UCRL-CONF-206034

Velocimetry Using Heterodyne Techniques

O. T. Strand, L. V. Berzins, D. R. Goosman, W. W. Kuhlow, P. D. Sargis, T. L. Whitworth

August 13, 2004

Velocimetry Using Heterodyne Techniques
Alexandria, VA, United States
September 20, 2004 through September 23, 2004

Velocimetry using heterodyne techniques

Oliver T. Strand[a*], Leon V. Berzins[a], David R. Goosman[a], William W. Kuhlow[b],
Paul D. Sargis[a], Tony L. Whitworth[a]

[a]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550
[b]Bechtel/Nevada, P.O. Box 98521, Las Vegas, NV 89193

ABSTRACT

At LLNL, we have been using heterodyne techniques for the past year and a half to measure velocities up to several kilometers-per-second on different types of experiments. We assembled this diagnostic, which we call the Heterodyne Velocimeter (HetV), using commercially available products developed for the communications industry. We use a 1550 nm fiber laser and single mode fibers to deliver light to and from the target. The return Doppler-shifted light is mixed with the original laser light to generate a beat frequency proportional to the velocity. At a velocity of 1000 m/s, the beat signal has a frequency of 1.29 GHz. We record the beat signals directly onto fast digitizers. The maximum velocity is limited by the bandwidth of the electronics and the sampling rate of the digitizers. The record length is limited by the amount of memory contained in the digitizers. This paper describes our approach to measuring velocities with this technique and presents recent data obtained with the HetV.

Keywords: velocimetry, heterodyne, fiber optics, fiber lasers, circulators, high-speed digitizers

1. INTRODUCTION

Time-resolved velocimetry is an important measurement in the study of shock physics. The range of velocities required for this discipline often exceeds 1000 m/s. The standard diagnostics for kilometer-per-second velocities include the VISAR[1, 2, 3] system and the Fabry-Perot-based[4, 5] system. Both of these systems use some form of interferometry to convert such high velocities into a more manageable parameter to measure. A third form of interferometry may be based upon the heterodyne technique to generate a measurable beat frequency. In this case, the light from a laser is launched onto the moving surface and a portion of the Doppler-shifted light is collected and sent to a detector. At the same time, an equivalent amount of non-Doppler-shifted light is sent directly from the laser to the detector where a beat signal is then generated. Using a laser with a wavelength of 1550 nm will produce a beat frequency of 1.29 GHz for a surface moving at 1000 m/s. Higher velocities produce proportionally higher frequencies. In the past, these frequencies were too high to measure directly for the tens of microseconds desired for many experiments. Recently, however, advances in the telecommunications industry have encouraged the development of various products that have made the heterodyne method relatively easy to implement for velocities up to several kilometers per second. The first section of this paper describes the concept of using the heterodyne method to measure velocities. The next sections describe the components assembled to build the Heterodyne Velocimeter (HetV) and the resulting performance characteristics of the instrument. The following sections show examples of the data and the corresponding methods of analysis. The final sections discuss the advantages and disadvantages of using the heterodyne method for measuring velocities on shock physics experiments.

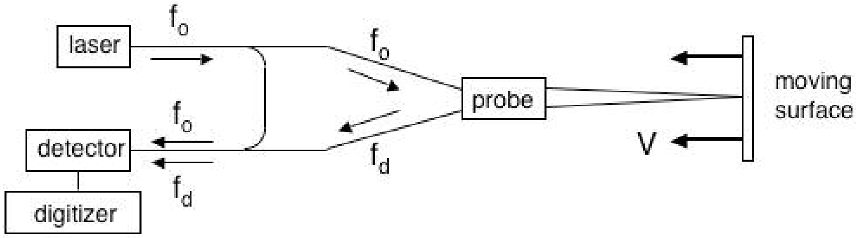
2. SYSTEM DESIGN AND PERFORMANCE

2.1. Basic concept

Our goal is to develop a velocimeter based upon the heterodyne technique. We prefer to use fiber transport, which allows a larger number of data channels in some geometries, than air transport. For each channel, then, a fiber transports

[*]otstrand@llnl.gov; phone 925-423-2062; fax 925-422-2382

the light from the laser to the experiment. At the experiment end of each fiber, a probe containing a lens may be used to launch the light onto the moving surface and collect a reasonable amount of the light reflected or scattered from the surface. The collected Doppler-shifted light is transported by fiber to the detector. By some means, a fraction of the light emitted by the laser is transported by fiber directly to the detector without being Doppler shifted. Such a scheme is shown conceptually in the following figure.



In this figure, the frequency of the light emitted by the laser is f_o, and the frequency of the Doppler-shifted light is f_d. The beat signal is generated at the detector with a frequency f_b equal to the difference between the Doppler-shifted frequency f_d and the un-shifted frequency f_o. The beat frequency is given by:

$$f_b = f_d - f_o = 2(v/c)f_o$$

With the speed of light $c = f_o\lambda_o$, where λ_o is the wavelength emitted by the laser, the velocity is given by:

$$v = (\lambda_o/2)\ f_b$$

With a laser wavelength of 1550 nm, the velocity is simply

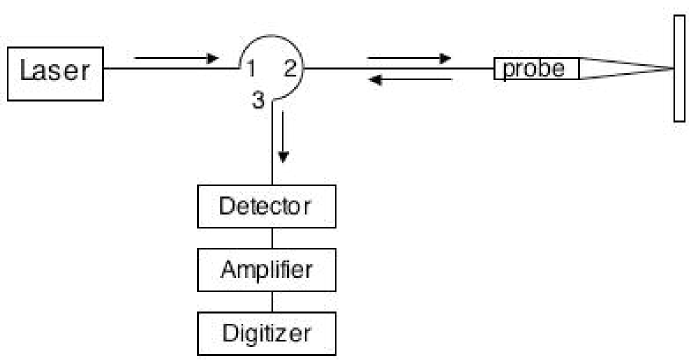
$$v(m/s) = 775\ f_b\ (GHz)$$

In shock physics experiments, the surface is almost always moving toward the probe so that $f_d > f_o$.

2.2. Telecommunications hardware

The telecommunications industry has built a huge variety of components that utilize single-mode fiber-optic components operating at 1550 nm, along with many high bandwidth electrical components. We decided to take advantage of these relatively abundant and low-cost components to construct our Heterodyne Velocimeter (HetV). There are some disadvantages with operating at infrared wavelengths rather than visible wavelengths—we cannot see the illuminated spots on the target surface, for example—but the advantages sufficiently out-weighed the disadvantages that we decided to base the HetV on the 1550 nm technology.

The heart of our HetV design is based upon a fiber optic component called a 3-port circulator (see the diagram below).



The 3-port circulator has the property that light injected into port 1 will be emitted out port 2, and light injected into port 2 will be emitted out port 3. We connect our fiber laser onto port 1, our probe onto port 2, and our detector onto port 3.

Once all the fibers are connected, the entire diagnostic is Class 1 for laser safety except at the probe. The fiber from port 2 to the probe may be many tens of meters long, depending upon the location of the experiment with respect to where the diagnostic is housed.

It is clear from the above sketch how the Doppler-shifted light is transported to the detector, but it may not be obvious how the non-Doppler-shifted light is generated. Essentially no light is transported from the laser directly to port 3 and then to the detector; the circulator allows less than –50 dB for that pathway, which is not enough to generator a good beat signal. Instead, we rely upon the reflection from the fiber endface inside the probe to provide the non-Doppler-shifted light. The vendor can build probes with a specified amount of back-reflection ranging from the full 4% of an air/glass interface to as low as –60 dB. The best beat amplitude is generated when the intensity of the Doppler-shifted light and the intensity of the non-Doppler-shifted light are nearly equal. For any given experiment, we decide upon the probe dimensions based upon such factors as desired depth of field and physical limitations of the experiment geometry. We use these factors to calculate the collection solid angle and corresponding signal returns from the moving surface, and order the probes with an equivalent back-reflection.

All of the components shown in the above figure are commercially available. A list of the parts shown above that we purchased for our system is given in the following table.

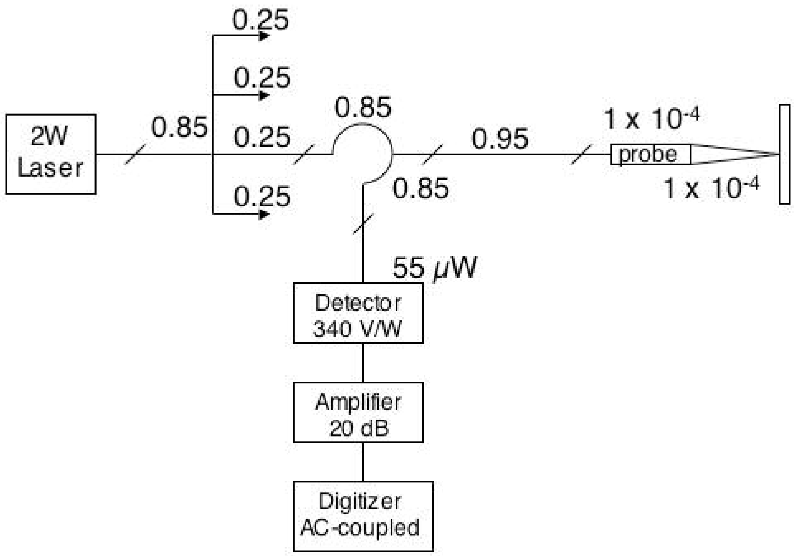
Component	Vendor	Model # or Type
Fiber laser	IPG Photonics	ELD-2-1550-SF
Circulator	JDS Uniphase	CIR-230031000
Single mode fiber	Corning	SMF-28
Probe	Oz Optics	Various
Detector	Newport Corporation	AD-70xr-FC
Amplifier	Picosecond Labs	5840A
Digitizer	Agilent Technologies	54885A Infinium

These are the primary components, but there are other parts required for a fully field-ready system. The digitizer has four signal inputs that can each sample at 20 GS/s simultaneously, so we built up a portable system with a custom-built chassis that supports four probes at once. In the above sketch, the laser actually feeds a 1x4 fiber splitter that then feeds four circulators, four probes, and four detector systems.

2.3. Performance characteristics

At LLNL, our standard diagnostic for measuring kilometer-per-second velocities on explosively driven experiments is the Fabry-Perot-based system. For a number of reasons, we designed our Fabry probes to have efficiencies on the order of 1×10^{-4} from reasonably reflecting Lambertian surfaces. There are the occasional experiments in which the desired number of channels exceeds the capacity of our Fabry-based system. One of the goals in the design of our HetV was to be able to field HetV probes along side Fabry probes on a given experiment to increase the channel count. This single criterion—probes with 1×10^{-4} efficiencies—drove much of the design of the HetV system. A second criterion—measuring velocities up to several kilometers per second—added additional constraints to the design. Building a HetV system for applications in which higher probe efficiencies are possible, and in which lower velocities are involved, would significantly ease many of the constraints and lower the cost of such a system.

The system efficiency of the HetV system is quite high because the entire system is fiber coupled with no air transport anywhere except at the probes. The following sketch shows the basic light budget for the HetV:



We purchased circulators with the highest CW power rating that we could find, which was 0.5 W. For a 4-channel system, we purchased a 2-W fiber laser with 1550 nm CW output. The output of the laser is connected to a 1x4 fiber splitter before being sent to the circulators. This assures that we do not inadvertently over-drive the circulators. The fiber splitter and circulators have approximately 85% efficiency and the fiber efficiencies are over 95% for the lengths of fibers that we use in our experiments. With these conditions and the probe efficiency of $1x10^{-4}$ plus another $1x10^{-4}$ from the surface, we obtain approximately 55 μW of CW light at the detector. The detectors saturate at nearly 300 μW, which gives us some dynamic range in case the intensity from the surface increases during the experiment. The 55 μW incident onto the detector (half from the surface and half from the probe) and the detector efficiency of 340 V/W yield a beat amplitude of approximately 10 mV from the detector, or 100 mV at the digitizer after the amplifier. These signal levels are sufficient to record useful beat signals that can be converted into velocity vs. time records.

The bandwidth of the HetV system is limited by the electrical components. Dispersion in the single mode fiber is in the picosecond range for the fiber lengths that we use and is not a limiting factor in our system response. The bandwidths of the electrical components are: 6 GHz for the detectors, 8 GHz for the amplifiers, and 6 GHz for the digitizer. These values yield a total bandwidth of approximately 3.7 GHz, which effectively limits our maximum velocity to approximately 2900 m/s. Digitizing a 3.7 GHz signal at 20 GS/s yields approximately 5.4 points per cycle, which is below the Nyquist limit. At velocities of 1000 m/s, we obtain over 15 points per cycle in the digitized waveform, which is sufficient to generate accurate determinations of the velocity.

3. DATA AND ANALYSIS

3.1. Analysis method

There are several mathematical methods to obtain frequency vs. time information from a time-varying sinusoid. The most obvious is to use a sliding Fourier transform (FT) on the frequency vs. time data. One of us (WWK) wrote a user-friendly analysis code using MatLab. This code performs several preparatory operations on the beat waveform prior to performing the actual FT. The user must input the time per point at which the data was taken, the start time for the data record, and the desired number of points (called the window) over which the FT should be performed. The code then displays the full time history of the data and allows the user to select a sub-set of the full data record for the remainder of the analysis. The code then removes any baseline fluctuations and displays that result. The code calculates the sliding FT and displays an image of frequency vs. time. The user is asked to zoom in to the region of interest and draw a polygon around the desired peaks in frequency, which are converted to velocity vs. time. Judiciously choosing the shape of the polygon effectively discards unwanted noise in the frequency spectrum and in the final velocity time history. In the case of multiple velocities, the user may select one velocity time history for analysis, and then re-run the calculation to select a different time history from the same frequency vs. time image.

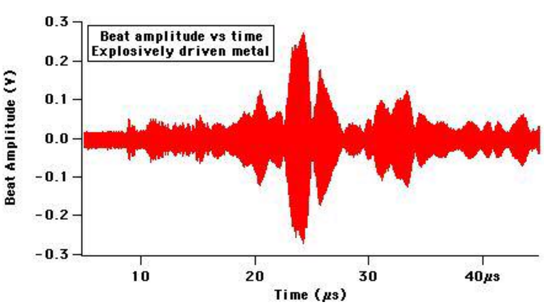
The time response of the final velocity vs. time record depends upon the length of the window originally chosen by the user for each FT. Shorter windows yield higher time response but generally noisier data. Longer windows yield lower time response but cleaner-looking data. The user may wish to run the code with different window lengths and then choose the result that is most satisfying or that makes the most physical sense. Care must be taken by the user not to choose windows that are too short in the hopes of obtaining very high time response. If the length of the window approaches the period of a single beat wave, then the code will return velocities with increased errors.

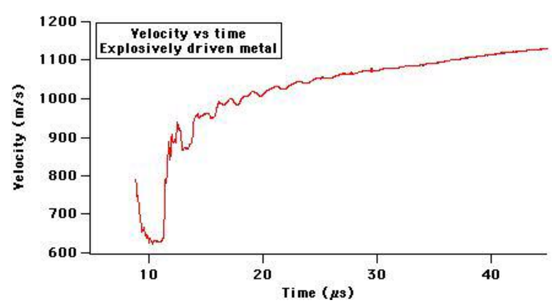
3.2. Examples of data

We have taken data with the HetV on a wide variety of experiments. Most of our measurements have been made on explosively driven metals with velocities in the kilometer-per-second range. We have also taken data on gas gun experiments, laser-driven targets, and various types of non-destructive tests. The total range of velocities over which we have taken data has been from sub-meter-per-second to 2000 m/s. For some of the gas gun measurements, the experimenters were interested in shock arrival times; for sabot velocities of 800 m/s, we were able to obtain sub-nanosecond uncertainties in the shock arrival times. With the FT method of data analysis, we have processed data with two discrete velocities and, on other experiments, have seen evidence of velocity dispersion. Here are two examples of the data we have taken:

3.2.1. Explosively driven metal

The following figures show the beat waveform vs. time recorded by the digitizer for an explosively driven metal (left figure) and the corresponding velocity vs. time (right figure). The actual beat frequency is too high to resolve the individual waves on this scale, so the figure shows only the envelope of the beat amplitude. We took this data with the Agilent digitizing oscilloscope sampling at a rate of 20 GS/s, or 50 ps per point, with a record length of 1 million points. We commonly see amplitude fluctuations similar to those observed here. We sometimes see baseline fluctuations also.

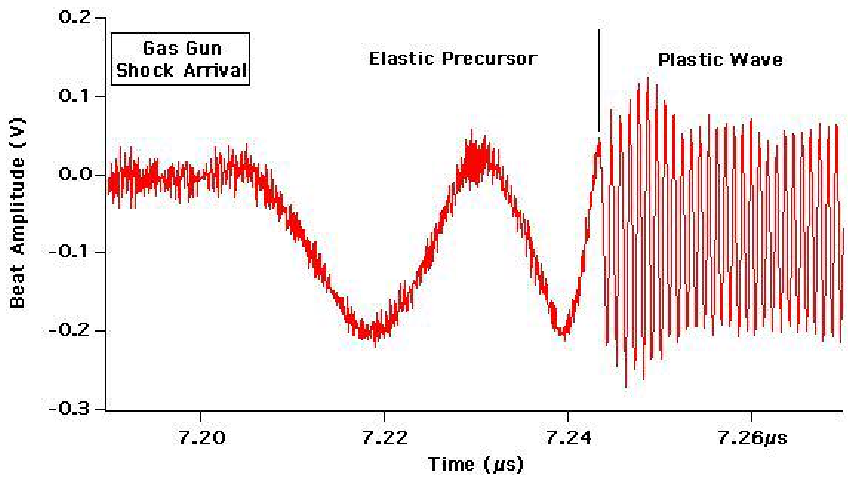




We processed the beat amplitude data using our FT code to obtain the velocity time history shown on the right. The FT time window was 1024 points, or approximately 51 ns, which essentially sets the time response for this analysis. The velocity in this case ranges from 600 m/s to nearly 1200 m/s over approximately 40 µs. There is very little noise in the resulting time history even though the beat amplitude signal-to-noise was less than unity for parts of the data record.

3.3.2. Shock arrival

A group doing gas gun experiments here at LLNL asked whether we could provide sub-nanosecond uncertainties in shock arrival times. We built an array of seven probes arranged in a hexagon, plus one in the center, to measure the shock arrival times at the back of an aluminum target. The sabot velocity was approximately 800 m/s for these tests. We set the digitizer with a sample rate of 20 GS/s and total record length of 12.5 µs. We set the scope with a 50% pre-trigger so that shock arrival would fall near the center of the data record. The figure below shows the beat waveform from one of the probes. This record shows approximately 80 ns of the beat amplitude around the region of interest. With this expanded time base, the individual beat waves may now be seen.



At these pressures, the elastic precursor is evident prior to the onset of the plastic wave. The analyzed data for all seven probes on each experiment showed a standard deviation of approximately 200 ps from the expected times. Experiments at higher shock velocities may provide even smaller standard deviations because the periods of the beat waves would be shorter than those obtained here.

4. DISCUSSION

The Heterodyne Velocimeter has become quite popular here at LLNL among several groups of experimenters. Physically, the 4-channel system is fairly small and quite transportable. The laser, digital oscilloscope, and custom fiber/detector chassis are installed in a shock-mounted rack inside a hard-shelled box with wheels and a handle. The outside dimensions of this box are approximately one meter on a side and can be lifted by two people into the back of a truck. We have taken the HetV to seven different facilities here in Livermore and one facility in Nevada. Operationally, it is fairly easy to set up and operate the HetV. Upon arriving at a facility, we can be ready to take data in only a few hours. Once the fibers and cables are connected and the probes are mounted on the experiment, the operator needs to adjust the laser output for the desired power levels at the detectors. At this point, the HetV is ready for the experiment. The laser is CW, so the operator turns it on several minutes before the experiment. The only input that the HetV needs is a single trigger for the digitizer at the appropriate time. (There are, of course, the laser safety issues that must be addressed ahead of time.) The data analysis is fairly quick and easy with our Fourier transform analysis code.

The data quality produced by the HetV has improved over the past year as we learn more about its capabilities and limitations. Although we continue to learn, we are now at the point that we can reliably deliver high quality data to the experimenter. There are still a few issues, however, that we continue to address. As can be seen in the first example of data above, we are sometimes subject to fairly large fluctuations in beat amplitude. We believe these are related to intensity variations from the shocked surface during the measurement. We must rely upon the dynamic range of the system to be large enough that we may still accurately determine the frequency even during times of low beat amplitude. Usually, the periods of time that the beat amplitude drops completely into the noise persist for only a few beat cycles. This corresponds to a few nanoseconds of lost data at kilometer-per-second velocities. For most of our applications, this is not a serious issue.

The HetV can easily take low velocity data as well. In these cases, there is no need for extremely fast digitization of the beat waveforms, and we may use our standard digitizers with more modest sampling rates. The experimenter must realize, however, that the beat waveforms will have periods in the tens of nanoseconds range for velocities below 80 m/s. If the data is to be analyzed by a Fourier transform method, the minimum time response may be over 100 ns. The HetV is not a particularly useful diagnostic in those cases with low velocities requiring nanosecond time response.

5. CONCLUSIONS

We have used the heterodyne technique to design and assemble a velocimetry system using commercially available components. Recent advances in the telecommunications industry have resulted in high-bandwidth digitizers with sampling rates high enough to measure velocities up to nearly 3000 m/s. In addition, high power fiber lasers simplify the use of single mode fibers that can maintain the required coherence to produce usable beat amplitudes. Our analysis code is based upon a sliding Fourier transform method and produces high quality velocity vs. time data. The time response of the processed data depends upon the chosen window over which the transform operates. Our 4-channel system is small and portable. We have taken data on a wide variety of experiments in a number of different facilities.

ACKNOWLEDGEMENTS

We would like to thank Bechtel/Nevada of Las Vegas, Nevada, for purchasing most of the HetV hardware. We have been using the HetV in Livermore to test the heterodyne system and to gain experience with it prior to its use on a series of experiments in Nevada.

We would like to thank the experimenters who have kindly agreed to let us display their data for use in this paper. Steve Bosson was very helpful in obtaining the data from the explosively driven metal, and the gas gun shock arrival data belongs to Neil Holmes, Ricky Chau, and Jeff Nguyen.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

REFERENCES

1. L. M. Barker, R. E. Hollenbach, “Laser interferometer for measuring high velocities of any reflecting surface”, Journal of Applied Physics, **11** (4669-4675), 1972.

2. D. R. Goosman, “Analysis of the laser velocity interferometer”, Journal of Applied Physics, **46** (3516-3524), 1975.

3. W. C. Sweatt, P. L. Stanton, O. B. Crump, Jr., “Simplified VISAR system”, SPIE Proceedings of Ultrahigh- and High Speed Photography, Videography, Photonics, and Velocimetry, **1346** (151-159), 1990.

4. M. Durand, P. Laharrague, P. Lalle, A. Le Bihan, J.Morvan, H. Pujols, “Interferometric laser technique for accurate velocity measurement in shock wave physics”, Review of Scientific Instruments, **48** (275-278), 1977.

5. C. F. McMillan, D. R. Goosman, N. L. Parker, L. L. Steinmetz, H. H. Chau, T. Huen, R. K. Whipkey, S. J. Perry, “Velocimetry of fast surfaces using Fabry-Perot interferometry”, Review of Scientific Instruments, **59** (1-20), 1988.