High Energy Density Physics 11 (2014) 26–29

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Internal target reflections and line-imaging velocimetry

D.E. Fratanduono [a,*], J.H. Eggert [a], T.R. Boehly [b], M.A. Barrios [a], G.W. Collins [a]

[a] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[b] Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14620, USA

ARTICLE INFO

Article history:
Received 16 September 2013
Received in revised form
3 January 2014
Accepted 4 January 2014
Available online 25 January 2014

Keywords:
Velocimetry
Diagnostics
EOS
Experimental

ABSTRACT

A commonly observed intensity modulation or "beating" in laser velocimetry (VISAR) data is examined and explained. It is found that internal target reflections between two surfaces moving relative to one another produces this intensity modulation in the VISAR steak record. The two partially reflecting surfaces define a Fabry–Perot cavity that creates an intensity interference pattern that is superimposed upon VISAR measurements. Experiments are conducted that demonstrate this phenomenon. Previous VISAR experiments that observe this beating pattern are presented and explained.

1. Introduction

Optical diagnostics are frequently used in high-pressure dynamic-compression studies as material response is easily probed, with high precision, using velocimetry techniques [1–4]. These diagnostics continuously record interface and shock velocities, either in one-dimensional line imaging or in single-point mode, over a velocity range of 10's m/s to 100 km/s for time durations ranging from 10's of ps to >1 μs. The information gathered is essential to measurements of material response to high-pressure compression [5]. Common forms of velocimetry used in the high energy density physics (HEDP) community are velocity interferometry for any reflector (VISAR) [1,2,6,7], photon Doppler velocimetry (PDV) [3] and Fabry–Perot interferometry (FPI) [4]. For dynamic compression measurements, VISAR and PDV have become standard tools to measure shock and ramp-compression wave profiles. In these studies, the temporal history of the velocity and intensity are commonly used to infer details about the material response to compression. An accurate understanding of the optical processes involved in velocimetry is important for interpreting these results.

This work investigates the effect of multiple internal reflections within a sample on VISAR measurements. We show that reflections between two surfaces moving relative to one another produce a time-varying Fabry–Perot interference pattern that is superimposed on the VISAR intensity. The observed interference pattern can be used to resolve the velocity of the moving surfaces and explains an intensity modulation commonly observed in VISAR experiments. For instance, in recent quartz decaying shock experiments [8], a beating pattern is observed at low pressure (∼2 Mbar) where the shock reflectivity is comparable to the free-surface reflectivity. Furthermore, in recent ramp-compression X-ray diffraction experiments [9], a beating pattern is observed when diamond anvils are used and the pressure remains the below the Hugoniot Elastic Limit (HEL) of diamond [10]. In those experiments, the elastic shock front is transparent and a beating pattern between an *in situ* reflective layer and the diamond free surface is observed. Similarly, in two-stage gas gun CaF_2 Hugoniot experiments, a beating pattern is observed at ∼1 Mbar. In this case, the shock front is partially reflective, and the beating occurs between the *in situ* reflective layer and the shock front. In all case, the beating phenomenon is independent of drive platform but instead due to the target characteristics. Experiments that use optical windows and the VISAR diagnostic may be affected by this phenomenon and the experimenter should take adequate care in the design if this phenomenon is undesirable.

2. Theory

Interference arises from the superposition of two or more waves. Optical interferometers exploit the resulting fringe patterns to measure the optical-path differences between two waves [11]. The Fabry–Perot interferometer, a displacement interferometer, contains two transparent, partially-reflective, parallel plates offset

* Corresponding author.
E-mail address: fratanduono1@llnl.gov (D.E. Fratanduono).

1574-1818/$ – see front matter
http://dx.doi.org/10.1016/j.hedp.2014.01.002

by gap shown in Fig. 1(A). The parallel plates create a reflective cavity that produces multiple coherent beams within the interferometer. Its transmission spectrum as a function of wavelength exhibits peaks of large transmission corresponding to resonances of that cavity. At a single wavelength, its transmission produces peaks and valleys as the cavity length is varied.

In contrast, VISAR is a velocity interferometer [12]. It normally comprises a Mach–Zehnder interferometer with a ‘delay’ etalon inserted into one of its legs shown in Fig. 1(B). At the output beam splitter, the two legs recombine and the intensity there is proportional to the relative phase of the input beam at two times defined by the time-delay introduced by the etalon. That phase difference is proportional to Doppler shifts (velocities of the ‘moving reflector’) that occur during that time delay. The output of a Fabry–Perot, if sent through a Mach–Zehnder interferometer produces an intensity modulation, whose frequency is defined by the Fabry–Perot cavity.

Fig. 1(A) shows a Fabry–Perot interferometer formed by surfaces S_1 and S_2. A probe beam enters from the right where a detector is also located. For a coherent, monochromatic source ($E(t) = E_o e^{i\omega_o t}$), the reflected signal from that interferometer is defined as

$$E_R(t) = E_o e^{i2\pi c\frac{t}{\lambda}} \frac{r_1\left(1+\frac{r_1}{r_2}e^{-i\delta(t)}\right)}{1+r_1 r_2 e^{-i\delta(t)}} \tag{1}$$

where r_1 and r_2 are the reflection coefficients of the surfaces S_1 and S_2, λ is the probe beam frequency, c is the speed of light, and $\delta(t)$ is the phase difference of the reflected beams. Equation (1) assumes that the refractive index of the cavity is less than the parallel plates which define the cavity boundary. The phase difference is defined as

$$\delta(t) = \frac{4\pi n_o L(t)}{\lambda}, \tag{2}$$

where $L(t)$ is the time dependent cavity length and n_o is the refractive index of the cavity. For simplicity, the reflection coefficients of the Fabry–Perot cavity are assumed to be equal but opposite ($r_1 = -r_2$). The output intensity for the Fabry–Perot interferometer is

$$I_{FP}(t) = 2r_1^2 I_i\left(\frac{1-\cos(\delta(t))}{1+r_1^4-2r_1^2\cos(\delta(t))}\right), \tag{3}$$

where the input intensity is defined as $I_i = |E_o|^2$. In contrast the output intensity of the Mach–Zehnder interferometer having a coherent monochromatic input source is described by

$$I_{MZ}(t) = 2I_i(1+\cos(\phi(t)-\phi(t-\tau))) \tag{4}$$

where τ is the temporal delay of the two interferometer legs and ϕ is the phase of the wave.

The Mach–Zehnder interferometer essentially integrates Doppler shifts accumulated between two different times. Therefore, it is important to consider the temporal delay that occurs in the Fabry–Perot etalon. For the experiments described herein, the cavity thickness is of the order of a micron. Assuming that the reflected signal is dominated by the first few round trips (i.e. finesse of the cavity is small (<1)), the wave fronts that generate the Fabry–Perot interference signal are separated by ~ 0.001 ps. This is significantly less than typical Mach–Zehnder etalon delays (~ 50 ps). Thus, the contribution to the Doppler shifted wavelength by the Fabry–Perot cavity is negligible when compared to that of the Mach–Zehnder etalon delay. In addition, if S_2 moves at velocities of a few km/s, the change in Doppler shift in the probe wavelength is $\Delta\lambda/\lambda_o \approx 10^{-5} << 1$. For such small changes in the probe wavelength, we will assume that $\lambda = \lambda_o$ and the phase difference defined in Equation (2) is

$$\delta(t) \approx \frac{4\pi n_o L(t)}{\lambda_o}. \tag{5}$$

Using these assumptions, we derive an analytic form of the output intensity of the combined Fabry–Perot and Mach–Zehnder interferometers.

The output of this combined interferometer (i.e. a Mach–Zehnder whose input is Eq. (1), a Fabry–Perot), is

$$I_C(t) = |E_R(t) + E_R(t-\tau)|^2. \tag{6}$$

If surface S_2, shown in Fig. 1, begins moving at a constant velocity (U_o), the difference in phase between VISAR legs is the constant value:

$$\delta(t) - \delta(t-\tau) = \frac{4\pi n_o U_o}{\lambda_o}\tau. \tag{7}$$

For simplicity in the analytic derivation, will assume that the constant value is $\delta(t) - \delta(t-\tau) = 2\pi$. Equation (6) becomes

$$I_C(t) = 4r_1^2 I_i\left(\frac{1-\cos(\delta(t))}{1+r_1^4-2r_1^2\cos(\delta(t))}\right)(1+\cos(\phi(t)-\phi(t-\tau))). \tag{8}$$

For this specific case, the combined output intensity is defined as the superposition $I_{MZ}(t)$ and $I_{FP}(t)$. Equation (8) shows that an intensity modulation is generated on the output signal due to the time dependent phase difference. The modulation is

$$f = \frac{4\pi n U_o}{\lambda_o}. \tag{9}$$

One may show that the frequency is independent upon the previous assumption ($\delta(t) - \delta(t-\tau) = 2\pi$). By measuring the frequency one can determine the velocity of U_o. Fig. 1(A) and (B)

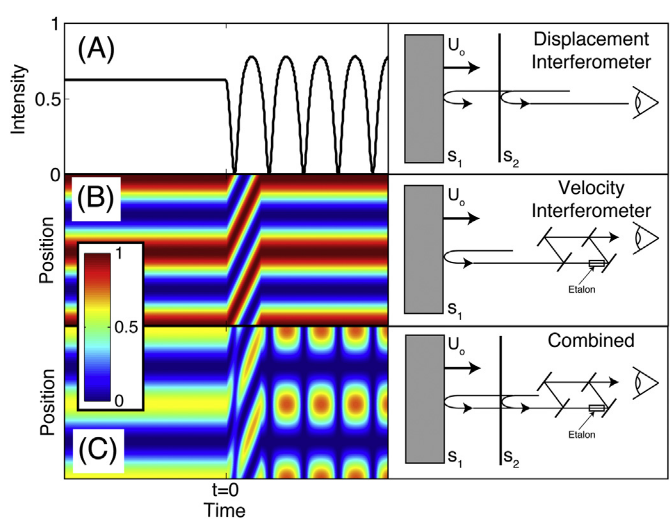

Fig. 1. Simulated velocity data for a Fabry–Perot interferometer, VISAR, and Fabry–Perot interferometer superimposed upon VISAR record. At $t = 0$, the target begins moving with constant velocity [U_o]. (A) The Fabry–Perot cavity produces intensity modulations as the cavity size changes. (B) VISAR fringe position (phase) is proportional to the target velocity. The rise time in the fringe position beginning at $t = 0$ is related to the etalon delay. (C) Combination of the Fabry–Perot cavity and VISAR diagnostics. In this special case, a “beating” in the VISAR intensity is observed after $t = 0$.