Bio-Speckle Phenomena for Blood Flow Measurements: Speckle Fluctuations and Doppler Effects

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Abstract. Both laser speckle and laser Doppler techniques can be used to measure human blood flows, but their interrelation is still unclear. This paper studies their differences, similarities, and relations in the moving rough surface and particle flow models, which are summarized in the table. The dominance of either speckle fluctuations or Doppler effects depends mainly on the coherence condition, particle concentration, and velocity distribution.

1 Introduction

Laser speckle and laser Doppler techniques are both based on dynamic light scattering phenomena. However, what is detected is originally different due to their different principles: the former is random intensity fluctuations and the latter is periodic beat signals. In spite of this, the terms "speckle fluctuations" and "Doppler effects" are carelessly mingled when they are applied to blood flow measurements. In fact, we have already reported bio-speckle flowmetry [1,2] for blood flow measurements, which is based on the speckle technique but very often it is considered to be the Doppler technique. The two techniques have been well established, but their interrelation is still unclear [3,4]. We discussed their differences, similarities, and mutual relations in the moving rough surface and particle flow models, and summarized results in the table.

2 Single Particle and Rough Surface Models

2.1 Single Particle

For the case of a single particle or very dilute particle suspension with a constant moving velocity, the laser Doppler technique works quite well. When the coherence condition is satisfied, the heterodyne mixing produces truly periodic Doppler beat signals with a Gaussian envelope due to the transit time τ_T. There is no speckle produced in this case because of a single or very few scattering centers.

2.2 Rough Surface

Single Beam Illumination. A moving rough surface illuminated by a single laser beam produces time-varying speckle fluctuations in the both diffraction and imaging fields. But, all the scattered waves from the surface are Doppler-shifted by different frequencies each other. No use of a reference beam means conventionally "*homodyne* mixing" which shows a monotonically decreasing spectrum. Thus, detected signals are truly speckle fluctuations and can be possibly considered homodyne components.

Dual Beam Illumination. When the differential-type Doppler arrangement is applied to a moving rough surface [5], detected components are Doppler beat signals with an envelope of speckle fluctuations. Then, the Doppler effects and speckle fluctuations coexist, but are not equivalent because of different frequency components. When the intersection angle θ of the two beams is reduced to zero degree, the Doppler heterodyne beat component disappears but the speckle fluctuation still remains.

Michelson Interferometer. Briers' model [4] using the Michelson interferometer in which one of reflecting mirrors is replaced by a rough surface moving along the optical axis corresponds to exactly the case of "Dual Beam Illumination" with $\theta = 90$ (deg). Thus, detected signals are again the Doppler heterodyne beat with the speckle fluctuation envelope. The in-plane movement in this model yields no Doppler effect and no heterodyne beat even with the reference beam. Detected signals are truly speckle fluctuations which are very similar to homodyne signals.

3 Particle Flow Models

3.1 Single-Beam Doppler Velocimetry (LDV)

Moderate Concentration. In the single-beam Doppler technique studied by Riva *et al*[6], the Doppler-shifted wave from a moving red blood cell is heterodyned with the non-shifted wave reflected back from the vessel wall. Moderate concentration of particles may produce time-varying speckle fluctuations while it maintains dominant Doppler components. Thus, detected signals are possibly Doppler beat with the speckle fluctuation envelope. Figure 1(a) shows a typical recorded signal and the corresponding power spectrum measured for 1-µm diam acrylic particles flowing with water (1% concentration) in a cylindrical glass tube under He-Ne laser beam illumination. The signal shows periodic beat components with the envelope of speckle-like random fluctuations, and the power spectrum demonstrates the heterodyne cut-off characteristics with some broadening as we expected.

Receiving Cone Angle Enlarged & Flow in Orthogonal Direction. When the receiving cone angle is enlarged, the coherence condition tends to be corrupted due to range of scattering angles. Thus, the heterodyne components are degraded and speckle fluctuations become dominant. When the illumination and detection are both made in the direction orthogonal to the flow, no Doppler effect is produced. Then, speckle fluctuation components only remain and make the broadened spectrum centered at the zero frequency, which may be referred to as the homodyne spectrum.

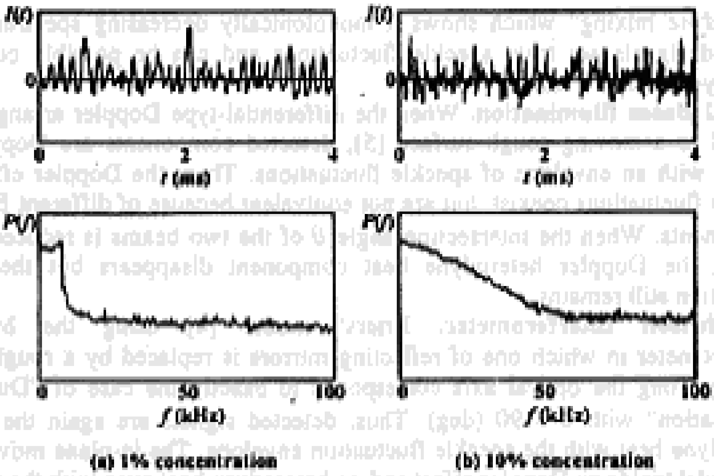

Fig.1. Typical signals $I(t)$ and power spectra $P(f)$ obtained from particles within water flowing in a glass tube for the particle concentration of (a) 1 % and (b) 10 %.

3.2 High Concentration and Bio-Speckle Flowmetry

Increased concentration of particles causes multiple scattering, correspondjng to the case of blood flow measurements. In fact, bio-speckle flowmetry has been developed for this case. Numerous random directions of illuminating and scattered waves and random velocity distribution cause randomly distributed Doppler-shifted frequencies. Random positions of particles result in the randomness of optical path length for scattering waves. All of these effects randomize the phases and, therefore, the phase-consistent time or the speckle correlation time is significantly shortened. Bio-speckle flowmetry employs both the extended illuminating spot and the enlarged receiving cone angle which enhance the speckle fluctuations. The Doppler heterodyne components are degraded significantly and finally wiped out by speckle fluctuations.

Figure 1(b) shows a typical signal and its power spectrum measured for 10% concentration of particles in water. The signal shows random speckle fluctuations, and the power spectrum demonstrates monotonically decreasing components, which wiped out the heterodyne cut-off characteristics. The mixing of various Doppler-shifted waves with themselves may also be interpreted as the homodyne, and possibly be referred to as the intensity correlation (or fluctuation) spectroscopy (ICS or IFS), light beating spectroscopy (LBS), and photon correlation spectroscopy (PCS).

4 Conclusion

The relations of speckle fluctuations and Doppler effects were discussed and results are briefly summarized in Table 1. Surely the two phenomena are not equivalent, but in some situations they coexist or are mixed. The homodyne components are quite similar to the speckle fluctuations. Whether the laser Doppler velocimeter covers only the heterodyne technique or also the homodyne technique is a problem of terminology and probably due to a difference of interpretation.

Table 1. Relations of speckle fluctuations and Doppler effects in various situations.

		Speckle technique	Doppler technique	Relations & remarks
Single particle (very dilute suspension)		--- (no speckle)	O	Doppler beat only
Rough Surface	Single beam	O	--- (no reference)	speckle only [possibly homodyne]
	Dual beam	O	O	envelope + beat signal [coexisting, not equivalent]
	Michelson interferometer (movement along axis)	O	O	envelope + beat signal [coexisting, not equivalent]
	Michelson interferometer [in-plane movement]	O	--- (no shift)	speckle only [similar to homodyne]
Flowing particles	Moderate concentration (single or dual beam)	O	O (broadened)	envelope + beat signals (various frequencies) [coexisting, not equivalent]
	Large receiving cone angle	O (enhanced)	Δ (degraded)	speckle dominant [possibly homodyne]
	Flow in orthogonal direction	O	--- (no shift)	speckle or homodyne
	High concentration (single or dual beam)	O (higher freq. fluctuations)	--- (wiped out)	speckle or homodyne, [also ICS, IFS, LBS, and PCS]

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