A Fabry-Perot Interferometer System for high-speed velocity measurement

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ABSTRACT

The Fabry-Perot Velocity Interferometer System (F-PVIS) is designed and built for measuring the Doppler shift of light by recording positional changes in the interferometric pattern behind the Fabry-Perot interferometer. The velocity of a surface can be deduced from the Doppler shift which is caused by reflection on the moving surface. The finesse of the Fabry-Perot interferometer is found to be about 50. The F-PVIS is designed for measuring velocities of up to 20 km/s. The sensitivity of this system can be tuned by changing the distance between the Fabry-Perot mirrors. In the most sensitive state of operation, the accuracy is found to be better than 100 m/s while the time resolution is typically a few ns. In addition to the velocity measurement of the moving surface in the electric gun experiments, the fiber optic F-PVIS can be used for other measurements. By embedding the optical fiber into the target material, information about the shock wave inside the target can be achieved.

Keywords: velocimetry, shock wave, Fabry-Perot, fiber optics, impact, interferometer, electric gun, high speed phenomena

1. INTRODUCTION

In this paper we present the development of the fiber optic Fabry-Perot Velocity Interferometer System (F-PVIS) by the TNO Institute of Applied Physics (TNO-TPD) in cooperation with the TNO Prins Maurits Laboratory (TNO-PML). This system is primarily designed and built for measuring the flyer velocity in an electric gun system (Mega Ampère Pulser (MAP) at the TNO-PML). The main part of the development of the F-PVIS concerns about the fabrication of a transparent slit with a width of about 150 μm in the reflection coating of the Fabry-Perot interferometer. Besides the flyer velocity, the F-PVIS can also be used for shockwave analysis by measuring the velocity of the boundary between the test material and a PMMA plate. Another application under investigation is the use of a fiber optic sensor probe for shockwave analysis inside the test material. In the future, the shockwave velocity inside the test material can also be deduced by applying multiple sensor probes.

The F-PVIS is based on measuring the Doppler shift $\Delta\lambda$ in the wavelength λ of the light which is reflected by a moving surface. In our electric gun system, in which a flyer is launched to strike onto the target, the moving surface is either the flyer or the target. For a velocity $v \ll c$, where c is the speed of light, we have:

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

For the green line of an Argon laser (λ=514 nm) and a velocity v of about 20 km/s, the Doppler shift $\Delta\lambda$ is about 0.07 nm. In the F-PVIS, the Doppler shift is converted into a change in the pattern behind the Fabry-Perot interferometer. This pattern is recorded by a streak camera.

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2. THE FABRY-PEROT VELOCITY INTERFEROMETER SYSTEM

The measurement system with the F-PVIS consists of the following components (Fig. 1):

- light source
- laser delivery system for transporting light to and from the moving surface
- optical system for collimating/focusing the light out of the optical fiber
- Fabry-Perot interferometer for converting the Doppler shift into a change in the interferometric pattern
- streak camera for recording the change in the interferometric pattern

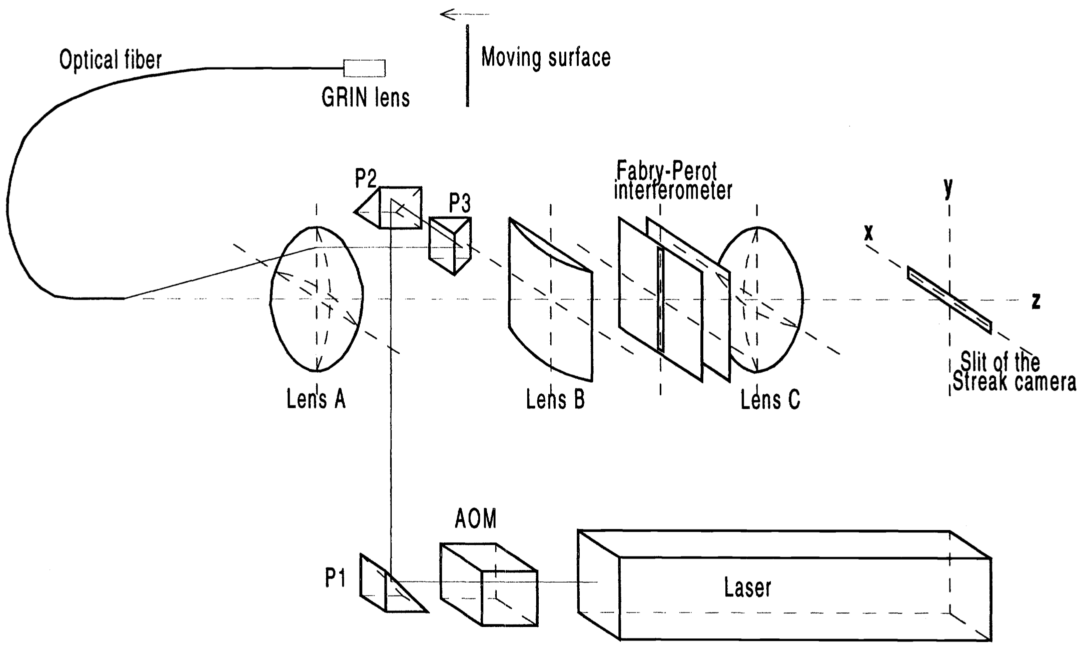

Figure 1 The fiber optic Fabry-Perot Velocity Interferometer System.

2.1 Light source

The light source in the F-PVIS system is a single mode, single frequency Argon laser with an optical power of 1W (CW, @ 514 nm).

2.2 Laser delivery system

An acousto-optic modulator (AOM) is used as a shutter for the system. When the AOM is activated, the laser light is guided to lens A (f = 80 mm, diameter = 40 mm) of the F-PVIS by a number of prisms. Lens A couples the laser light into a step index fiber with a core diameter of 100 μm. This fiber is used to transport light to and from the moving surface. A GRaded INdex (GRIN) lens with a pitch of 0.23 is attached to the end of the optical fiber to enhance the collection of the reflected light.

2.3 Optical system

The light reflected by the moving surface is transported to the optical system by the optical fiber, and is collimated by lens A of the optical system. The cylindric lens B (f = 150 mm) focuses the light in the x-direction into a transparent slit in the first reflective coating of the Fabry-Perot interferometer.

2.4 The Fabry-Perot interferometer

The most important component in the F-PVIS is the Fabry-Perot interferometer which consists of two parallel, high reflective mirrors with a reflectance R of about 96%. The transmission of a Fabry-Perot interferometer is given by Hecht[1]:

$$\frac{I_t}{I_i} = \frac{T^2}{1 + R^2 - 2\,R\cos(\delta)} \quad . \tag{2}$$

Where T(=1-R) is the transmittance of each of the mirrors. I_i is the intensity of the light which has an angle of incidence θ with the optical axis of the Fabry-Perot interferometer. Furthermore, δ is defined as:

$$\delta = \frac{4\pi d\cos\theta}{\lambda} \quad , \tag{3}$$

where d is the spacing between the mirrors of the interferometer.

For a given d and λ, the Fabry-Perot interferometer can be regarded as a filter with an angular dependent transmission[2]. The transmitted light can be collected and focused by lens C (f = 200 mm, diameter = 40 mm). Since the system is rotation symmetric, a ring pattern will occur in the focal plane of lens C if the light is incident from all θ. The diameter D_j of the j^{th} ring depends among others on the spacing d and the wavelength λ. By measuring the change in D_j for constant spacing d, the change in λ can be deduced. When this system is applied to the electric gun system, the velocity of the flyer can be measured. The theory and the basic design of a system using Fabry-Perot interferometer to measure very high velocity is extensively describe by McMillan[3]. The relation between the velocity v and the diameter $D_j(v)$ is given by:

$$v = \frac{c\lambda}{4d}\left(i + \frac{D_j^{\,2}(v) - D_j^{\,2}}{D_{j+1}^2 - D_j^{\,2}}\right) \quad . \tag{4}$$

Where D_j and D_{j+1} are the diameters of the j^{th} and $(j+1)^{th}$ ring when the velocity v=0 and i is the number of new rings that have arisen from the center of the ring pattern.

The position of the rings has to be measured with an as high as possible accuracy. For the Fabry-Perot interferometer, the sharpness of the rings is indicated by the finesse F which can be defined as the ratio of the separation of the rings to the FWHM of the rings.

The Fabry-Perot interferometer is a Burleigh RC-150 with a 50 mm diameter fused silica mirror set. The flatness of this mirror set is λ/200. According to Burleigh[4], the finesse of this Fabry-Perot interferometer with R=96% is expected to be about 50.

In the F-PVIS, the pattern in the focal plane of lens C is registered by a streak camera with a slit on the x-axis of the F-PVIS (Fig. 1). Therefore, only light with a propagation direction in the x-z plane will be recorded by the streak camera. To avoid wasting of the light out of the fiber, the light beam before the Fabry-Perot interferometer is modified to have only a divergency in the x-direction. This is realized by the optical system described in Section 2.3. Light out of the fiber is collimated by lens A and the cylindric lens B focuses the light in the x-direction.

The major disadvantage of using a conventional Fabry-Perot interferometer for velocity measurements is that the incoming light will be reflected by the first mirror of the Fabry-Perot interferometer. In the F-PVIS, this problem is solved by creating a transparent slit in the first mirror, and focusing the light into the Fabry-Perot interferometer via this slit[5,6] by lens B. In the F-PVIS, the width of the slit is designed to be about 150 μm.

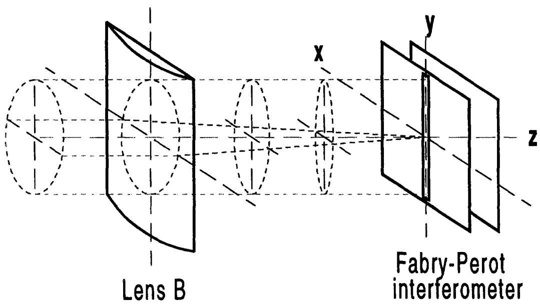

Figure 2 Coupling of light into the Fabry-Perot interferometer by the cylindric lens B.

2.5 The streak camera

The streak camera is a high speed rotating camera (Cordin 132A). The slit of the camera is adjustable from 50 μm to 200 μm and the maximum scanning speed is 20 mm/μs. The time resolution of the F-PVIS depends among others on the speed and the slit of the streak camera and is found to be typically a few ns.

3. FABRICATION PROCESS OF THE SLIT IN THE REFLECTIVE COATING

The 96% reflection coating is a multilayer coating of SiO_2 and TiO_2. To achieve a transparent slit of about 150 μm in the first reflective coating, the following fabrication process are investigated:

- Applying a mask for the slit during the coating process.
- Applying a second multilayer over the original multilayer on the place of the slit. The combination of the two multilayer will be transparent for 514 nm.
- Using photoresist for lift-off process to create the slit.

We have found that the best result is obtained by the third process. This process is used for fabricating the slit in the reflective coating in the F-PVIS. The width of the slit is found to be 140 μm (Fig. 3).

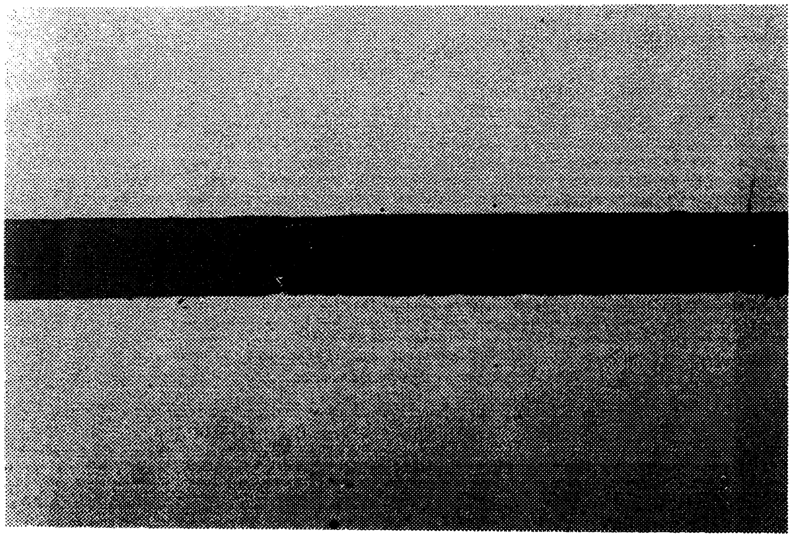

Figure 3 A transparent slit of 140 μm in the 96% reflective coating in the Fabry-Perot interferometer of the F-PVIS.

The finesse of the Fabry-Perot interferometer is measured by a linear CCD array located at the position of the slit of the streak camera. The finesse is found to be about 48 which is near to the maximum achievable finesse of about 50. A streak camera record with v = 0 km/s is shown in Fig. 4. This figuur provides us an impression of the performance of the Fabry-Perot interferometer in the F-PVIS.

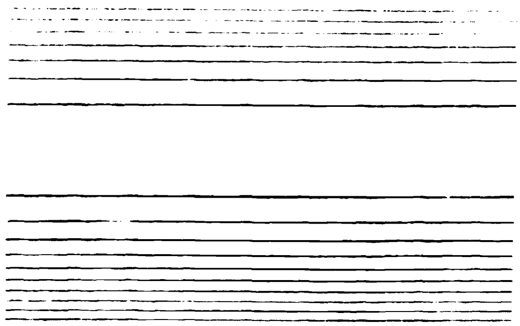

Figure 4 Streak camera record for v = 0 km/s.

4. EXPERIMENTAL RESULTS

According to Eq. 4, the separation between the rings corresponds to $c\lambda/4d$ which is called the fringe constant. In most of the experiments with the F-PVIS, the distance d between the mirrors is chosen to be 12 mm. In this stage of operation, the fringe constant is 3.2 km/s. Since the finesse of the Fabry-Perot system is about 50, the accuracy of the F-PVIS is expected to be approximately 65 m/s. From the experimental results, an accuracy of better than 100 m/s is found. By applying the redundancy of the many rings which are recorded by the streak camera, the accuracy enhances to about 50 m/s. The measurement range of the F-PVIS is not limited by the fringe constant. By counting i, the number of new rings arises from the center of the pattern (Eq. 4), the measurement range can be extended without affecting the accuracy of the system. For i = 3, a maximum velocity of about 20 km/s can be measured.

4.1 Measurement of flyer velocity

The F-PVIS is primarily designed for measuring the flyer velocity in the Mega Ampère Pulser (MAP). Light reflected from the flyer is coupled into the optical fiber by the GRIN lens and transported to the F-PVIS. The Doppler shift is converted into a change in the pattern which is recorded by the streak camera. An example of this pattern is shown in Fig. 5.

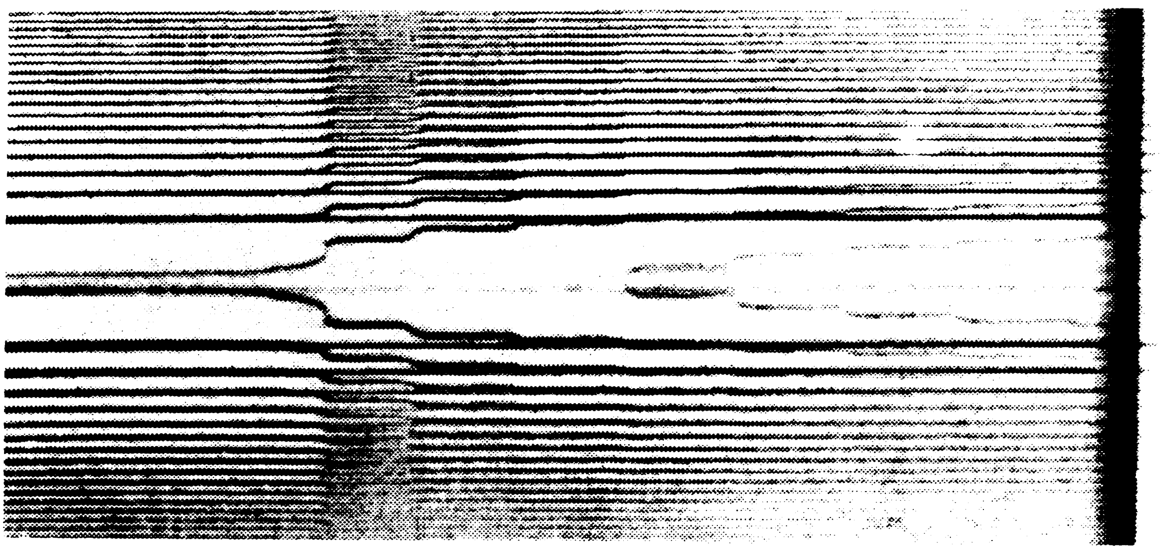

Figure 5 Streak camera record of the flyer velocity measured by the fiber optic F-PVIS.

4.2 Measurement of surface velocity

The F-PVIS can also be used for measuring the surface velocity of the target in an electric gun system. To perform this experiment, a buffer plate of PMMA with a reflective coating is attached on the target (Fig. 6). An example of the test result is given is Fig. 7.

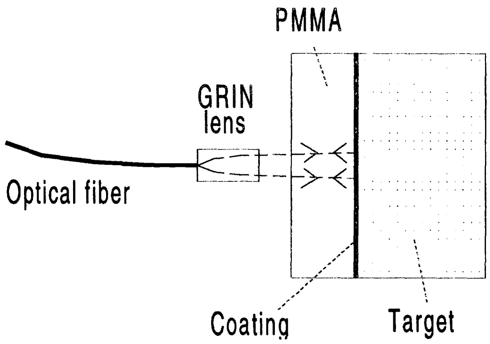

Figure 6 Measurement of the surface velocity with the fiber optic F-PVIS.

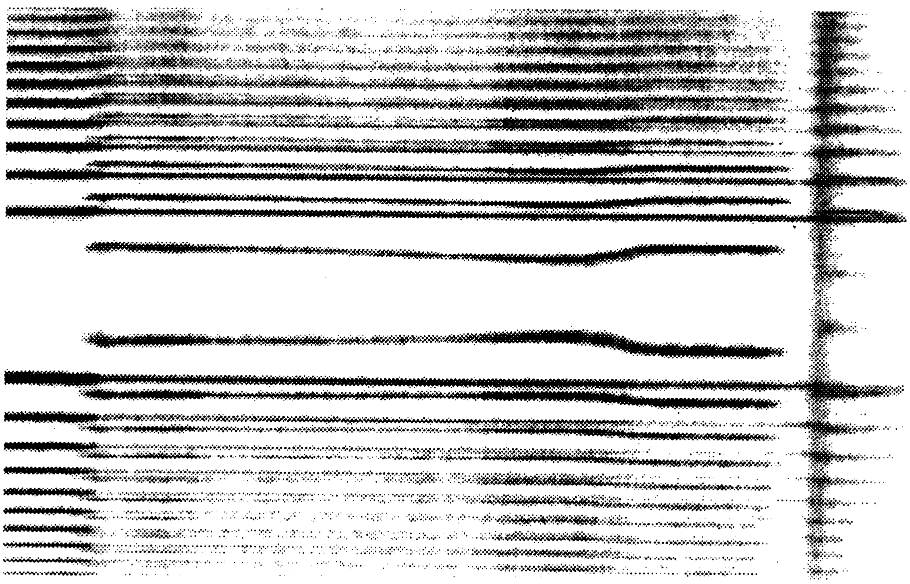

Figure 7 Streak camera record of the surface velocity of the target measured with the fiber optic F-PVIS.

4.3 Shock wave analysis inside the target material

Besides the measurements described in Section 4.1 and 4.2, we have also used the fiber optic F-PVIS for shock wave analysis inside the target material. Therefore the optical fiber without GRIN lens is inserted in the target material. A reflective coating is applied on the end tip of the fiber. When the shock wave passes the end tip of the fiber, the local particle velocity will induced a surface velocity of the reflective coating. The F-PVIS is able to measure this velocity (see Fig. 8) and will provide us with information about the shock wave inside the target material. At this moment, we are working out a model for this experiment. In the future, this measurement can be extended to a multi fiber system. By embedding the fiber tips at different locations of the target material, we will be able to monitor the shock wave velocity in the target material.

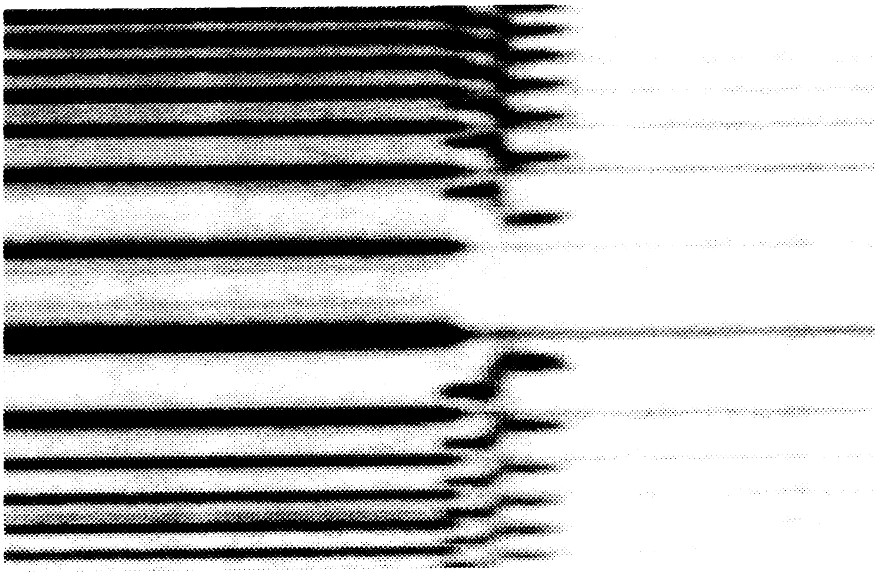

Figure 8 Streak camera record of shock wave analysis inside the target.

5. CONCLUSIONS

The fiber optic F-PVIS system is designed and built by the TNO Institute of Applied Physics in cooperation with the TNO Prins Maurits Laboratory. This system is successfully applied to different impact experiments in an electric gun system, the Mega Ampère Pulser. The experimental results will be extensively described by Prinse[7] in another paper of this conference. In this investigation, a 140 μm width transparent slit is successfully fabricated in the first reflective coating of the Fabry-Perot interferometer by using photolithographic technique. In the most sensitive stage of operation, the F-PVIS has an accuracy of better than 100 m/s, a time resolution of typically a few ns and the measurement range can be extended to more than 20 km/s. By applying the redundancy of the many rings which are recorded by the streak camera, the accuracy enhances to about 50 m/s.

The fiber optic F-PVIS system has two major advantages compared to other optical systems for high velocity measurement in electric gun experiments. The advantages are the lack of precision optical alignment by using an optical fiber to and from the moving surface, and the low optical power consumption. We have found that in most of the experiments the amount of light is abundant. In combination with the replacement of the mechanical streak camera by an electronic streak camera with a higher sensitivity, we expect that the required optical power of the laser for the F-PVIS can be reduced to about 100 mW. In the future, the Argon ion laser can then be substituted by a diode laser or a diode pumped solid state laser which can be integrated into the F-PVIS to form a small and rigid system.

6. ACKNOWLEDGMENTS

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