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Manybeam velocimeter for fast surfaces

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ABSTRACT

For the past 5 years, we have conceived, built and successfully used a new 10 beam laser velocimeter for monitoring velocity vs time histories of fast moving surfaces, and will have a 20 beam capability soon. We conceived a method to multiplex 5 to 10 beams through a single Fabry-Perot interferometer, without losing any light that our equivalently-performing single beam system could use, and with negligible cross-talk. This saves the cost of 16 interferometers, simplifies operation and takes less space than without multiplexing. We devised special efficient light collecting probes, streak cameras that change sweep speed during the course of the record, and a new double cavity interferometer which is better, cheaper and more flexible than our previous versions. With the 10 recorders, we conceived and employ a method of using both a fast and a slow streak camera on each of 5 beams without reducing the light that is available to either camera separately. Five new galvanometrically-driven triggerable CCD streak cameras will be installed soon.

Keywords: velocimetry, double cavity Fabry-Perot, multiplexing many beams

1. INTRODUCTION

Lawrence Livermore National Laboratory (1) has used optical velocimetry using Fabry-Perot interferometers (FP's) operating in the fringe mode for many years to study the velocity-time history of objects accelerated by propellents, electromagnetics and explosives. The frequency of highly monochromatic laser light reflected from a moving surface is analyzed continuously as a function of time to infer velocity. Ref. 1 and references within it cover developments up to 1991, when we had only one or two beam velocimetry facilities. We describe our new 10 beam facility, which has recorded to date over 150 velocity-time histories.

2. THE LASER AND FIBER FEEDER

Although we had reproduced and tested the multi-frequency laser source concept of Gidon and Behar², we wanted a single frequency system for our manybeam facility. Multi-frequency systems have lower finesse, and in addition the finesse depends upon the target velocity³. Also, double cavity interferometers⁴, which provide unambiguous velocities, work better with single frequency sources than with multifrequency ones. We contracted for design and construction of a 1000 watt, 40 MHz source with a pulse length variable to 80 microseconds. Because it was rather new, we placed a loose specification on the product of the waist radius and the half-angular divergence of several mm*mrad. We intended to fill up to 20 low NA optical fibers with diameters between 50 and 100 microns with this beam. Figure 1 shows a rosette scheme we devised in order to do this with the largest possible mm*mrad product for the laser beam. Our measurements show that 95% of an expanded CW laser beam enters the cores of the 5 fibers. With our pulsed beam, the efficiency was 92%. The rosette is designed to accept laser beams with a mm*mrad product as large as 1.6 times that of each of the 5 individual fibers. This design involved a complex mechanical fiber adjuster, and recent studies have shown that the beam quality is good enough to use a more conventional beamsplitter technique to fill the fibers, which we now use.

3. MULTIPLEXING

Having one FP per beam is not desirable, especially if the FP's are of the variable spacing type, due to thermal drifting. We need to pass the light efficiently from several fibers through a single stable FP. As

mentioned in ref. 1, the light collected by a single beam velocimeter is limited in one plane by the product of the width of the streak camera slit and the angular divergence of the light passing through that slit, which for our systems is vertical. The light used by the system is also limited by the product of the waist radius and vertical angular divergence of the $j=4$ fringe¹ at the FP. For striped interferometers^{1,5}, that waist radius is the half width of the stripe. For example, for FP's with 6 cm spacing, the $j=4$ fringe corresponds to a vertical angle of 6 mrad, and the stripe has a halfwidth of 0.36 mm, making a vertical $r*\theta$ product of 2.2 mm*mrad. For 50 micron wide slits and a horizontal half angular divergence of 40 mrad, the horizontal acceptance product is 1.0 mm*mrad.

To fill the acceptance of the system, the optical fiber bringing Doppler-shifted light to the system should have $r*\theta$ exceeding 2.2 mm*mrad. The $r*\theta$ product of our collection fibers is $0.05\text{mm}*.22\text{NA} = 11\text{ mm*mrad}$. Thus we use less than 10% of the horizontal width of the collection fiber.

One cannot simply place 5 fifty micron radius fibers adjacent to each other in a horizontal line and produce 5 very useful FP dot patterns displaced from each other horizontally. The horizontal width of the fiber determines the horizontal length of the circular arc illuminated at the fringe plane, and 4 of the 5 patterns would extend so far off axis that the slit width would significantly degrade finesse for the off-axis patterns. One wants to place all 5 patterns well within the angle corresponding to the $j=0.5$ fringe, so as not to degrade velocity resolution. As far as the FP is concerned, the apparent horizontal fiber to fiber separation should be reduced by about 4 times.

3.1 The shaper

Rather than deal with 25 micron diameter fibers, connectors and collection issues, we designed a combination of spherical and cylindrical optics which has vertical and horizontal magnifications of 1.0 and 0.25, respectively, denoted as the shaper, shown in figure 2. It takes a linear fiber array as input and makes an elliptical image of each fiber. This is done in such a way as to keep the NA of the exiting light 0.22 both vertically and horizontally at the shaper image plane. To do this, light must be thrown away within the shaper, since the $r*\theta$ product is an invariant.

However, it is to be emphasized that this in no way reduces the intensity of light in each of the resulting 5 FP dot patterns compared to our equivalently-performing single beam system. We throw away only the light from the 11 mm*mrad collection fiber that the system's 1 mm*mrad horizontal acceptance could never use anyway. The resulting pattern is shown in figure 3 for five fibers. Experimentally we have also done this successfully with 10 very distinct beams through one FP.

The only slight penalty for multiplexing is that the off-axis fringes have a few percent less finesse than the on axis fringe pattern, due to the finite slit width on the streak camera. For our typical setup with 50 micron slits, the total system finesse is 5.7% smaller for the $j=0.5$ fringe for the most off axis fibers. The penalty is less for j greater than 0.5 and less for the fibers closer to the axis.

4. THE MANYBEAM TABLE

Figure 4 shows a simplified arrangement for multiplexing 5 beams. The five 100 micron diameter fibers are placed about 0.3 mm apart center to center in front of the shaper, which image to five ellipses 0.1 mm high and 0.025 mm wide, separated by about 0.075 mm. This light is approximately collimated by a 165 mm focal length pickup lens just upstream of a 2 m focal length cylindrical lens, which itself converges the light vertically to just overfill the horizontal stripe on the FP. The beams from each fiber enter the FP at different non-overlapping horizontal angular ranges, and the 1.8 m focal length spherical lens forms fringes at the 5 faceted mirror, detailed in figure 5. The facets on this mirror are 25 mm high and 0.9 mm wide, and flat to about 2 waves. They need not be very flat, since they are all within 1 mm of an image plane. They direct each dot pattern from a given fiber onto a unique streak camera, through relay lenses with a magnification of 0.5. The 50 micron wide slits can see 100 micron wide areas of each facet, which is illuminated by a circular arc about 300 microns wide. We make the illumination on the facet wider than the slit can view in order to facilitate alignment, but again, no intensity is lost by doing so.

For our 10 beam multiplex (not shown), the fiber separation at the shaper image is 37 microns, and the arcs at the faceted mirror are 300 microns wide, with two distinct images residing on each facet. In the

future, we plan to image them onto a double slit on each camera, and distinguish them by acoustic-optical chopping of the laser that feeds them.

5. THE DOUBLE CAVITY INTERFEROMETER, VerIII

To date we have developed three different types of double cavity FP's for velocimetry, in order to reduce the velocity ambiguity associated with single cavities. The first version⁴ used the glass in the mirror substrates as extra cavity length, but the glass quality limited the performance. The second version⁴ used only air cavities, but included a 1 cm thick step in one of the mirrors. It has produced records for us for two years, but the stresses on the mirror with the step limit performance. We have recently devised and built our third version, which is far less expensive, much better performing, and more flexible than the prior versions. A top view of it is shown in figure 6. It is simply a rectangular piece of extremely good quality glass that is inserted into the cavity, and rotated slightly to change the fractional order. It introduces no stress on the primary cavity mirrors, can be used on any existing single cavity interferometer already in possession, can be removed if damaged, and can be replaced with another thickness. By rotation, it can be set so that the coincident velocities, where primary and secondary cavity fringes overlap⁴, do not fall into a region of interest. One can also vary the fraction of the light that goes to the secondary cavity by positioning the insert. We plan to have several interferometers of this type, each with a different but fixed value of the primary cavity spacing. The fixed spacing etalons are much easier to operate than the variable spacing ones, due to drifting.

For versions I and III, where the referee cavity beam passes many times through glass, the velocity per fringe formula must be corrected for dispersion in the glass, similar to what is done for VISAR velocimetry.

All our FP's are now striped^{5,1}, which means a small strip of coating has been removed along a diameter of the upstream circular mirror. For light that can be made to enter this stripe, the transmission through the first mirror can increase by 50 times for a mirror pair with 99.8% and 92.3% reflectivities. Losses back through the stripe are about a factor of 2 for the $j=1$ fringe, so the overall gain due to striping for us is about a factor of 25. The main penalty for using striped mirrors is the small 2.2 mm*mrad vertical acceptance, vs a theoretically possible 35mm*5.7mrad = 200 mm*mrad acceptance for 70 mm diameter mirrors and angles from zero degrees out to the $j=4$ fringe.

Thus the striped mirror has 90 times less acceptance vertically, but only about 25 times the intensity gain. Are we losing a factor of nearly four in intensity by striping? The answer for us is no. Our experimental constraints on depth of travel, maximum collection probe diameter, and other considerations allow us to collect only 5 to 16 mm*mrad of light from the reflecting surface with a single collection probe, even with optimized collection efficiency. We would need to collect 55 mm*mrad with our probes and use an unstriped FP to match our striped FP's intensity. But for lower reflectivity mirrors, the intensities for the striped and unstriped FP's could match if configured properly.

Using striped FP's, however, involves three other minor penalties. The first is that given two methods (with different mm*mrad acceptances) of obtaining the same intensity, one is usually better off using the method that uses the larger acceptance, to maximize statistical smoothness of the illumination. The second is that unstriped systems take less space. The third is that for a fixed FP mirror diameter, our total system finesse is about 3% less for $j=1$ for unstriped systems, due to less walk-off. Actual system performance, including time resolution, velocity resolution, writing speed, mirror flatness, etc can be estimated by using the formulae of ref 1.

On the positive side, however, the up and over configuration described below does not reduce intensity with striped systems, but it would with fully-filled 200 mm*mrad unstriped systems.

An example of data taken with our version II double cavity interferometer and the analysis of it is shown in Fig. 12 of ref. 4.

6. THE STREAK RECORDERS

We designed our own electronic streak cameras, denoted the HHP camera, for the last names of Dr. Tony Huen, Don Hein, and Stephen Perry, who did most of their design and construction. They are based upon the Hamamatsu N2214 tube, and an external S-20/P-11 40 mm microchannel plate intensifier. They

are unique in that they can be programmed via a keyboard on the camera to change the streak rate during the course of the streak from a fast value to a slower value. This allows long record lengths to be taken, while obtaining good time resolution during the first part of the record. These cameras record on film and have been in use reliably for several years. The only significant drawback is the 60% transmission mesh near the cathode of the N2214, which makes the effective quantum efficiency of our tubes only average about 6.5%. To assure proper fringe-slit alignment, magnified slit images are viewed by a CCD cameras built into each streak camera front optic assembly.

In 1992 we reported development of a new type of streak recorder⁶. It uses a pair of mirrors in a wedge, with one mirror stationary and the other pulsed from a stationary initial condition. The FP dot image is swept by this scheme across 25 mm of CCD recorder in about 18 microseconds. The time resolution and spatial distortions are excellent, and the record is already digitized. The unique feature of these cameras is that they are triggerable, unlike most rotating mirror cameras. Given a trigger 3 msec in advance, they will provide the desired records with only 50 nsec jitter from trigger time to when the FP image hits the first column of the CCD array!

Because of the success of this development, the next 5 cameras of our 20 beam facility will use the CCD version. They will be thermo-electrically cooled rather than liquid nitrogen cooled for operational convenience.

Both cameras use an optical fiducial train located on the top and bottom of the slit, which has a set of 1, 2 and 3 dimmer fiducials for absolute timing reference. Both the fid time separation and location of the three sets of dimmer fids is programmable.

We find that a convenient method of characterizing the cameras is to place a Ronchi ruling with about 5 lp/mm over the slit and back light it with a acoustically chopped laser. This produces up to 40000 dots of light on a single piece of film, which we call the linen pattern. One can infer sweep speed, resolution in both space and time directions, magnification, and slit rotation vs position everywhere on the film with only one record.

7. THE UP AND OVER CONFIGURATION

Many experiments require better time resolution during the early part of the record than during the latter part, yet the reflector is to be followed for a long time. Time resolution is affected by many things¹, but the streak camera slit width is very often the most important factor, especially for long record lengths. With our 10 recorders, we devised an efficient method of using 5 beams and 10 recorders on a single experiment, such that each beam is recorded by a camera with a short record length for good time resolution and a slower camera to cover the entire time history.

If 70% of the light exiting a beamsplitter with a total efficiency of 80% went to the fast cameras and 30% to the slow cameras, the fast cameras get only 56% of the light that they could get without splitters. Our up and over method does not use beamsplitters. We take some of the light exiting the shaper of table 1 vertically (with about 11 mm*mrad) that cannot be used by the FP on table 1 due to the vertical acceptance being 2.2 mm*mrad. This light is air-transported to the second table about 8 meters away and injected into the cylinder lens and FP of that table. This way each table received just as much light (and mm*mrad) as it could ever receive. The light path on table 1 (intensity, mm*mrad acceptance, or beam quality) is not affected in any way whatsoever by using the up and over scheme.

8. CROSS TALK

We initially installed the fiber array in the horizontal plane as the input to the shaper. In this configuration, a small amount of cross talk can occur, if the transverse positions of the fibers are not right. If the 3rd fiber is on the optical axis, then light from the 2nd fiber that slightly overfills the stripe will reflect back through and image onto the 4th fiber. About 4% of that light from the uncoated fiber end will reflect from fiber #4 and appear to have come from that fiber. Fibers 1 and 5 will interact similarly. The magnitude of this effect is about 0.2%, and is not serious. We use two methods to reduce this even further. On table 1, we simply translate the input fiber array so that fiber #3 is 1/2 of a fiber spacing off axis, this way the reflections end up between two fibers. We also reduce this cross talk by angling the fiber array slightly vertically with the 5 fiber ends still in a horizontal line. The ends are bevelled so the light from

within will propagate normally through the rest of the system, but reflections from the striped mirror back onto those fiber ends will be reflected upwards and vignetted by the shaper.

9. ALIGNMENT AIDS

After several other methods, we have developed a fairly simple alignment scheme for the analyser tables. If the up and over scheme is used, the separation between the small and larger groups of lenses in the shaper shown in figure 2 must be set so that the vertical and horizontal image planes coincide. This is not necessary for single 5 beam table operation, however.

A simple alignment mask consisting of 1 mm diameter holes punched in a white card backed by aluminum foil is adequate for further alignment of the shaper. First all the system components with the exception of the fiber array are aligned to a beam provided by a 532 nm CW laser. Then fiber #3 positioned on that axis is used without the cylinder lens to provide an almost collimated beam to hit the mostly-coated upstream FP mirror. Just downstream of the shaper we insert our mask with at least 5 holes; one in the center and the others at the edge of the beam 90 deg apart. The aluminum side of the mask faces the shaper and blocks transmitted light, except for that passing through the 1 mm holes. Denoting the z direction as along the beam, we then move the pickup lens along the z direction until the reflected beams from the 3 and 9 o'clock holes have the same separation as the holes themselves. Then the z coordinate of the fiber holder is adjusted until the 12 and 6 o'clock reflected beamlets do the same. Then the x and y positions of the 3rd fiber are adjusted until the center beamlet retroreflects. Then the fiber array and the shaper are ready to use.

9.1 Monitoring slit alignment without fiber disconnections

Sometimes there are time intervals exceeding one hour between the final dry run and the dynamic experiment. During this time, it is possible for thermal drifts to misalign the FP dot pattern on the slit of the streak camera. We dislike disconnecting fiber couplers to insert CW light to monitor this possible drift, so we devised a novel method that does not require fiber disconnection. We use a small amount of the light exiting the shaper which is not usable by either table 1 or the up and over scheme for table 2. We image 20% of that light onto a CCD and 80% to another fiber located about 20 cm above the main optical axis of the table. This fiber is not a receiver, but is a sender of 1 mW of light generated by our 532 nm CW alignment laser. Part of this light images back to the 5 fiber array, enters those fibers (whether the array is vertically angled or not) transports to a fiber patch board about 1 m away and reflects from imperfections in those connections. This light, although only about 1% of the original 1 mW, then passes through the system fibers normally, and produces FP patterns on our streak camera slits, which are always viewed with separate CCD cameras. Just before the dynamic experiment, the CW laser is switched off.

10. FUTURE WORK

We are striving to improve the time resolution and light collection of experiments by several modifications. We plan to try tapered laser fibers and better injection technology to fill smaller mm*mrad fibers. We have designed and constructed our own double-cylinder version of the work presented by Gidon et al⁷ to increase the horizontal mm*mrad product acceptance of the HHP cameras. We expect a gain of 2 times for cameras 2, 3, and 4 of a given 5 beam table, with little loss of time resolution due to the decreased slit finesse associated with the elliptical fringes compared with circular fringes. We intend to use a fiber next to the slit-position monitoring fiber mentioned in section 9.1 to add un-Doppler shifted light onto our dynamic records, to facilitate analysis. We are also working heavily on collection probe developments, reproducible reflecting surface preparation and striving to make the system as turn-key as possible, so that a 20 beam system can be operated by 3 or perhaps 2 personnel.

11. ACKNOWLEDGMENTS

The expert help of Dr. Charles McMillan, Don Hein, Ken Griffin and Richard Whipkey of LLNL is much appreciated in both design and construction of our present 10 beam system. Mike Nicholls of the LLNL optics group fabricated the precision 5 faceted mirrors.

12. REFERENCES

1. D. R. Goosman, "Formulas for Fabry-Perot velocimeter performance using both stripe and multifrequency techniques," *Appl. Opt.* 30(27), 3907-3923 (1991).
2. S. Gidon and G. Behar, "Multiple-line Doppler velocimetry," *Appl. Opt.* 27, 2315-2319 (1988).
3. D. R. Goosman, "Dynamic fringe broadening in multi-line laser Doppler velocimetry," *Appl. Opt.* 29, 107-110 (1990).
4. L. L. Steinmetz, D. R. Goosman and G. R. Avara, "A dual, parallel cavity Fabry-Perot interferometer," *SPIE proceedings of the 21st Int. Congress on High Speed Photography and Photonics*, 2513, 380-386 (1994).
5. C. F. McMillan, N. L. Parker, and D. R. Goosman "Efficiency enhancements for Fabry-Perots used in velocimetry," *Appl. Opt.* 28, 826-827 (1989).
6. C. C. Lai, "A new tubeless nanosecond streak camera based on optical deflection and direct CCD imaging," *SPIE proceedings of the 19th Int. Congress on High Speed Photography and Photonics*, 1801 454-469, (1992).
7. S. Gidon, G. Garcin, and H. Behar, "SPIE proceedings on the 16th Int. Congress on High Speed Photography and Photonics," 491 894-898 (1984).

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Filling the laser fibers efficiently

Segmented lens method
Fibers are placed coaxially with optical centers

Fiber bundle method
Illuminated by a single lens

Fig. 1. The rosette scheme for efficiently filling 5 fibers.

Fig. 2. The upstream elements of the shaper lenses (top view).

Fig. 3. The five-beam fringe pattern. One column arises from each input fiber.

Fig. 4. The major components of the five-beam table, and the actual 10 beam velocimeter.

Fig. 5. The five-facetted mirror.

Fig. 6. Top view of the version III interferometer.

Fig. 7. Schematic ray traces of a retro-reflective wedge-gap deflector. It attains a high-gain deflection speed amplification and the multi-speed streak recording capability through many bouncing reflections inside the wedge shape gap.

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