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EXPLOSIVE COMPONENT ACCEPTANCE TESTER USING LASER INTERFEROMETER TECHNOLOGY

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Abstract

Acceptance testing of explosive components requires a reliable and simple to use testing method that can discern less than optimal performance. For hot-wire detonators, traditional techniques use dent blocks or photographic diagnostic methods. More complicated approaches are avoided because of their inherent problems with setup and maintenance. A recently developed tester is based on using a laser interferometer to measure the velocity of flying plates accelerated by explosively actuated detonators. Unlike ordinary interferometers that monitor displacement of the test article, this device measures velocity directly and is commonly used with non-spectral surfaces.

Most often referred to as the VISAR technique (Velocity Interferometer System for Any Reflecting Surface),it has become the most widely-accepted choice for accurate measurement of velocity in the range greater than 1 mm/μs. Traditional VISAR devices require extensive setup and adjustment and therefore are unacceptable in a production-testing environment. This paper describes a new VISAR approach which requires virtually no adjustments, yet provides data with accuracy comparable to the more complicated systems. The device, termed the Fixed-Cavity VISAR, is currently being developed to serve as a product verification tool for hot-wire detonators and slappers. An extensive data acquisition and analysis computer code has also been created to automate the manipulation of raw data into final results.

This paper describes the unique aspects of the hardware and the requirements for installation at the production facility. The algorithms for the data analysis are presented to show how the raw data are converted into flyer velocity as a function of time. Representative results from hot-wire detonators are described.

VISAR Operating Principles

Laser velocity interferometry is based on the Doppler principle that light reflected from a moving object has a shift in frequency related to the velocity of that surface. This shift in frequency is superimposed on the original frequency of the light. The shift is detected by dividing the light returned from the target into two or more paths that appear equal (the optical length), but in fact have appreciably different delay times (transit time). The delay is accomplished by placing one or more etalons into one path. The apparent position of the mirror in the delay leg is closer to the beamsplitter by the amount:

$$x = h(1-1/n) \qquad (1)$$

where h is the length of the etalon and n is the index of refraction of the material. The corresponding delay time is given by:

$$\tau = (2x/c) \qquad (2)$$

where c is the velocity of light in free space. The factor of two in the equation is caused by the fact that the light passes through the etalon a total of two times, once before and then after reflection from the mirror.

In a single-leg VISAR, the incident light returned from the target is split by a beam splitter (BS) into two paths, each terminated by a mirror. A quarter wave plate in the delay path causes the P portion of the light to be retarded by a phase angle of 90° with respect to the S component. The light passes through the etalon once before reflection from the mirror and then a second time before returning to the BS. The light in the reference path travels a shorter distance because the etalon is not in position. The components are aligned so that the two returned beams are recombined on a different portion of the BS than where the initial separation took place. The BS splits the recombined light into two separate beams that are 180° out of phase. Either or both of the recombined beams can be used to detect the interference caused by the phase shift in the incident beam.

Passing one beam through a polarizing BS allows the P component to pass while reflecting the S component at 90° from the original direction. The electrical signals from the photomultiplier (PM) tubes are termed Data-1 and Data-2, for the S and P components, respectively. In a push-pull VISAR arrangement, the second recombined beam from the BS is transmitted to a different polarizing BS and to an additional set of PM tubes. The signals from these detectors are designated as Data-1′ (S) and Data-2′ (P). The signals contain the same interference information as the first path, but opposite in phase. The signal from each of the PM tubes in one leg is inverted electronically and added to the corresponding signal from the other leg. Thus, Data-1 is added to the inverse of Data-1′ and Data-2 is combined with the inverse of Data-2′. This eliminates spurious common mode signals such as self-light, which are equally added components in both PM tube signals. The signal amplitude of the combined output is twice that of a single PM tube.

A PZAT (piezoelectric angular translator) is used in Path 1 to mount the mirror, allowing minute changes in the path length to be induced by applying a corresponding electrical signal. This feature allows target motion to be simulated during setup to check the output of the detecting devices. A second purpose is that the light level at the start of the experiment can be set to cause the output of the S-component detector to be at the full-dark (minimum output) level. This simplifies the trigger level setting on the digitizers used to record the output of the PM tubes. Thirdly, minor adjustment to the parallelism of the mirrors can be done by applying a different voltage to each of the three segments of the PZAT.

The recorded output from the combined signals is used to determine the target velocity in accordance with the following equation:

$$u = \frac{\lambda \, \phi(t)}{2\tau \, (1 + \Delta\nu/\nu)} \; \frac{1}{1 + \delta} \tag{3}$$

where λ is the wavelength of the laser, $\phi(t)$ is the instantaneous phase angle between Data-1 and Data-2, $\Delta\nu/\nu$ is a correction for shock-induced changes in the index of refraction of a window, and δ is the correction for the etalon index of refraction dependence with the doppler-shifted wavelength. The correction factor δ is 0.0339 for the fused silica typically employed as etalon material. The correction factor $\Delta\nu/\nu$ is zero unless a clear "window" is placed against the rear surface of the target. From the definition of the velocity-per-fringe (VPF) constant, equation 3 can be rearranged to yield:

$$u = \frac{\lambda\ \phi(t)}{2.0678\ \tau} = VPF\ \phi(t) \qquad (4)$$

A "circle plot" is obtained by combining the Data-1 and Data-2 records, with Data-1 on the abscissa and Data-2 on the ordinate and time as a parameter. Because the two records are in quadrature, a perfect result would be a circle centered about zero. Loss of signal level causes the amplitude of the two records to decrease resulting in a shorter length instantaneous vector. The phase change is determined from the circle plot using the following:

$$\phi(t) = \arctan\left[\frac{\text{Data-2}(t)}{\text{Data-1}(t)}\right] - \phi(0) \qquad (5)$$

where $\phi(0)$ is the initial phase angle at time 0. Various factors can contribute to imbalance of the two signals with resulting distortion or displacement of the circle plot. Variations in amplitude or vertical shift of the raw data cause relatively small uncertainties in the final result, but specification of the center of the plot is important because it serves as the reference point for the phase angle determinations using equation 5.

In some instances, the acceleration of the target is so great that the fringe frequency (number of fringes produced per unit time interval) exceeds the capability of the electronics. In this instance, it is said that fringe information is "lost" and the standard data reduction will result in an abnormally low velocity. (The same principle applies for rapid decelerations except that the resulting velocity will be higher than the actual value.) Simply stated, the phase angle calculated from the data points before and after the loss region represents only the fractional part of the lost information, but not the integer number of fringes. Thus, the data analysis technique for these situations requires specification of the time when the loss occurred and the integer number of missing fringes. This process results in ambiguity because the number of fringes specified directly affects the value of all subsequent velocity values. Resolution of this issue is provided by the use of a dual-delay-leg VISAR as described in a later paragraph.

Dual-Delay-Leg VISAR

The ambiguity caused by rapid target acceleration is resolved by means of a dual-delay-leg VISAR. This system consists of two separate VISAR units monitoring the same target motion. The key element is that each system has a different VPF constant created by means of different length etalons. The technique uses an equal BS in the path of the light returned from the target to spilt the light into two portions. Each of the two beams is then directed to a separate, but nearly identical VISAR.

During the data reduction process following the event, the records from each system are analyzed separately and then compared. When fringes are added to the data of the one system, the resultant velocity must agree with the value obtained by a similar process for the other system. Because the VPF's are significantly dissimilar (typically at least 20% different), the fringe addition process will result in only a few combinations that provide agreement between the results from the two different systems. For example, assume system 1 has a VPF of 0.7, while system 2 is 1.0. Adding three fringes to the former results in a velocity change of 2.1 mm/μs. The obvious operation is then to add two fringes to system 2 to give an additional 2.0 mm/μs. Exact agreement between the two multiples is not required at this point because the final result is dependent on the fraction-of-a-fringe portion that is also available from the actual records. The accuracy of the fringe addition process is determined visually by comparing the resulting velocity profiles to judge the correspondence in the results.

Note that the ambiguity in the above example is not completely resolved because equivalent agreement could be attained by a simple multiple of the fringe addition. In other words, the fringe addition could as well have been six and four for system 1 and system 2, respectively. The determination would then have to be if these operations result in clearly unrealistic velocity values. For typical explosive components such as detonators or slappers that have terminal velocities on the order of 2.5 to 4.5 mm/μs, selecting VPF constants similar to those in the example will yield only one realistic set of velocity records through fringe addition operations.

Fixed-Cavity VISAR Component Acceptance Tester

The fixed-cavity VISAR (FCV) was developed with the objective of simplifying the operation of the more traditional table-type system. To this end, the goal was to replace most of the optical components with a system that does not require operator adjustment for proper operation. In the systems mentioned above, most of the components are mounted in laboratory fixtures that permit virtually endless adjustment. This capability is not desirable in a production-testing environment because of the high level of expertise required and the potential for compromising the results. After several years of development, the FCV has now been implemented into a production tester.

The cavity portion of the FCV consists of an aluminum tube nominally 42 mm in diameter and 100 mm long, which holds the optical components in precise alignment. The delay bar acts as an etalon placed directly in contact with the main BS. The light from the target is directed onto the rear surface of the delay bar, where it passes through the length of the bar before reaching the main BS at the front surface. The portion of light transmitted is reflected from a small front-surface mirror mounted on a PZAT. The fraction of the light reflected from the BS passes back through the delay bar to an 1/8-wave plate. The plate is mirrored on the rear surface to cause the light to pass back through to create a total delay of 1/4-wave (90°). The two beams are recombined at the delay bar/BS interface, with one portion passing out the front of the delay bar where it is reflected from a small mirror adjacent to the PZAT. The second portion of the recombined beam travels through the delay bar and out the rear surface.

The FCV module contains PM tubes and the VISAR cavity. Each of the PM tube fixtures has two tubes and a BS to split the light into S and P components. The PM tubes each have a high voltage input and a coaxial cable output. Light is transmitted from the target by a fiber optic cable, where it is expanded and collimated by a lens assembly on the FCV module. Adjustments are only required during the initial assembly for the position of the PM tube fixtures and the alignment of the collimating lens assembly. The entire module is placed in a closed box to prevent damage to the components.

A second module is used to direct the laser beam into the target chamber and collect the light returned from the target's surface (Module D). The open light beam from the laser source to the target is contained within a light-tight enclosure to prevent accidental exposure. The beam is reflected by two small mirrors so as to pass through a hole in the large collection mirror. The beam is focused onto the target placed in an explosive chamber by a lens (225 to 325 mm focal length). The target is placed on a fixture that allows three directions of motion through servo motor drives. The diffuse light returned from the target is collimated by the focusing lens and collected by the large mirror arrangement. Because the beam is expanded at this point, most of the light is reflected from the large collection mirror. A dichroic mirror deflects approximately 90% of the laser light into the telescope and fiber coupler where it is transmitted to Module A. The remaining 10% of the laser light and all of the broadband light is viewed by a standard TV camera that allows active viewing of the beam to target alignment. Only a minor portion of the return beam is lost by passing through the small drilled hole in the large collection mirror. The small turning mirrors are positioned so that this portion of the returned light does not enter into the laser cavity.

All of the electrical devices and the laser are controlled by the PC located in the tester rack outside the test area. The software has been designed to perform a series of checks on the system prior to the actual firing of the component. For example, a ramp wave signal generator causes the PZAT to change the length of the reference beam path in the cavity. This results in an apparent constant change in velocity that produces a number of "fringes" from the combined PM tube outputs. The tester verifies that the fringe patterns are of the correct frequency and phase relationship. It also calculates the positive and negative amplitudes to insure that the PM tubes are "balanced". Any signal loss or degradation in any of the light paths will cause the program to halt processing and warn the operator.

During a normal shot sequence, the operator is instructed to perform certain actions, such as supply the component serial number, verify bridgewire resistance, and actuate the firing button. Data reduction is fully automated to produce plots of the firing pulse current and voltage waveforms, shot statistics (i.e. function time, flyer velocity, standoff distance, etc.), and a determination of whether the unit passed or failed (based on preset specifications supplied by the component engineer). The program accumulates the test data and performs calculations to determine lot reliability and uncertainty parameters that are required by the Department of Energy. It then stores all of the information onto a removable hard disk cartridge for permanent retention.

Listing of Figures Used in Presentation

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BACKGROUND

HISTORY:

- TRADITIONAL TABLE-BASED VISAR'S REQUIRE CONTINUOUS ADJUSTMENT BY A SKILLED OPERATOR.
- PRODUCTION TESTER DESIGN PHILOSPHY DICTATES THAT A SYSTEM BE AUTOMATED AND THAT THE TESTER RESULTS BE UNAFFECTED BY HUMAN SUBJECTIVITY.
- THE FIXED-CAVITY VISAR IS VIRTUALLY FREE OF ADJUSTMENTS AND THEREFORE LENDS ITSELF WELL TO IMPLIMENTATION INTO A PRODUCTION TESTER.

PROJECT OBJECTIVE:

- BUILD FULLY AUTOMATED TESTER BASED ON VISAR TECHNOLOGY THAT CAN BE USED TO MEASURE THE VELOCITY OF EXPLOSIVELY DRIVEN FLYING PLATES.

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SYSTEM DESIGN CONSIDERATIONS

- EXISTING PT3506 SIP GAGE TESTER CHOSEN TO PROVIDE FIRESET STIMULUS, COMPUTER I/O, AND INTERLOCK CONTROL.

- VISAR MODULES AND EQUIPMENT ARE PLACED IN SEPARATE RACK.
  - FIBER OPTIC CABLE TO LASER AND COMPONENT
  - HPIB INTERFACE TO PT3506

- NO ABSOLUTE CALIBRATION STANDARD BY WHICH THE SYSTEM CAN BE CHECKED.
  - BEFORE EACH SHOT, USE COMPUTER CONTROL TO VERIFY ALL SYSTEM PARAMETERS THAT COULD AFFECT TEST RESULTS
  - PROVIDE COMPONENT FIXTURE WITH KNOWN STANDOFF TO COMPARE TO DISPLACEMENT RECORD

- UNIT SURFACE PREPARATION:
  - SURFACE OF COMPONENT PREPARED BY MICRO-SAND BLAST
  - SURFACE DIFFUSENESS MEASURED BY SCATTEROMETER

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APPROACH

- MINIMAL NUMBER OF OPERATOR ADJUSTMENTS OR INPUTS
  - FIXED-CAVITY TECHNOLOGY
  - TESTER CONTROLS OPERATION
  - AUTOMATED DATA REDUCTION TO VELOCITY AND DISPLACEMENT PLOTS
- BUILD TWO IDENTICAL SYSTEMS
  - UNIT 1 AT UNIDYNAMICS-PHOENIX
  - UNIT 2 AT EG&G-MOUND
- ABLE TO MEASURE HOT-WIRE AND EBW DETONATORS
  - CAN BE USED FOR SLAPPERS

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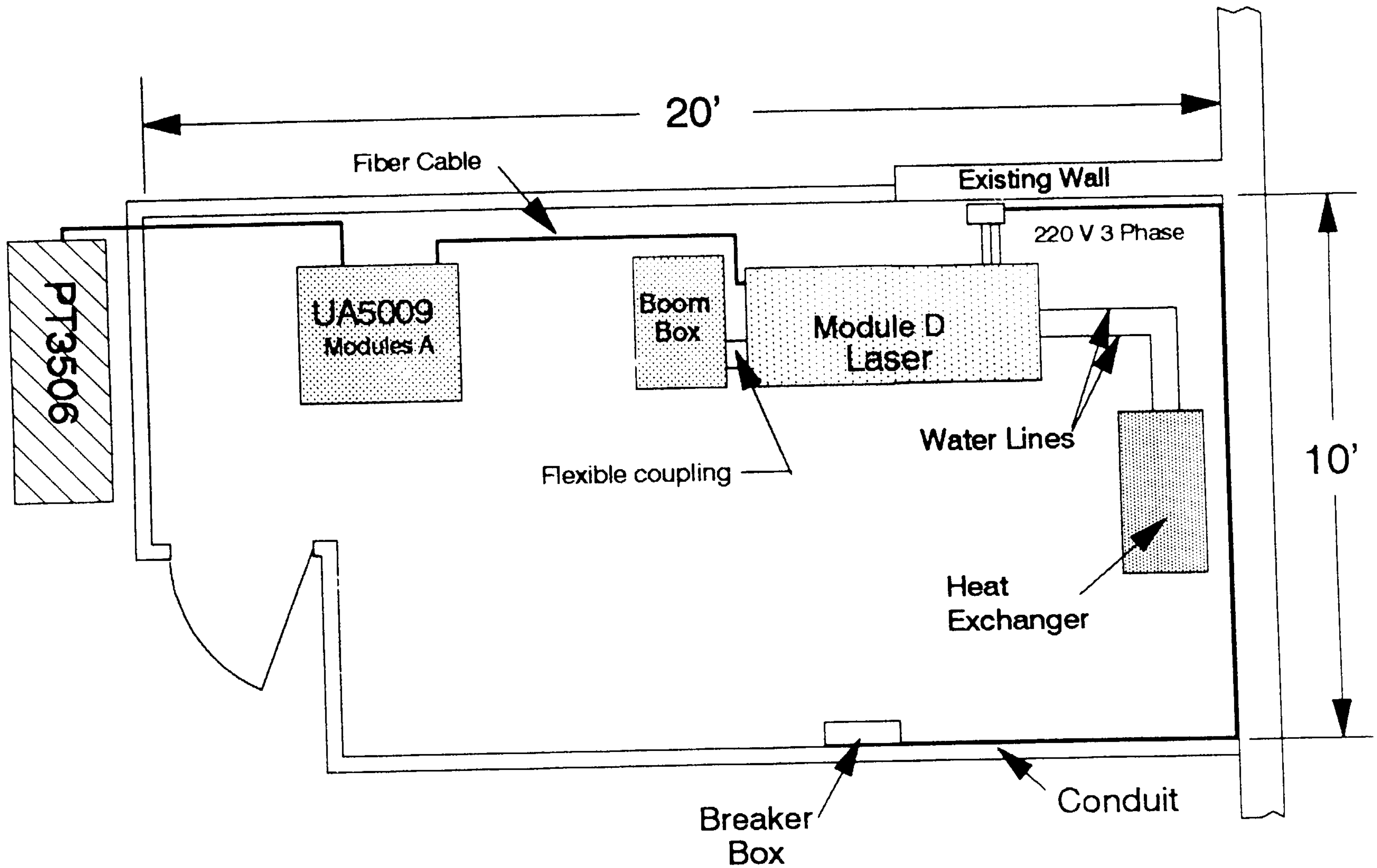
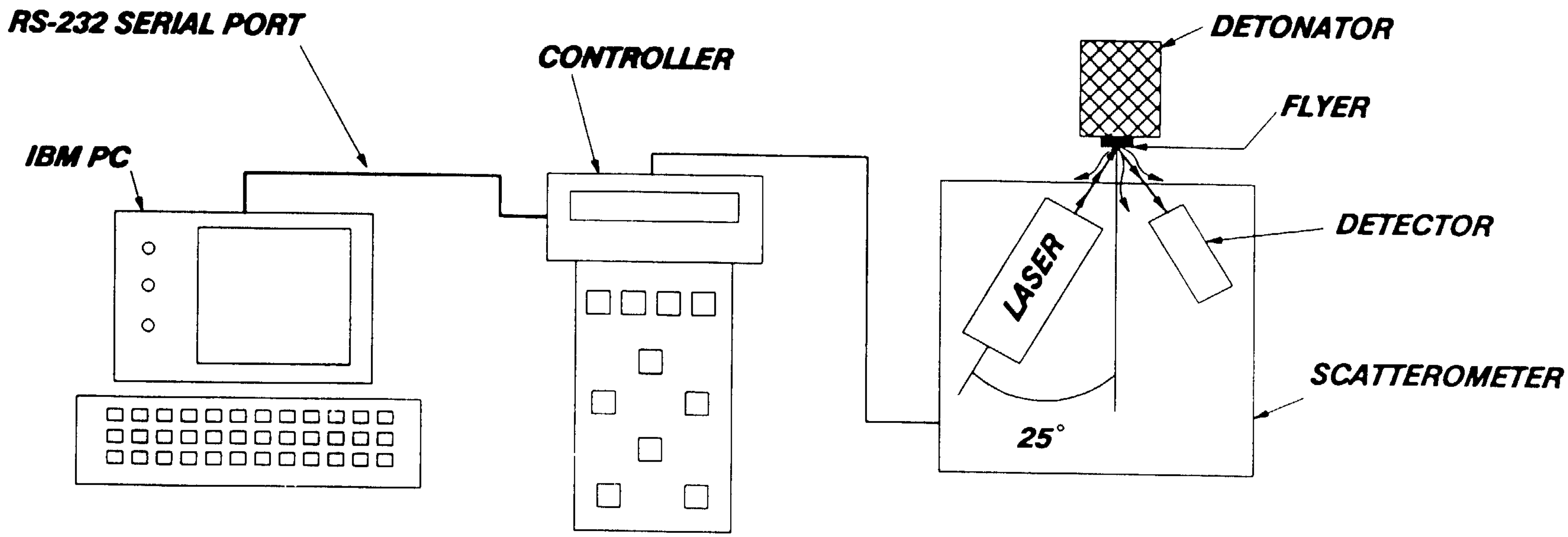
VISAR TEST BAY AT UPHX



OPTICAL SYSTEM FOR SURFACE CHARACTERIZATION OF VISAR TARGETS



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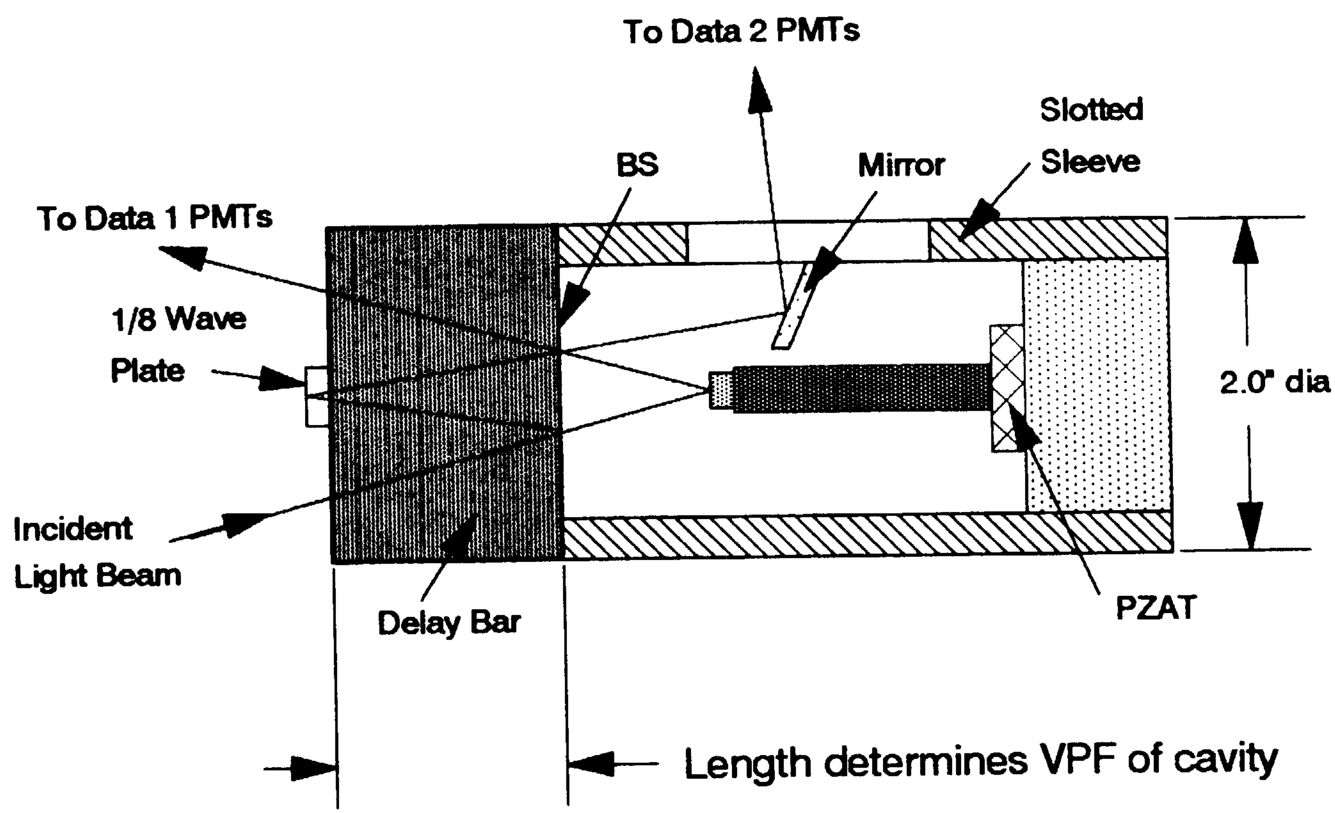
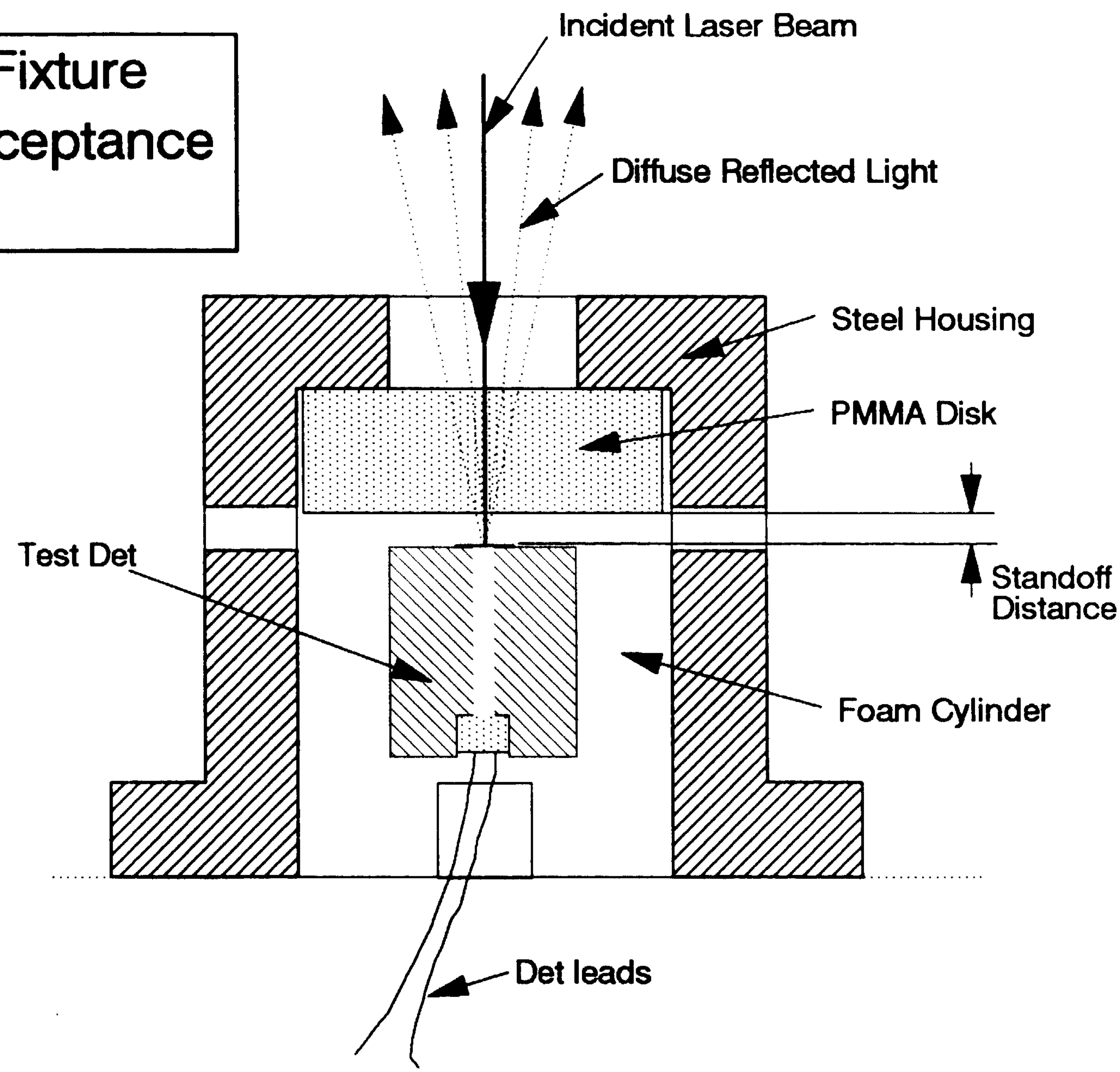
Fixed-Cavity Interferometer



Detonator Fixture for FCV Acceptance Tester



RESULTS/TYPICAL DATA

- RAW DATA:
  - FOUR CHANNELS OF INTERFERENCE DATA FOR EACH MODULE
  - COMBINATION OF INTERFERENCE WAVEFORMS GIVES "FRINGE" RECORDS (DATA 1 AND DATA 2)
  - CIRCLE PLOT CREATED BY PLOTTING DATA 1 AGAINST DATA 2
  - VELOCITY INCREMENT IS PROPORTIONAL TO PHASE ANGLE BETWEEN TWO CONSECUTIVE POINTS (ONE TIME INTERVAL)

- VELOCITY DATA:
  - VELOCITY HISTORIES FROM THE TWO LEGS SHOULD AGREE WITHIN EXPERIMENTAL UNCERTAINTY
  - ABRUPT INFLECTION POINT SHOULD APPEAR ON BOTH RECORDS WHERE THE FLYER CONTACTS THE STOPPER PLATE

- DISPLACEMENT DATA:
  - OBTAINED FROM TIME INTEGRATION OF THE VELOCITY HISTORIES
  - INFLECTION POINT COMPARED TO KNOWN STANDOFF DISTANCE

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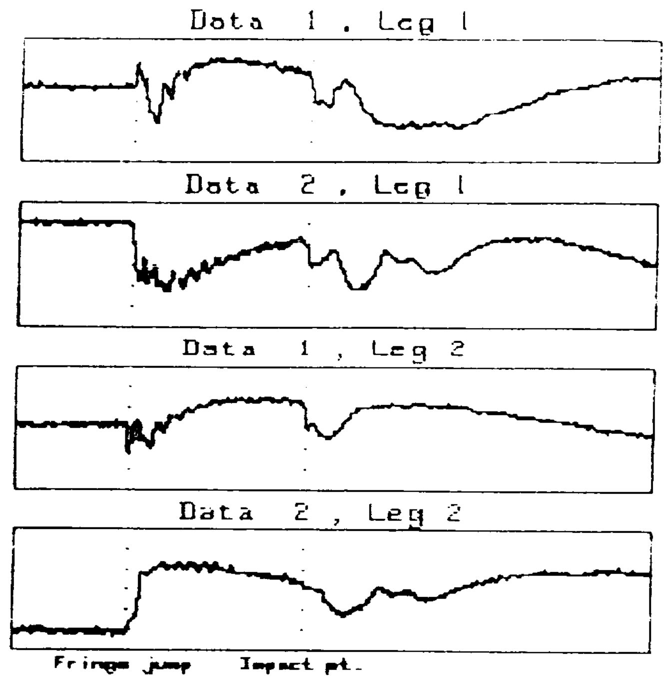
DETONATOR
AMBIENT ROOM FIRING
TESTER: Test-O-matic S/N 001
SERIAL NUMBER 000018

REDUCTION STATISTICS

Start reduce time:	-5.E-7
Stop reduce time:	2.E-6
Maximum dv/dt (L1):	7.2427E+7
Pt 1st motion (L1):	1996
Maximum dv/dt (L2):	6.2643E+7
Pt 1st motion (L2):	1971
Add fringes L1:	2
Add fringes L2:	1
Maximum dv/dt (L1):	2.131E+8
Impact pt (L1):	2327
Maximum dv/dt (L2):	2.7235E+8
Impact pt (L2):	2324
Impact distance L1:	1.9096
Impact distance L2:	1.881



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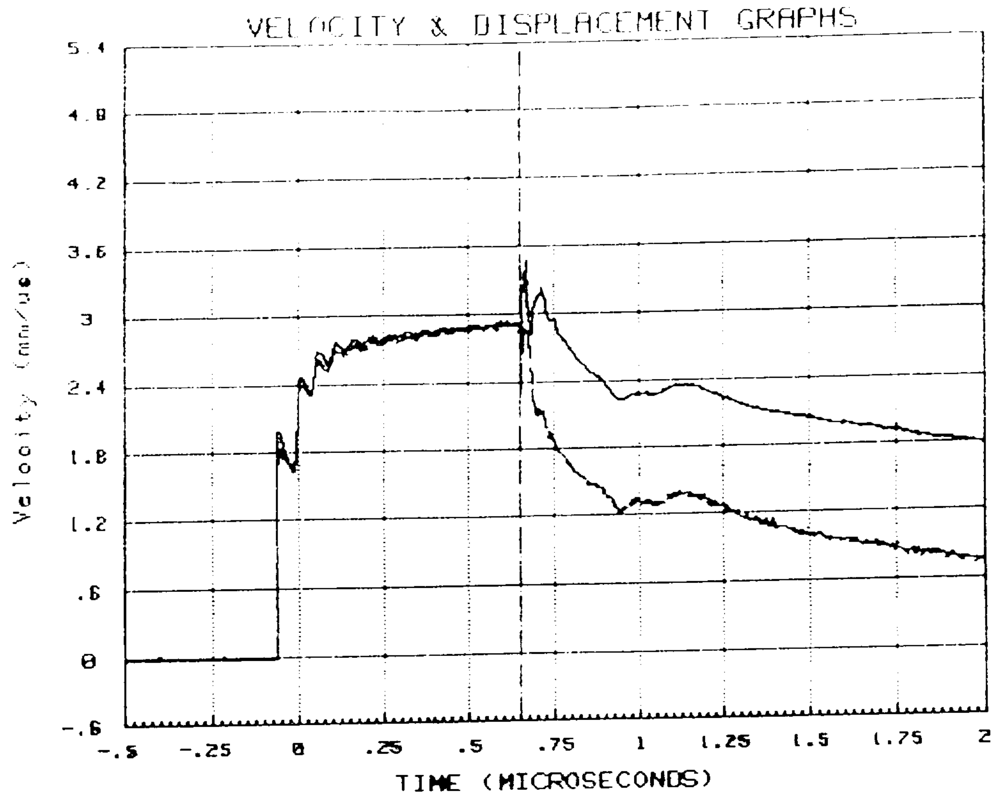

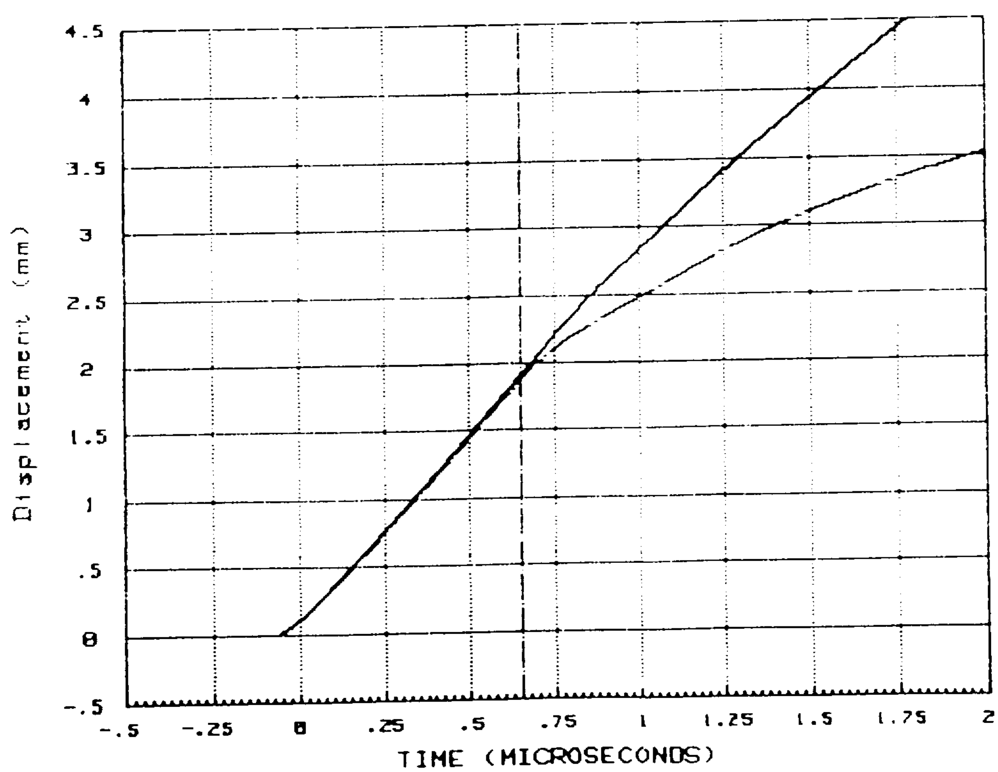

CHECKOUT TEST RESULTS

SHOT NO.	DET NO.	VELOCITY (MM/US)	DISPLACEMENT (MM) MEAS	PRETEST
1	01	2.88	2.78	2.03
2	34	2.87	2.00	2.03
3	16	2.93	2.04	1.91
4	18	2.90	1.91	1.91
5	86	2.89	1.91	1.91
6	40	2.90	1.71	1.79

UNIT 1 MEAN VELOCITY - 2.88 0.02 MM/US (6 TESTS)

SNL AREA II VISAR - 2.833 0.036 MM/US (30 TESTS)

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CONCLUSIONS

- SUCCESSFUL RESULTS WERE OBTAINED FOR EACH OF THE TEST DETONATORS FIRED TO DATE.
- VELOCITY RESULTS AGREE WITH PREVIOUS FULL TABLE DATA.
- STOPPER PLATE PROVIDES ACCURATE FIDUCIAL FOR CALIBRATION OF DISPLACEMENT RESULTS.
- SYSTEM DIAGNOSTICS ARE RESPONSIVE TO CHANGES IN HARDWARE OR COMPONENTS.
- SURFACE PREPARATION AND MEASUREMENT PROVIDES ACCURATE INDICATOR PRIOR TO PLACEMENT INTO FIXTURE.
- SYSTEM CAN EASILY BE EXTENDED TO MEASURE EBW AND SLAPPER DETONATORS.

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