Speed measurement of a rotating diffuser by means of the Doppler shift of the scattered light

Gladis Graciela Romero[1], Elvio Edgardo Alanís[1], Andrea Carolina Monaldi[1], Héctor Jorge Rabal[2]

[1]*GOL – Grupo de Óptica Láser, Facultad de Ciencias Exactas, Consejo de Investigación. - Universidad Nacional de Salta - Av. Bolivia 5150- 4400- Salta – Argentina.*

[2]*Centro de Investigaciones Ópticas (CONICET-CIC) and UID OPTIMO Dpto. Cs. Básicas, Fac. de Ingeniería, UNLPP.O. Box 124, 1900 La Plata Argentina.*

E-mail: romeropelayog@gmail.com

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Abstract

An experiment designed to detect the Doppler shift frequency of light scattered by a moving diffuser when the speed of the scatters has a component in the line of sight direction is described. The device proposed is similar to a Michelson interferometer, in which the mirrors have been replaced by two diffuse surfaces, one of them moving with constant angular speed, while the other remaining at rest. The coherent superposition of the light dispersed in both surfaces results in a dynamic speckle pattern, whose intensity fluctuation contains the beat frequency between the component frequencies. The intensity fluctuations are recorded by means of a photodetector which signal is digitized with a sound interface of a PC multimedia system. The spectral distribution of the signals shows peaks centered in the corresponding beating frequency of the light dispersed by the moving diffuser. These frequencies are correlated with the tangential speed of the diffuser at several distances from the axis of rotation.

Keywords: Doppler shift, dynamic speckle, speed measurement.

Resumen

Se describe un experimento diseñado para detectar el corrimiento en frecuencia de la luz dispersada por un difusor móvil cuando la velocidad de los dispersores tiene una componente en la dirección de observación. El dispositivo propuesto es similar a un interferómetro de Michelson en el que los espejos han sido reemplazados por dos superficies difusoras, una de ellas se mueve con velocidad angular constante, mientras que la otra permanece en reposo. La superposición coherente de la luz dispersada en ambas superficie da lugar a un patrón de speckle dinámico, cuyas fluctuaciones de intensidad contienen la frecuencia de batido entre las frecuencias componentes. Las fluctuaciones de intensidad se registran por medio de un fotodetector cuya señal se digitaliza utilizando la interfaz de sonido del sistema multimedia de una PC. La distribución espectral de las señales muestra picos centrados en la correspondiente frecuencia de batido de la luz dispersada por el difusor móvil. Estas frecuencias son correlacionadas con la velocidad tangencial del difusor a diferentes distancias del eje de rotación.

Palabras clave: Desplazamiento de Doppler, speckle dinámico, medición de la velocidad.

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I. INTRODUCTION

Whenever a diffusing object is illuminated by laser light, a characteristic granular pattern can be observed. Widely known as a *speckle* pattern, this phenomenon is caused by the interference of the light scattered by neighboring points in the object [1]. When the object moves, changes in the relative phase are produced between the waves scattered by different points. It results in a fluctuating or dynamic speckle pattern. The intensity fluctuations in the dynamic speckle pattern can be used to measure the speed of the scatters [2, 3]. Briers [4] has discussed the equivalence between this technique and others based on the Doppler shift of the scattered light to measure the speed of the moving scatters component in the observation direction. To establish the equivalence aforementioned, Briers uses a Michelson Interferometer as it is described in Section II. Temporal fluctuations of the dynamic speckle pattern produced by a moving diffuser have been widely studied, and different parameters that correlate favorably with the diffuser speed [5, 6] have been defined.

Although in recent decades the dynamic speckle phenomenon has been extensively studied and widely used in applications ranging from industry to biology and medicine [7], its inclusion as a tool to carry out laboratory experiments for physics and engineering students is not widespread. In this paper, the beating frequencies between the Doppler shifted scattered light and the light coming from a reference beam (local oscillator) are measured.

These beating frequencies are present in the intensity fluctuations of the speckle pattern and are correlated with the component of the diffuser speed in the line of sight direction. The experiment and results are described in Section III.

II. INTERFEROMETRY AND DOPPLER EFFECT

Let us imagine a Michelson Interferometer (see Fig. 1) illuminated with a laser light of wavelength λ and adjusted in such a way to produce equal inclination fringes, (concentric circular Haidinger fringes [8]), like those showed in the inset of Fig. 1. As M_2 moves, a detector (D in Fig. 1), records a fluctuating intensity signal. The classical interferometric interpretation is as follows: the beam reflected by M_2 interferes with the beam coming from M_1 (reference beam). The detector records an intensity that depends on the phase difference between the two beams at that point. If M_2 is moved a distance equal to $\lambda/2$, the optical path difference between the two beams changes in λ and the detector records a complete cycle of interference (for example, bright-dark-bright, when an interference fringe crosses the detector window). If Δn cycles are recorded in 1 second, the mirror M_2 moves a distance u in that second, where

$$u = \Delta n \frac{\lambda}{2}, \tag{1}$$

is the velocity of M_2 and Δn is the frequency of the intensity oscillations recorded by D. By using the relationship $c = \nu\lambda$ and by rearranging Eq. 1, the following result is obtained:

$$\Delta n = \nu \frac{2u}{c}, \tag{2}$$

where ν is the light frequency and c the light speed. Note that in this analysis $u << c$ and relativistic effects are ignored.

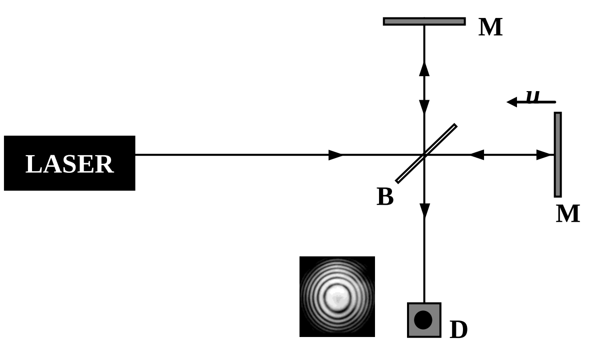

FIGURE 1. Michelson Interferometer. M_1, fixed mirror; M_2, moving mirror; BS, beam splitter; **u**, velocity; D, detector.

The result of this experiment can be also shown as follows: in the incident beam, ν crests will occupy a distance c. This will also be the case of the beam reflected by M_2 if it lies stationary. However, if this mirror moves with velocity u then, after reflection, the ν crests will have an extension of c-$2u$, provided that the mirror has travelled a distance u towards the incident wave. The frequency of the reflected wave that reaches D will now be higher, *i.e*.

$$\nu' = \frac{c}{c - 2V} \nu, \tag{2}$$

this reflected wave is mixed with that from the reference wave of frequency ν and the beat frequency detected by D is the difference between the two frequencies, or:

$$\Delta \nu = \nu \frac{2u}{c}, \tag{3}$$

which is identical to Eq. 1. Both models give the same result and the two approaches are, in fact, two ways of seeing the same phenomenon.

However, this experiment requires the use of a special translation stage to move the mirror at constant speed, in a sufficiently smooth and uniform manner in order to keep the level of noise below that of the signal [9]. To avoid this and to make the experiment simpler we propose replacing the mirrors by diffusers.

If the mirror M_2 is replaced now by a diffusing surface, the light scattered from it will produce a speckle pattern in the detector plane. This speckle pattern is coherent with the reference beam and interferes with it producing another speckle pattern. As the diffuser moves, the intensity in each point fluctuates and the frequency of the Doppler beat will be present in those fluctuations. Both interpretations given above will still be valid, and the speed of the diffuser in the observation direction can be determined from Eq. 2.

III. EXPERIMENT DESCRIPTION

A. Experimental arrangement

The experimental set up is shown in Fig. 2. It is similar to the Michelson Interferometer of Fig. 1, where the mirrors have been replaced by diffusers. One of them is a rotating disk of ground glass, mounted on the shaft of a gear reducer driven by a DC motor, and the other is a metallic diffuser. The disk moves with constant angular speed ω, so that the speed of the scattering points is given by the relation $V = \omega r$, r being the distance to the rotation axis. The speckle patterns produced by the rotating disk and the reference diffuser are coherent and interfere at the detector plane, giving rise to a new speckle pattern whose intensity fluctuates due to the movement of the disk. The incident beam is perpendicular to the diffusers, and their angular aperture is determined by means of the lens L to obtain an adequate speckle size [1]. The interferometer is aligned in such a way that from the detector, two adjacent point sources are seen, as proposed by Alanís *et. al* [10]. These sources seem to be located in the incidence points of the beams over the respective diffusers. This results in the presence of Young's fringe systems inside each speckle grain as shown in Fig. 3. This optical configuration has two advantages; on the one hand, the interferometer is less sensitive making the alignment easy for the students. On the other hand, speckle sizes become larger and contain several interference fringes.

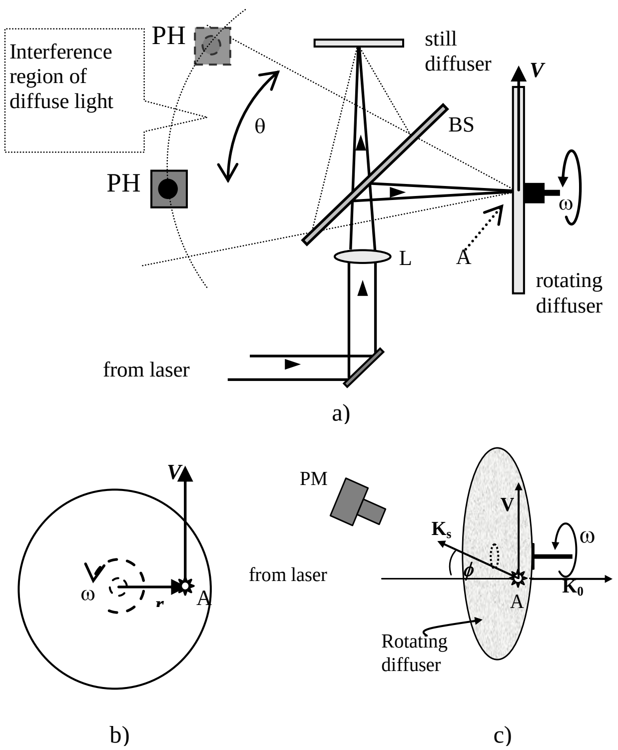

FIGURE 2. Experimental set up. a) Top view: ω, angular speed of the disk; L, lens; BS, beam splitter; PH, photomultiplier; **V**, tangential velocity of the disk. b) Front view of the disk. c) Lateral view: Vector diagram, $\mathbf{K}_o$ and $\mathbf{K}_s$, wave vectors of the incident and scattered light respectively.

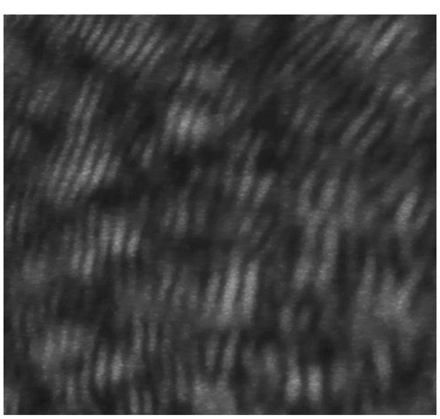

FIGURE 3. Resulting speckle pattern at the photo detector plane, showing Young's fringes inside the speckle grains.

The scattered beam that falls into the detector window forms an angle ϕ, in the vertical plane, with the incident beam on the moving diffuser, so that the tangential speed V of the rotating disk has a component in the observation direction given by $u = V \sin \phi$, as it can be seen from the vector diagram of the involved magnitudes in Fig. 2c). The scatters move towards (as represented in this figure) or away from the observer, depending on the sense of rotation of the disk with respect to the detector position.

When the disk is set into rotation, the frequency of the scattered light is Doppler shifted, so that the Young's fringes displace laterally over the window of the detector, which aperture must be small as compared to the spacing of the Young's fringes. This produces a fluctuation in the intensity that is superposed to the speckle pattern. Hence, the output signal contains the beat frequency between both beams. The intensity fluctuations *I(t)* of the speckle pattern are registered by using a photomultiplier tube Hamamatsu P28A and digitized by using the data acquisition system described below.

B. Data acquisition and processing

A sound card is a hardware device commonly available on a PC. This device can be used as an A/D converter for data acquisition. Usually, the card has an *in line* connector where the photodetector is connected (alternatively, a microphone connector can be used if the level of the input signal is low). The digitalized signal will be stored in "wav" format, but it must be converted into an adequate format to be read by the software used for processing the signal. In this work, a Microsoft EXCEL© spreadsheet was used.

C. Results

A typical time-dependent signal is plotted in Fig. 4a), where intensity fluctuations due to Doppler beats are seen. For comparison purposes, the intensity fluctuation of the dynamic speckle pattern of the rotating disk, obtained when the reference beam is blocked out, is shown in Fig. 4b). Note that the signal without reference beam is noisy and the temporal fluctuations are due to the intensity variation inside a speckle grain caused by the rotation movement of the diffuser.

Signals for different distance r from the rotation center and for an observation angle $\phi = 10º$ are registered. In order to have mean values, ten signals are recorded for each radius, and the Fast Fourier Transform is calculated for each one and averaged. The average Fourier Transform for signals recorded at a radius of 0.01 m is plotted in Fig. 5.

The presence of a peak corresponding to the beat frequency can be observed. When the experiment is repeated for different values of r, the results show the dependence of the beat frequency with the radius. These results are shown in the plot of Fig. 6, which shows that the experimentally obtained frequencies are in accordance with the theoretical ones, calculated by means of Eq. 2.

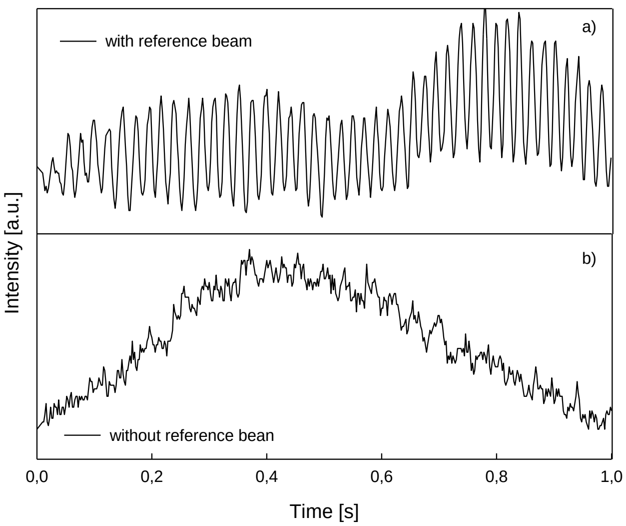

FIGURE 4. Fluctuations in the intensity of the speckle pattern as registered by the photodetector (the illuminated point on the disk is at distance $r = 0.01$ m from the center), a) with and b) without reference beam.

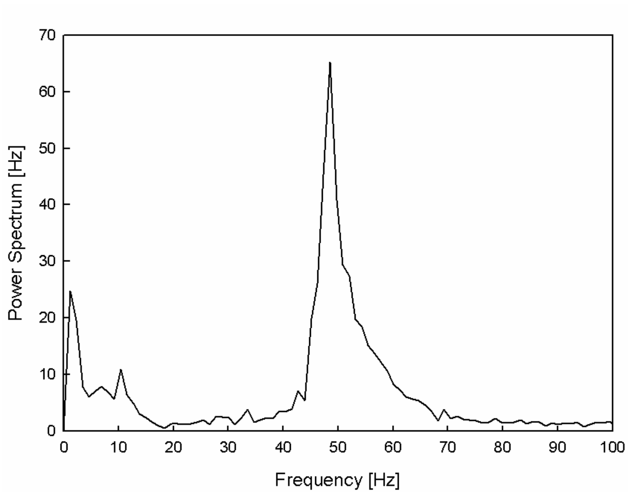

FIGURE 5. Average Fourier Transform of the speckle intensity fluctuations signals for $r = 0.01\ m$ from the disk center.

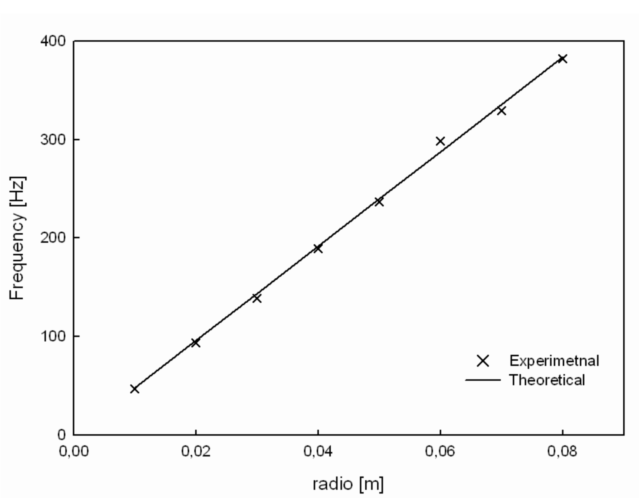

FIGURE 6. Measured and calculated beat frequencies as a function of a radius.

IV. CONCLUSIONS

A good correlation between light Doppler beats produced by a moving diffuser surface and its velocity was found. The experiment proposed is not difficult to implement and provides an easy way to detect light Doppler beats in the laboratory by means of a simple experimental setup and a relatively straightforward measurement method. A demonstration experiment based on this research was introduced to students of the 2010 Optics course and proved interesting from a didactic perspective. This is because it allows introducing some ideas about the dynamic speckle phenomenon and optical information processing in advanced optics courses. Professors of the Course Optics I have planned to incorporate the experiment as a regular experience for students attending classes for a BA degree in Physics at the National University of Salta, Argentina.

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