, we model Sagnac-based vibrometry and LDV and compare them from the perspective of shot noise limit.

## Velocity noise analysis of Sagnac-based vibrometry and LDV

As shown in Fig. 1 (b), the Sagnac-based vibrometry structure consists of a light source that can be coherent or incoherent, three polarization beam splitters, a circulator, and a balanced PD (BPD) using balanced detection. The light source is a CW laser with the power of $P_0$. The splitting ratios of $PBS1$ and $PBS2$ are set as 50:50 to ensure the system's optimal performance. Then we can obtain the signal at the BPD as

$$I(t) = 2\mu\sqrt{P_c \cdot P_{cc}} \cdot \cos\big(\theta(t-\Delta T) - \theta(t)\big)$$

where $P_c$ and $P_{cc}$ are the clockwise and the counterclockwise light power in Sagnac. $\Delta T$ is the time delay brought by the fiber delay line of Sagnac structure and $\mu$ is the responsivity of BPD. The time delay can be derived as $\Delta T = \frac{l \cdot n}{c}$, where $l$ is the length difference of the two fibers, $c$ is the speed of light, and $n$ is the effective refractive index of fiber. Since the lights of both the clockwise and counterclockwise directions travel through the same devices, their power $P_c$ and $P_{cc}$ can be obtained as $P_c = P_{cc} = \frac{1}{2}P_0 L$, where $L$ is the is the percentage of optical power transmitted via the optical link of the clockwise and counter-clockwise paths. The $\theta(t)$ and $\theta(t-\Delta T)$ are the phase shifts brought by the vibration of measured target in the directions of clockwise and counterclockwise, respectively. The DC component of each PD can be derived as

$$I_{DC} = \mu\frac{P_0 L}{2}$$

And amplitude density of the total shot noise of the BPD can be expressed as

$$I_{shot\ noise}(\omega) = \sqrt{2q\mu P_0 L}$$

We assume that the interferometer is working at the most sensitive point of $\theta(t-\Delta T) - \theta(t) = \frac{\pi}{2}$. Since the phase change brought by the shot noise is sufficiently small, we can approximate the phase change equals to the current of shot noise divided by $2\mu\sqrt{P_c \cdot P_{cc}}$. Therefore, the amplitude density of the noise in the demodulated displacement $\rho_{D_{\mathrm{noise}}}(\omega)$ can be obtained as is

$$\rho_{D_{noise}}(\omega) = \frac{\lambda}{4\pi} \cdot \sqrt{\frac{2q}{\mu P_0 L}} \cdot \frac{1}{(e^{j\omega\Delta T} - 1)}$$

where $\lambda$ is the wavelength of the light source. The nonlinear factor $\frac{1}{(e^{j\omega\Delta T}-1)}$ at the right side of the equation originates from the time delay between the clockwise and counterclockwise signals. Moreover, the amplitude noise in the velocity signal is

$$\rho_{V_{\text{noise}}}(\omega) = \frac{\lambda}{4\pi} \cdot \sqrt{\frac{2q}{\mu P_0 L}} \cdot \frac{1}{(e^{j\omega\Delta T} - 1)} \cdot \omega$$

The same analysis can be applied to LDV. Since the two arms of LDV have very different optical losses, the best splitting ratio $S$ is not 50:50 in practice. The noise amplitude of the velocity output of an LDV is

$$\rho_{v'_{noise}}(\omega) = \frac{\lambda}{4\pi} \sqrt{\frac{q\mu(P_{ref} + P_{mea})}{P_{ref} \cdot P_{mea}}} \cdot \omega$$

where the $P_{ref} = P_0 \cdot S$ is the optical power on the reference arm, and the $P_{mea} = P_0 \cdot (1 - S)L$ is the light power on the measurement arm before the beam splitter 2 (BS2), as shown in Fig. 1(b). Based on the analysis above, we are able to derive the velocity noise density of both techniques, and make a side-by-side comparison of them.

## Comparison between the Sagnac-based vibrometry and LDV

According to the analysis above, we calculate the theoretical velocity noise density of the Sagnac-based vibrometer and LDV. The light source of LDV and Sagnac is operating on 1550 nm and the optical powers coupled into both the systems are set to be 1 mW, and the responsivity $\mu$ of PD is 1 A/W. The length difference between the two fibers of the Sagnac-based vibrometer is 10 m long with the effective refractive index of 1.5. We consider the frequency range of the detected vibration is from 0.1 MHz to 100 MHz, which can cover a wide frequency range, including the measurement range in [2]. Firstly, we consider the ideal situation: that is, the optical link of both the Sagnac-based vibrometer and LDV are lossless, and the splitting ratio $S$ of LDV is set 50:50 to match the lossless condition.

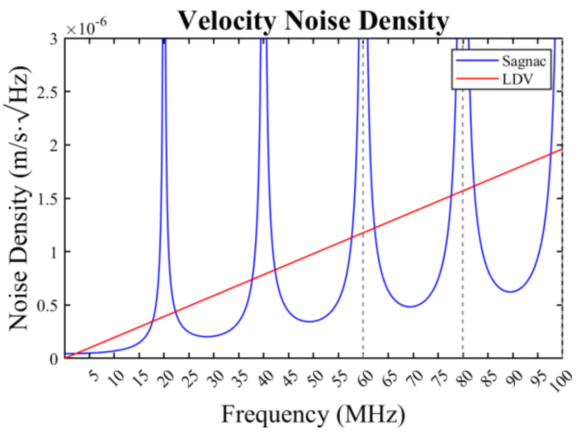



Figure 2: Comparison of the velocity noise density of Sagnac-based vibrometer and LDV in an ideal setup: the light source is operating on 1550 nm with the power of 1 mW, the optical path is lossless, the splitting ratio $S$ of LDV is 50:50, and the fiber delay line in Sagnac is 10 m with the effective refractive index of 1.5.

From the result in Fig. 2, we can observe that with the ideal setup of light source and loss from measurement, the Sagnac-based vibrometry shows better performance for most of the frequency points with the lower noise level, since the velocity noise density of Sagnac-based vibrometry is nonlinear to the frequency. Because of the periodic property of the velocity noise density of Sagnac-based vibrometry, the noise level deteriorates around the frequency of 20 MHz, 40 MHz, 60 MHz, and 80 MHz. Then, we consider a more practical setup in that the loss brought by the measurement is 20 dB. Meanwhile, the splitting ratio $S$ of LDV is set to be 10:90, which is the optimal splitting ratio cooperating with the loss.

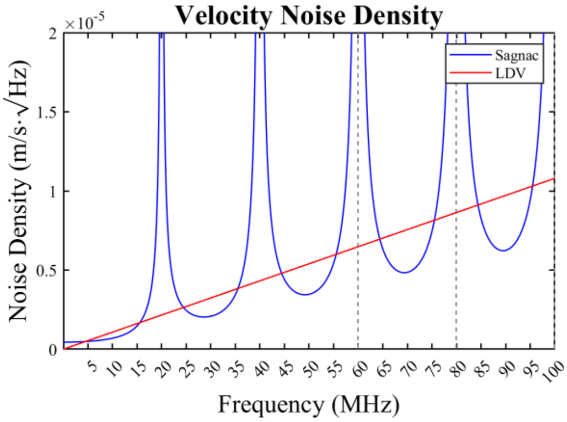



Figure 3: Comparison of velocity noise density of the Sagnac-based vibrometer and LDV in a pragmatic setup: the light source is operating on 1550 nm with the power of 1 mW, the loss brought by the measurement is 20 dB, the splitting ratio S is 10:90, and the fiber delay line in Sagnac is 10 m with the effective refractive index of 1.5.

As shown in Fig. 3, the performance of both Sagnac-based vibrometry and LDV deteriorated with the higher noise level. However, even with a certain loss, the velocity noise of the Sagnac-based vibrometer and LDV remain roughly the same, which convinces the potential of the Sagnac-based vibrometry.

## Conclusion

In this paper, we model, calculate and compare the velocity noise density of Sagnac-based vibrometry and LDV. We observed that with the same amount of optical power, the noise floor of shot-noise-limited Sagnac-based vibrometry and LDV is at roughly the same level over the frequency range from 0.1 MHz to 100MHz. However, at some frequency points, the Sagnac-based vibrometry provides a slightly lower noise level due to its periodic property in velocity noise density. Moreover, a setup with lower loss also helps in improving the performance of the system. Considering the implementation of the system, Sagnac has the advantage of using a broadband light source because the clockwise and the counterclockwise light undergo the same path. Although a broadband light source can also be applied for an interferometer like the LDV, it cannot be named an LDV as its optical source is no longer a laser source.

## References

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