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O. T. Strand, D. R. Goosman, C. Martinez, T. L. Whitworth, W. W. Kuhlow

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O.T. Strand, D.R. Goosman, C. Martinez, T.L. Whitworth
Lawrence Livermore National Laboratory, Livermore, CA

W.W. Kuhlow
Bechtel Nevada, Las Vegas, NV

Abstract

We have built a high-speed velocimeter that has proven to be compact, simple to operate, and fairly inexpensive. We assembled our velocimeter using off-the-shelf components developed for the telecommunications industry. The main components are fiber lasers, high-bandwidth high-sample-rate digitizers, and fiber optic circulators. The laser is a 2-watt CW fiber laser operating at 1550 nm. The digitizers have 8-GHz bandwidth and can digitize four channels simultaneously at 20 GS/s. The maximum velocity of our system is approximately 5000 m/s and is limited by the bandwidth of the electrical components. For most of our applications, we analyze the recorded beat frequency using Fourier transform methods, which determines the time response of the final velocity time history. We generally analyze our data with approximately 50 ns Fourier transform windows. We have obtained high-quality data on many experiments such as explosively driven surfaces and gas gun assemblies.

Subject terms, keywords

Velocimetry, heterodyne, single-mode fibers, fiber laser, circulator, Fourier transform

Introduction

Velocimetry is one of the primary diagnostics for shock physics experiments. Surfaces may be driven to kilometer-per-second velocities by several methods, including explosives, gas guns, or lasers. There have traditionally been two methods used for measuring velocities in the km/s range—VISAR[1,2] and Fabry-Perot[3,4]. Each method has its advantages and disadvantages. The VISAR system is more compact and less expensive than the Fabry system. VISARs may be obtained from commercial vendors, while Fabry systems are generally custom built. Both systems may be built to have fast time response, but Fabry systems record the data on streak cameras with limited record lengths, while the VISAR data may be recorded on digitizers with much longer record lengths. Both systems are vulnerable to abrupt changes in velocity and rely upon having a second etalon built into the system to resolve fringe jump ambiguities. The data analysis for the VISAR system is quite different from that of the Fabry system. The VISAR uses absolute intensities to obtain the velocity information, while the Fabry system relies upon fringe positions on a film record. The intensity of the light returned from a shocked surface often changes during the course of a measurement, so that the Fabry system is less sensitive to this effect than the VISAR. Analysis of the VISAR data involves the adjustment of a number of parameters to obtain “good-looking” Lissajous figures. The velocity record in a Fabry system is uniquely defined by the fringe positions on the film record, but the data is subject to various distortions caused by the streak camera. The main advantage of the Fabry system is its ability to measure multiple discrete velocities simultaneously and even velocity dispersion over a limited range, which the VISAR cannot do.

The velocimeter described in this paper uses the heterodyne method and has many of the advantages of both the VISAR and Fabry systems, while avoiding many of the disadvantages of both systems. The heterodyne velocimeter is compact and relatively inexpensive. The heterodyne velocimeter described here is custom built, but may be easily assembled from commercially available parts. The derived velocity time history is directly related to the frequency of the beat waveform, so that there is no need for extra components in the system to resolve such effects as fringe jump ambiguities. The data is recorded on digitizers, which allows long record lengths and avoids such effects as camera distortions. Fluctuations in the intensity of the light returned from the surface are seen in the data, but the heterodyne system appears to be robust against large variations. Finally, analyzing the data using Fourier transform techniques allows the heterodyne method to observe multiple discrete velocities and even dispersion.

The first section of this paper discusses the heterodyne method in general and its application to velocimetry. The next section describes the details of the heterodyne velocimeter system presented here and covers some of the details of setting up the system for an experiment. The third section describes several methods of data analysis and explains how the time response of the derived velocity time history is directly linked to the method of data analysis. The fourth section shows examples of data for four different types of experiments. The final sections discuss the capabilities and limitations of the heterodyne velocimeter and draw some conclusions.

Heterodyne Method

In the case of building a velocimeter, a laser is generally used to illuminate the moving surface to be measured. We use optical fibers to transport light from the laser to a probe containing a lens that focuses the light onto the moving surface (Figure 1). This same probe then collects a fraction of the light that is scattered or reflected from the moving surface and sends the Doppler-shifted light to the detector. For the heterodyne method, we also need to send a similar amount of undoppler-shifted light directly from the laser to the detector in a manner described below. The beat signal is generated at the detector by the mixing of the two individual signals of different frequency. We record the beat signal on a digitizer.

The notion of mixing two sinusoidal waveforms of different frequency to generate a beat frequency is well known. One of the sinusoidal waveforms has the original frequency of the laser itself, and the other waveform has the Doppler-shifted frequency. Both frequencies are

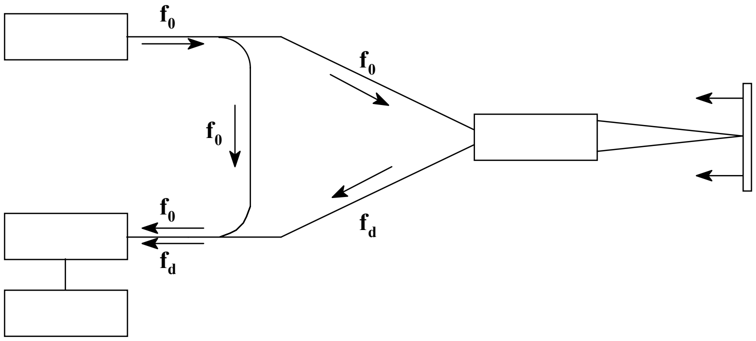

Figure 1. The basic geometry of a velocimeter using the heterodyne technique uses fiber optics to transport light from the laser to a probe that launches light to the moving surface. A portion of the Doppler-shifted light is collected by the probe and transported to the detector. In addition, undoppler-shifted light is transported directly to the detector. The beat frequency equal to the difference between the Doppler-shifted and undoppler-shifted frequencies is generated at the detector.

sent to a detector system with a bandwidth high enough to respond to the difference in the two frequencies, which is the beat frequency. At optical and infrared frequencies, the original laser frequency and the Doppler-shifted frequency are higher than the detector response and appear as CW components in the signal at the detector. The time dependent intensity I(t) to which the detector can respond is given by:

$$I(t) = I_0 + I_d + \sqrt{I_o I_d}\,\sin[f_b(t) + \phi] \qquad (1)$$

where I_0 is the undoppler-shifted intensity from the laser, I_d is the Doppler-shifted intensity from the moving surface (which may vary with time), f_b is the beat frequency, and ϕ is the relative phase between the Doppler-shifted and undoppler-shifted light. The first two terms, I_0 and I_d, represent the CW components of the total signal, while the third term contains the beat frequency information. The amplitude of the beat signal is determined by the CW components, while the frequency of the beat signal is given by the absolute value of the difference between the Doppler-shifted frequency and the undoppler-shifted frequency $f_b(t) = |f_d(t) - f_0|$. The beat frequency $f_b(t)$ is then related to the velocity v(t) by:

$$f_b(t) = 2\left(\frac{v(t)}{c}\right) f_0 \qquad (2)$$

where c is the speed of light. For our system, the laser has a wavelength of 1550 nm, which corresponds to a frequency f_0 = 193414 GHz. At a velocity of 1000 m/s, the beat frequency f_b = 1.29 GHz. We routinely measure velocities greater than 1000 m/s, so that our system must have a total bandwidth in the multi-gigahertz range.

For most of our experiments, the intensity returning from the surface I_d varies during the course of the measurement. As equation 1 shows, we would expect a time varying I_d to affect both the baseline level and the beat amplitude. We have seen I_d vary slowly (> 1 μs periods) on almost every experiment, but occasionally it varies quickly (< 1 μs periods) for brief moments. A slowly varying intensity from the surface shows up as a modulation of the beat amplitude during the course of the measurement as expected from equation 1. We do not see slowly varying baselines, however, because our electronics have low frequency cut-offs (to eliminate the CW components for our DC-coupled digitizers) that do not allow such low frequencies to be recorded. Abrupt changes in I_d, however, can have high enough frequencies that we observe momentary baseline fluctuations along with beat amplitude fluctuations at the same time.

In nearly all of our applications, the observed surface is moving toward the probes that launch the laser light to, and collect the Doppler-shifted light from, the surface, so that the Doppler-shifted frequency is greater than the original laser frequency, that is, $f_d > f_0$. As mentioned above, the heterodyne system responds to the absolute value of the beat frequency, and cannot tell the difference between a surface moving toward the probe and a surface moving away from the probe with the same speed. This property may render the heterodyne method less useful in applications where the surface alternatively moves toward and then away from the probe in an erratic manner, if the absolute position of the surface must be followed.

System Design

We built our heterodyne system using off-the-shelf components developed by the telecommunication industry. This choice forced us to operate with a laser wavelength of 1550 nm, which has both advantages and disadvantages compared to visible light lasers. One main advantage is that the beat frequency is lower for a given velocity than it would be using visible light lasers. The standard laser for our Fabry-Perot system is a doubled-YAG with a wavelength of 532 nm. With this laser and a velocity of 1000 m/s, the beat frequency would be 3.76 GHz, rather than 1.29 GHz for our system. The upper limit of our velocity range would have been severely limited with such high beat frequencies using the technique given in this paper. One main disadvantage of operating at 1550 nm is that the laser light cannot be seen with the unaided eye. In addition to the safety issues of working with high-power invisible laser radiation, there are the practical issues of performing probe alignments with respect to the target surface and verifying bookkeeping details of which probe actually sends signals to which detector. We have resorted to using small hand-held visible light lasers for these functions. There are other disadvantages of operating at 1550 nm compared to visible light lasers, such as a decreased ultimate velocity resolution limit at the longer wavelength, but we have found such disadvantages to be quite minor or even negligible compared to the overall advantages of using commercially available products to build a simple and compact system.

There are three main components developed by the telecommunication industry that made this technique easy to implement. Figure 2 shows a schematic of the system layout:

1. The newly developed class of lasers called fiber lasers has made it very easy to launch high power light into the 9-µm cores of single mode fibers. These lasers are simple to operate, are compact, and emit CW radiation. We bought lasers from IPG Photonics with 2-watt outputs

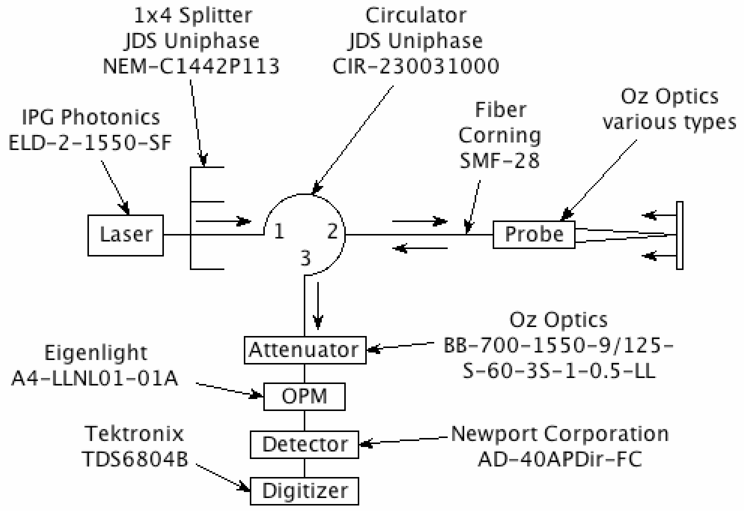

Figure 2. The heterodyne velocimeter is assembled from commercially available parts. The output of the laser is input into a 1x4 fiber splitter, which is connected to the four circulators. Each circulator transports light to a probe that launches light onto the moving surface. The Doppler-shifted light is collected by the probe and sent to the detector. The back-reflection from the fiber endface inside the probe provides the undoppler-shifted light.

(ELD-2-1550-SF). For recording data from a single-shot transient event, a CW laser means that no triggers are required for the laser. We generally turn our lasers on manually several minutes before the experiment and check our signal levels, and then turn them off manually after the experiment is over.

2. The heart of our heterodyne system is a fiber optic component called a 3-port circulator (JDS Uniphase CIR-230031000)). The circulator has the property that light launched into port 1 will exit from port 2, and light launched into port 2 will exit from port 3. The circulator has high efficiency (85%) for transporting light in these two directions, and very low efficiency (<-60dB) for transporting light in any other direction. We simply connect our fiber laser onto port 1, our probe onto port 2, and our detector system onto port 3. The entire system is fiber coupled, except at the probes, which yields quite high overall efficiencies. It is obvious from this assembly how the Doppler-shifted light is transported from the moving surface to the detectors, but it may not be obvious where the source of undoppler-shifted light is. The circulator does not allow enough light from port 1 to port 3 to serve this purpose, so we use the probe itself to provide the source of undoppler-shifted light. For a given experiment geometry, we calculate the expected collection efficiency of the probe and then require that the fiber endface inside the probe have approximately the same amount of back-reflection to provide the undoppler-shifted source. Probes are readily available from commercial vendors. When ordering the probes, the back-reflection may be specified anywhere from the full 0.04 of a standard glass-air interface to as low as -60 dB.

3. A new class of digitizers has recently come onto the market with very high bandwidth, very high sample rate, and large amounts of memory. Our

Tektronix digitizers (TDS6804B) have 8-GHz bandwidth, can record four channels of data simultaneously at a rate of 20 GS/s on each channel, and have enough memory to record for 1.6 ms at that rate. The Nyquist limit for recording a waveform such as our beat signals is equal to one half the sample rate, which means we could in principle record a 10 GHz beat waveform and still determine the frequency. A beat signal with this frequency corresponds to a velocity of 7750 m/s. In actuality, our maximum velocity is limited by the electrical bandwidth of the system. We have detectors with 12-GHz bandwidth, which when coupled with the 8-GHz bandwidth of the digitizer, gives us a total bandwidth of approximately 6.7 GHz and a maximum velocity of 5160 m/s. Most of our data have velocities less than 3000 m/s, so we are safely away from the Nyquist sampling limit and can generally determine the beat frequency, and hence the velocity, with low uncertainty. For applications with lower velocity ranges, these high-speed digitizers and high-bandwidth detectors may not be needed. These are the most expensive components of our system, so a system with a lower velocity capability would be considerably less expensive.

We built our heterodyne system as a 4-channel package; the 4-channel input of the digitizer made this a natural choice. The output of the laser, then, is input directly into a 1x4 fiber splitter that feeds four circulators. The maximum CW power rating of the circulators is 500 mW, therefore we bought a 2W CW laser to drive each system. This assures that we do not inadvertently damage the circulators with too much laser power. The output of the four circulators is input to the four probes via fiber optic jumpers, which may be many tens of meters long. We usually buy commercially available probes (Oz Optics), although we sometimes build custom probes for special applications. Our probe efficiencies have ranged from a high of 0.04 to as low as 10^{-4}. With high probe efficiencies or with unexpectedly high surface reflectivities, it is possible to saturate the detectors, so care must be taken when adjusting the laser power that the detectors are operating at a comfortable level. Our detectors saturate at 500 μW, so we typically try to set the laser power to keep the total optical power to the detectors around 60 μW. This usually gives us sufficient dynamic range to handle unexpected changes in signal levels returned from the moving surface during a measurement. We have inserted an optical power meter in front of each detector so that we can monitor the power delivered to each detector as we adjust the laser power. Sometimes we have situations in which the amount of light returned from the surface may vary greatly from probe to probe. Therefore, we have also included an optical attenuator in front of each power meter to maintain approximately equal power to all the detectors. We have assembled the 1x4 splitter, the circulators, the attenuators, power meters, and detectors into a single chassis (Figure 3). The chassis has bulkhead connectors for access to the input of the 1x4 fiber splitter, to port 2 of the four circulators, and to the electrical output of the four detectors. We can also adjust the four optical attenuators from the front panel of the chassis. Figure 4 shows a complete 4-channel system installed into a portable container with the laser in the top rack, the fiber/detector chassis in the

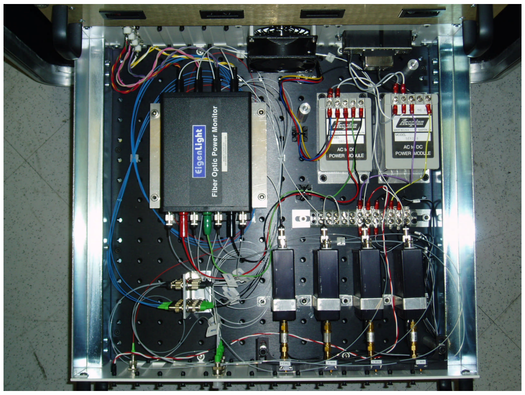

Figure 3. The fiber/detector chassis is custom built and contains the 1x4 fiber splitter, the circulators, optical attenuators, optical power meters, and detectors.

Figure 4. The 4-channel heterodyne system is packaged into a portable case. From top to bottom are the 2-W fiber laser, the custom fiber/detector chassis, and the high bandwidth digitizer. The digitizer shown here is built by Agilent Technologies; it has 6-GHz bandwidth and a sample rate of 20 GS/s on all four channels simultaneously for 50 μs.

middle rack, and the high-bandwidth digitizer in the bottom rack.

We tend to be quite conservative when we adjust the laser power in preparation for an experiment. We initially set the laser at a very low value, usually 200 mW, and verify that we are not getting an unusually high return from any of the probes. Then we step the laser power up in 200-mW increments and record the return from each probe at each laser setting. If, at any level, we see that the return from any probe is too high before the return from other probes is not high enough, we adjust the optical attenuators of the high probes to obtain returns that are approximately equal to the low probes. For probes with 10^{-4} efficiencies looking at a relatively shiny diffuse surface, we generally find that we end up with the laser set at approximately 1 W. Dark surfaces may require the full output of the laser with low efficiency probes. There is one aspect of setting the laser power that is worth mentioning. Recall that we are beating the signal from the soon-to-be-moving surface against the return from the fiber endface inside the probe. Sometimes those signals are in phase and we obtain full signals, but other times those signals are out of phase and we obtain nearly zero signal at the power meters. It takes a relative motion of only 387 nm between the probe and the surface to change from full constructive interference to full destructive interference. As we watch the power meters, the signals wander slowly from full value to nearly zero and back again as the experiment package reacts to mechanical vibrations or thermal motions. Even wind blowing with thermal gradients between the probe and the surface will change the optical path length enough to change the measured optical power. So, after increasing the laser power to the next higher setting, we need to have the patience to wait for the signal from each probe to wander through a few cycles to make sure we record the peak value. This behavior was a little disconcerting to us originally, but now we realize this is telling us that we are receiving a good return from the surface to be measured. In fact, if the power meter monitoring the return from a probe shows a very constant power reading, we know that we are not receiving any signal from the surface to be measured. Some assemblies that we have measured are very small, compact, and stable, so we may not see the varying signals just because the set-up is so rigid. In these cases, we may tap on the assembly to induce some vibration. Another group[5] at our lab will sometimes set an ice cube on their assembly housing to induce some thermal motion just to verify that they are receiving signals from the surface. Setting the laser power and adjusting the optical attenuators for four probes prior to an experiment may take 10 to 15 minutes, if all goes well.

When we arrive at a facility to take data on an experiment, we connect the output of the laser into the fiber/detector chassis, we connect the fiber jumpers to the chassis and run the jumpers to the experiment where we connect the probes to the other end of the jumpers, and finally we connect high-bandwidth electrical jumpers from the chassis to the digitizer. It usually takes only an hour or so to be ready to take data after we arrive at the experiment facility. Quite often, we operate the laser and digitizer manually, but we do have situations in which we must operate the heterodyne system remotely. We have a laptop running LabView programs to operate the laser and digitizer via GPIB for remote operations. Finally, we have the ability to download the data from the digitizer to the laptop via Ethernet after the experiment. The laptop also has MatLab loaded onto it, which runs our data analysis code.

Data analysis and Time Resolution

The electrical components of the heterodyne system have a composite bandwidth of nearly 7 GHz and our digitizer can sample at a rate of 20 GS/s, but this does not necessarily mean that we achieve sub-nanosecond time resolution with this diagnostic. Our recorded data contains a time-varying beat frequency that is usually in the gigahertz range, so we need the high bandwidth and high sample rate to faithfully follow the rapidly time-varying signal. The time response of the final velocity-versus-time data file depends upon how the data is analyzed. Some methods of analysis perform single cycle, or even sub-cycle, determinations of the frequency and may achieve sub-nanosecond time response if the recorded data is sufficiently noise-free. Other methods of analysis operate on many consecutive cycles to determine the frequency averaged over those cycles, resulting in much lower time response, but are much less sensitive to noise in the recorded data. The time response and the method of data analysis are intricately related for the heterodyne system, and are discussed together here. The method of data analysis eventually chosen by a user of this system depends greatly upon the individual requirements of the user, and the competition between lower velocity resolution at the expense of greater temporal resolution, or vice versa.

Even though we refer to the heterodyne system as a velocimeter and talk about recording a beat frequency proportional to the velocity, it is important to remember that this is actually a displacement interferometer. Every time the surface to be measured moves through a distance equal to one half the laser wavelength, we obtain a full cycle in the beat signal; that is, we obtain a full beat cycle for every 775 nm of motion of the surface. Measuring the period of a full beat cycle gives us a simple method of determining the velocity averaged over that cycle:

$$v(m/s) = \frac{775}{P(ns)} \tag{3}$$

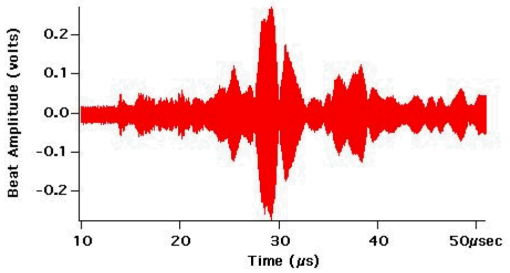

Figure 5a. The beat waveform often shows amplitude fluctuations as the intensity of the light from the moving surface changes during the experiment. The individual beat cycles cannot be resolved with this timebase.

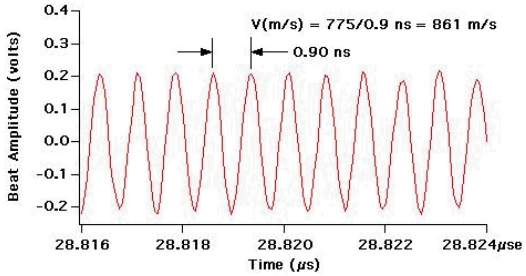

Figure 5b. Expanding the time base reveals the individual beat cycles. A measured period of 0.90 ns corresponds to a velocity of 860 m/s.

where v is the velocity in meters per second and P is the measured period of the beat cycle in nanoseconds. Immediately after an experiment (after we have saved the data, of course), we commonly expand the timebase on the digitizer until we can observe the individual beat cycles and measure a few periods to obtain a quick measure of how the experiment went. Figure 5a shows a typical digitizer trace after an experiment. The frequency is so high that the individual cycles cannot be resolved when displaying the full timebase. The observed waveform is actually the modulation of the beat amplitude as the signal intensity returning from the surface varies during the measurement. The expanded timebase in Figure 5b shows individual beat cycles along with the measured period and derived velocity for that portion of the data. In principle, the entire data record may be analyzed by this method. Our first analysis code (called the PeakFind routine) used this method of scanning through the data looking for the maximum and minimum of each cycle (two points per cycle) and using the time between these points to obtain a velocity averaged over a half-cycle. This method is sensitive to noise in the data, requiring carefully chosen amounts of smoothing so that the algorithm would find only one point per half-cycle. It is a labor-intensive process and yields quite large data files of velocity versus time. For example, a velocity of 1000 m/s recorded for 40 µs (not unusual for us) would yield a data file with over 100,000 v-t pairs. This is an excessive number of points and we do not actually realize sub-nanosecond time resolution because the data is usually too noisy. Much of our data consists of only 4 to 5 points per cycle and it is difficult to accurately determine the times at which the maxima and minima of the beat cycles occur with noise in the data. For the times that we do obtain low velocities with many points per cycle, we can successfully use the PeakFind routine. We have also explored the use of sliding sine fits to determine the frequency versus time. This method also works better with more points per cycle than most of our data has; it is too sensitive to noise in the recorded data with only 4 or 5 points per cycle. Both the PeakFind routine and the sliding sine fit method fail in the cases with multiple velocities or dispersion.

For most of our data, we use a sliding Fourier transform method of analysis. One of us (WWK) wrote this analysis code using MatLab. The inputs to the code include the laser wavelength, the time per point in the data record, and the desired number of points (w) in the Fourier transform window. The first part of the code calculates the spectrogram of frequency versus time. This part of the process requires no interaction from the operator and can be set up in batch mode to process all the data files obtained on the experiment. The frequency axis (vertical) in the spectrogram ranges from zero to the Nyquist limit; the number of frequency bins (rows) is (w/2+1). The temporal axis (horizontal) has the same range as the original data file; the code calculates the Fourier spectrum for the first w points and then advances w/2 points to calculate the spectrum for the next w points (50% overlap). As an example, much of our data is recorded at 20 GS/s (50 ps per point) for 50 μs, which results in 10^6 points in each data file. We often analyze the data using Fourier transform windows containing 1024 points (w = 1024). This provides 51 ns windows, which is the temporal resolution of the final velocity versus time file, and a temporal data point every 26 ns for a total of approximately 2000 v-t pairs. The Nyquist frequency is 10 GHz (one half the sample frequency), or 7750 m/s, which is the upper frequency limit in the spectrogram. The number of frequency bins is (w/2+1) = 513 bins, so that each bin corresponds to approximately 20 MHz, or 15 m/s. With a measured velocity of 1000 m/s, each frequency bin corresponds to 1.5% velocity resolution.

The second part of the code is interactive and is the part in which the velocity trace is extracted from the spectrogram. Figure 6 shows the sequence of steps that extract the velocity trace from the spectrogram. The code displays the spectrogram and allows the operator to zoom in to or out of any region of the spectrogram to look at the details of the peaks of the Fourier transform. The code then asks the operator to use the mouse to click a polygon around the regions of the spectrogram containing the peaks of interest. Drawing a polygon around the desired regions serves two purposes: 1) any extraneous noise in the spectrogram can be rejected, and 2) in cases with multiple velocities, each velocity trace may be extracted separately. After the polygon is completed, the code performs a column-by-column search for the peaks inside the polygon and then performs a 2nd order fit to the three points around the peak to obtain a sub-bin determination of the frequency. The final step is to convert the frequency into velocity using equation 2. We have tested the code using constructed beat waveforms containing up to 100% random noise. The algorithm easily provides sub-percent accuracy of the input velocity so long as the chosen Fourier transform window contains more than three beat cycles. In the case presented above with 1000 m/s velocity and 51 ns Fourier transform windows, each window contains 65 beat cycles. Our code tests with 100% random noise in this case showed a velocity error of 0.01%. This level of uncertainty seems

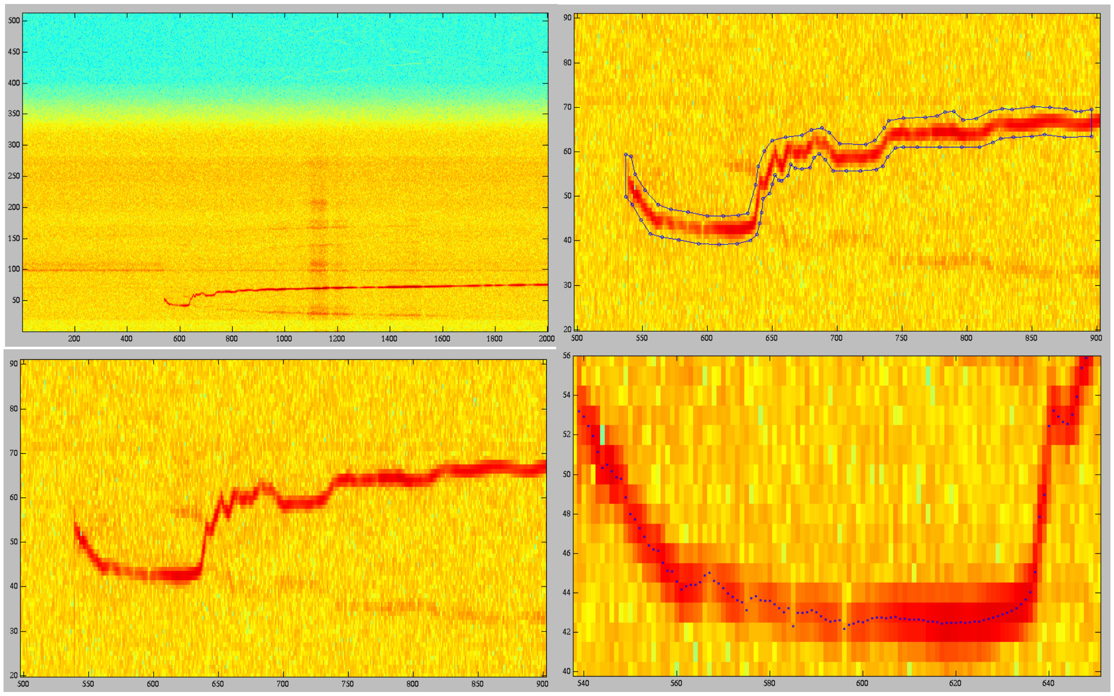

Figure 6. Our sliding Fourier transform code is written in MatLab. These figures show the analysis process for the data shown in Figure 4. Upper left: The Fourier transform was calculated with 1024-point windows, so the full spectrogram contains 513 frequency bins (0 to 7750 m/s) and 2000 temporal bins (0 to 50 µs). Lower left: Zoom in to the region of interest. Upper right: Draw a polygon around the frequency peaks corresponding to the desired velocity profile. Lower right: The location of the peak for each time bin is found by performing a 2^{nd} order fit to the three points around the peak. Zoom in again to the first part of the frequency profile to see the results in greater detail.

overly optimistic when dealing with real data. We generally feel that we can provide 1% velocity uncertainty so long as the original recorded beat waveform is of reasonable quality.

Examples of Data

We have four portable 4-channel heterodyne systems and have taken data at nine different facilities. We have fielded our system on over 100 experiments and have recorded nearly 400 data records. The experiments are exclusively single-shot transient events such as explosively driven surfaces or gas gun targets. We have recorded velocities below 1 m/s and as high as 2000 m/s, sometimes all in the same data record. We have recorded multiple velocities when looking through windows or when surfaces break up, and have even observed velocity dispersion caused by clouds of small particles ejected from the main surface. We have found the heterodyne system to be quite robust and have successfully obtained data even when the amount of light from the moving surface varies by factors of 25 or more. The following are some examples of the types of data that we have obtained.

Explosively driven metal Most of our experience is with explosively driven metals. Our first example is data taken from a metal surface using a probe with 6-mm diameter lens and focal length of 97 mm; we use this type of probe extensively and purchase them from Oz

Optics. The probe was set at an initial distance of 102 mm from the surface; setting the initial probe distance beyond the focal point allows us to follow the surface for a longer distance. These parameters gave a collection efficiency of approximately 10^{-4}. The laser power was set at 1.0 W; taking into account the system efficiency means 180 mW was launched from each probe to the target surface. We ran the digitizer at a sample rate of 20 GS/s and recorded for approximately 40 µs. The vertical sensitivity was 100 mV/div. Figure 7a shows the recorded beat waveform and Figure 7b shows the resulting spectrogram obtained with a 51-ns Fourier transform window. The individual beat cycles cannot be seen in Figure 7a, but it is interesting to note features in the envelope of the beat amplitude. The initial shock arrived at approximately 9 µs and can be seen by a slight increase in the beat amplitude above the noise level. This portion of the data had poor signal-to-noise, and yet the spectrogram showed a strong peak in the frequency spectrum at that time. Later, at approximately 23 µs, there was a sudden change in the intensity of light from the moving surface. The intensity change was abrupt enough to simulate a high enough frequency to pass through the low-frequency cut-off of the electronics, as discussed earlier, and resulted in a baseline fluctuation at the same time the amplitude changed. The spectrogram in this region showed a stronger peak in the frequency spectrum corresponding to the larger beat amplitude. Figure 7c shows the extracted velocity versus time profile. The data is noise-free and shows quite a bit of structure in the behavior of the metal.

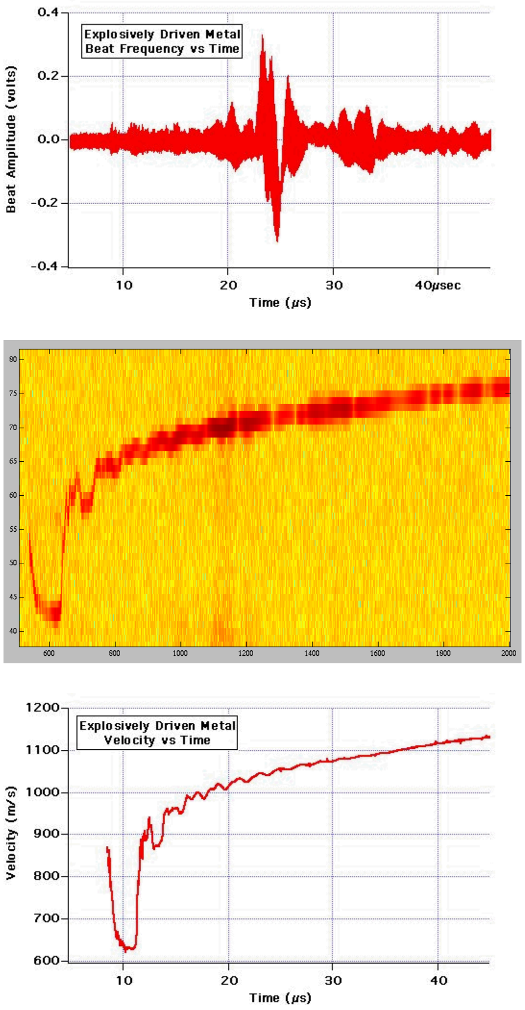

Figure 7. Top: Beat waveform obtained from explosively driven metal. Middle: Full spectrogram performed with 1024-point Fourier transform windows. Bottom: Resulting velocity versus time data.

<u>Cook-off Experiment</u> We have taken data on a few experiments in which an explosive package is slowly heated to deflagration—these are called cook-off experiments. The heating period may last two to three days before the explosion finally occurs. The experiment package, usually a metal cylinder packed with explosives, is heated by a combination of resistive heating coils attached to the ends of the cylinder plus three radiative heaters placed 120 degrees apart illuminating the sides. For the heterodyne coverage, we usually

place three probes approximately midway between the three radiative heaters looking at the motion of the side of the cylinder. These probes have 12.5 mm diameter lenses with 250 mm focal length, and we set them 260 mm away from the cylinder for an efficiency of approximately 10^{-4}. The long standoff places the probes far enough away that they are not also cooked by the side heaters. It is not known exactly when the explosion will occur, so all the diagnostics must be prepared to record the data regardless of when it happens.

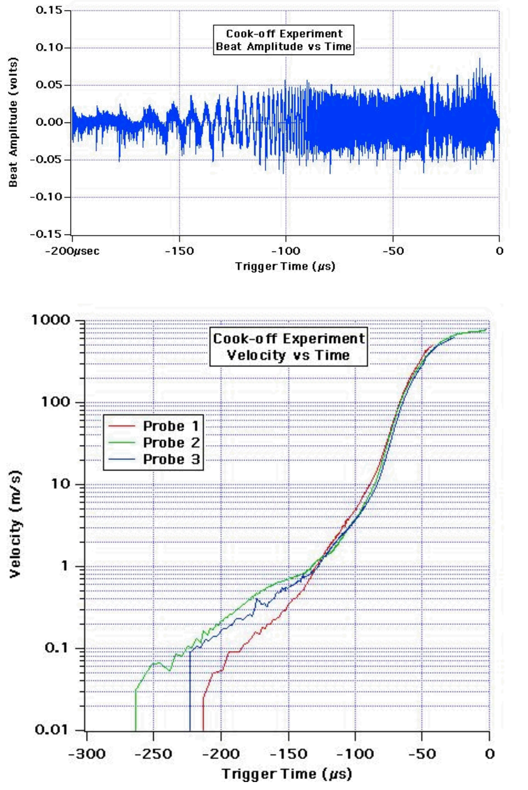

Figure 8. Top: Beat waveform for probe 1 on the cook-off experiment. Bottom: The velocity time histories span 4 decades. The velocity range above 2 m/s was analyzed using the sliding Fourier transform method and the velocity range below 10 m/s was analyzed using the PeakFind method. The two methods agree very well in the overlap region.

For the heterodyne system, this means that the laser must be on for the entire heating period; for this experiment the laser was set to 600 mW and illuminated the target continuously for three days. The experiment package was assembled with trigger wires to trigger the digitizers. The heterodyne digitizer was set with 500 µs of pre-trigger and a sample rate of 20 GS/s. The vertical scale was set at 100 mV/div. Figure 8 (top) shows the beat waveform for one of the three probes. The initial velocity from -150 µs to -100 µs was so slow that the individual beat cycles can be seen in the early part of the record. Figure 8 (bottom) shows the resulting velocity time history from all three probes. The data span approximately four decades of velocity—from less than 0.1 m/s to nearly 1000 m/s. The upper part of the velocity range above approximately 2 m/s was analyzed using the Fourier transform method. The lower part of the velocity range was too slow for the Fourier transform method, so the PeakFind method was used below approximately 10 m/s. There was excellent agreement between the two methods in the 2 m/s to 10 m/s region of overlap, and the transition from one to the other is not observable.

Multiple Velocities Our first data from a gas gun assembly required shining the light from the heterodyne probe through two lithium fluoride (LiF) windows to an aluminum surface. The probe used here was the same type mentioned in the first example with 6-mm diameter lens, 97-mm focal length, and 102-mm standoff. We ran the digitizer at a sample rate of 10 GS/s for 5 µs and the vertical scale was 50 mV/div. Figure 9 (top) shows the beat waveform; there was a slow baseline drift prior to the start of motion that we attribute to electrical ground plane fluctuations. Figure 9 (middle)

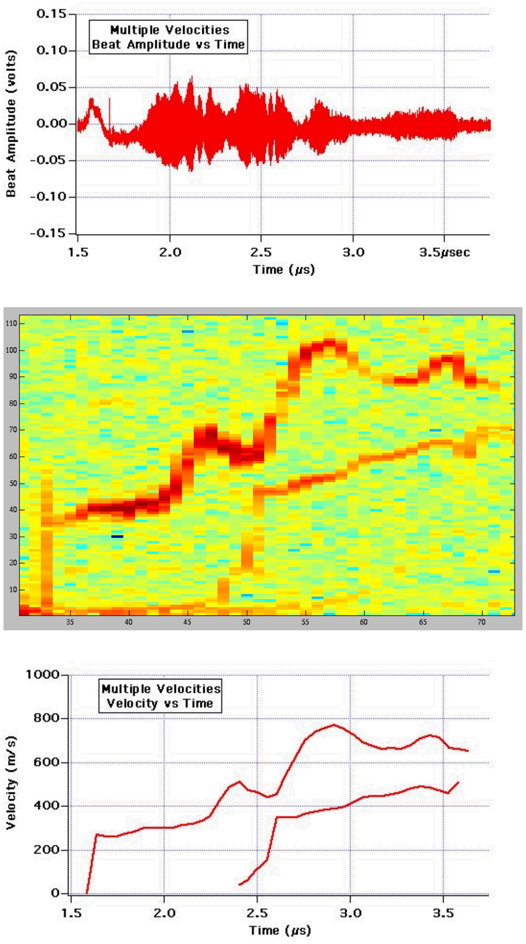

Figure 9. Top: Beat amplitude for the gas gun shot with the heterodyne probe shining light through two LiF windows. Middle: The resulting spectrogram shows a second velocity. Bottom: We can extract each velocity profile separately. The timing of the second velocity is consistent with the sound speed through the LiF window.

shows the resulting spectrogram. The upper set of peaks in the frequency spectra represent the expected data profile. Starting at approximately 2.5 µs, another set of peaks appears that represents a slower velocity profile. The time interval from the start of the first set of peaks to the start of the second set of peaks is consistent with the sound speed transit time through the first LiF window. Apparently, a small amount of light from the probe was reflecting from the surface of the LiF window, which started to move when the shock reached it. The final velocity time history for both the aluminum surface and the LiF surface are shown in Figure 9 (bottom). (There are no corrections to the velocity for looking through a LiF window in the data shown here.) This was the first data in which we had seen multiple velocities simultaneously with the heterodyne system. The Fourier transform method of analysis has the capability to extract multiple frequencies. Since taking this data, we have seen numerous examples of data with multiple velocities.

Shock Arrival Measurements Many gas gun experiments use electrical pins to measure shock arrival times. The heterodyne system is also useful for providing shock arrival data with sub-nanosecond precision on gas gun experiments. A typical shot geometry calls for six probes arranged in a hexagon at some radius looking at the back of a target sample. This probe geometry provides enough information to correct for a slight tilt in the projectile when it hits the sample. The probes used here had approximately 10 mm stand-offs. For the example shown here, the target sample was made of copper and the velocity of the copper projectile was 0.49 km/s. The digitizers were operated at 20 GS/s with 200 mV/div and a record length of 12.5 µs. Figure 10 (top) shows the beat waveform from one of the channels; the timescale has been expanded around the time of the shock arrival. The elastic precursor is seen as the initial slowly varying waveform, while the arrival of the plastic wave is seen as the abrupt change in frequency. Correcting the shock arrival times for the probe-to-probe system delays and plotting the arrival times versus probe number for the six probes resulted in the sinusoidal pattern, shown in the lower

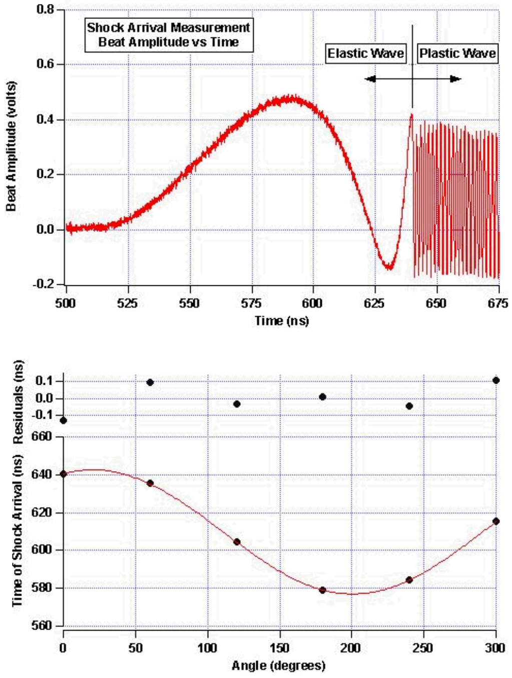

Figure 10. Top: The beat amplitude shows a slowly varying region as the elastic precursor arrives at the surface, and then a rapidly varying region once the actual shock arrives. Bottom: Fitting the shock arrival times to a sine wave yields residuals with a 90 ps standard deviation among the six probes.

part of Figure 10 (bottom), caused by a slight tilt of the projectile when it hit the sample. Fitting the data to a sine wave resulted in residuals with a 90 ps standard deviation in the fit to the data, shown in the upper part of Figure 10 (bottom). A number of experiments with varying projectile velocities give residuals to the sine fit that are easily sub-nanosecond; most of the results are in the 200 ps to 300 ps range. Even though the original goal was to obtain only the initial shock arrival times, the subsequent velocity time histories are also available in the data and have proven to be useful as well.

Capabilities and Limitations of Heterodyne System

This configuration of fiber lasers with circulators and high-sample-rate digitizers to perform high-speed velocimetry has proven to be quite successful. We have supported many programs on a large number of experiments and have achieved a nearly 100% return rate of high-quality data. We built our system into 4-channel units and packaged them into portable cases with wheels that allow us to easily transport the system to different laboratories and facilities. Once in place, it is straightforward to run the jumper fibers from the system chassis to the experiment location and connect the probes. At the minimum, we require only a trigger for the digitizer, but, in practice, we usually record a timing mark generated by the facility to cross time our data with other diagnostics on the same experiment.

The heterodyne system has the capability of observing multiple discrete velocities and even dispersion, which is one of the main advantages of a Fabry-Perot system, and yet has the advantages of small size, ease of use, and low cost that the VISAR system enjoys. The heterodyne technique described here is completely fiber coupled, which results in a very high system efficiency. Normally, the overall efficiency of a given set-up is dominated by the efficiency of the probes.

The main disadvantage of the heterodyne system compared to the Fabry-Perot or VISAR techniques is the limited maximum velocity of the heterodyne method. The velocity range of the Fabry-Perot or VISAR may be adjusted to arbitrarily high velocity by the choice of etalons. The heterodyne system described here is limited by the bandwidth of the high-sample-rate digitizer. Fast digitizers currently on the market have sample rates high enough that the bandwidth limits the maximum velocity well before the Nyquist limit is approached. To be sure, the 5000 m/s limit of the system described here satisfies most applications in shock physics experiments, but there are a few applications that require even higher velocity limits.

A second disadvantage of the heterodyne method is the inability to discern whether the velocity of the moving surface is toward the probe or away from the probe. The beat frequency depends upon the absolute value of the difference between the Doppler-shifted signal and undoppler-shifted signal, and so is insensitive to direction. For most shock physics experiments, the direction of the moving surface is toward the probe, but other applications may require knowing the direction of motion.

Conclusions

We have built a high-speed velocimeter using commercially available parts developed for the telecommunications industry. The system is simple to assemble and provides high-quality data in a large variety of experiments. The system described here has a maximum velocity limit of approximately 5000 m/s, but similar systems with lower maximum velocities are substantially less expensive. The beat signal may be analyzed in a number of ways, but analyzing the data using sliding Fourier transform techniques allows the diagnostic to record multiple discrete velocities and dispersion. We usually analyze data from explosively driven metals with 50 ns Fourier transform window.

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References

1. L. M. Barker and R. E. Hollenbach, “Laser Interferometry for Measuring High Velocities of Any Reflecting Surface,” J. Appl. Phys. **43**, 11 (November 1972).

2. W. F. Hemsing, “Velocity Sensing Interferometer (VISAR) Modification,” Rev. Sci, Instrum, **50**, 1 (January 1979).

3. C. F. McMillan, et al., “Velocimetry of Fast Surfaces Using Fabry-Perot Interferometry,” Rev. Sci. Instrum. **59**, 1 (January 1988).

4. D. R. Goosman, “Formulas for Fabry-Perot Velocimeter Performance Using

Both Stripe and Multifrequency Techniques," **30**, 3907 (September 20, 1991).

5. Palakkal P. Asoka-kumar, Lawrence Livermore National Laboratory, Livermore, CA (personal communication, 2005)