Coupling Experiment and Simulation in Electro-magnetic Forming Using Photon Doppler Velocimetry*

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Abstract

Modeling electromagnetic forming processes is in many ways simpler than modeling traditional metal forming processes. In electromagnetic forming the problem is often dominated by inertial acceleration by a magnetic field. This is a much better posed problem than the more traditional ones that are often dominated by complex three dimensional constitutive behavior and frictional effects. However, important aspects of the problem are dominated by the constitutive properties of the material, and often electromagnetic forming is performed in a regime where there is little reliable material strength data. Strain rates are often high (10^2 to 10^4 s^{-1} is the typical range for electromagnetic forming). Also, heat is generated both by ohmic heating as well as by plastic deformation, and peak temperatures can be quite high. Also, while high-temperature, high-strain-rate data is scarce, there is little or no data in cases where temperature rises significantly over very short times (tens of micro-seconds) as happens in electromagnetic metal forming. This rapid temperature rise is very important to the material response because the short time scales largely preclude the material from recovery and recrystallization processes and precipitates cannot dissolve as they normally would in an age-hardening alloy in these time scales.

This presentation will show how advanced instrumentation, particularly the Photon Doppler Velocimeter (PDV) can be coupled with electromagnetic forming and provide both avenues to characterize material as well as to provide very critical tests of numerical models of the process.

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Keywords

Sheet metal, Forming, Aluminum

1 Introduction

High speed and impulse metal forming methods are an ideal complement to traditional processes in stamping, cutting, hemming and welding [1]. This potential has been clear for some time, but these techniques have still seen very limited utilization to date. One of the primary issues is that while design methods for traditional processes are well-established, they are presently being developed for these impulse based methods. Once they are robust, available and have been validated, its reasonable to expect the design and implementation of impulse-based or impulse-augmented methods, such as electromagnetic forming, will become much more routine.

It can be argued that the key to effective electromagnetic forming design is related to the design of electromagnetic actuators that provide the proper spatial distribution of magnetic pressure. The temporal variation of the pressure is controlled by the electrical (LRC circuit) characteristics of the capacitor bank system. The magnetic pressure typically produces stresses in the workpiece that can exceed the flow stress in the material by a large factor. The pressure in excess of what is needed for yielding goes into accelerating the workpiece in accord with Newton's First law. To instrument the process to collect data that will provide a critical check on a model, it is probably more important to be able to measure rates of acceleration (with microsecond time resolution) than simply measuring average or peak velocities). This paper describes the use of an instrument, the Photon Doppler Velocimeter, that is capable of such measurements, which is also robust and can make measurements in tight geometric conditions, and will describe its use in the analysis of electromagnetic metal forming.

2 The Photon Doppler Velocimeter (PDV)

The traditional instrument for capturing the surface velocity has been the Velocity Interferometer for Any Reflector System (VISAR) which was developed by Barker and Hollenbach at LLNL in 1972. These instruments have been the standard for velocity measurement, but have significant shortcomings. Most importantly they essentially require dedicated technicians and data analysis is time-consuming and requires some judgment. As a result this is an expensive technique that is not suited to use in 'difficult' environments, as may be encountered in manufacturing facilities. Recently Strand and co-workers [2] at LLNL introduced a new method of measuring the velocity of free surfaces with exceptional temporal resolution, the Photon Doppler Velocimeter (PDV). This equipment leverages newly-available fiber optic lasers and components as well as higher speed oscilloscopes. The equipment represents a breakthrough in robust and inexpensive velocimetry. The equipment is durable, relatively inexpensive, and easy to use and requires very little specialized training or background. Most-importantly data analysis is has minimal ambiguity and can be performed rapidly. The technique provides sub-micron displacement resolution, temporal resolution in the nanosecond range, and it is straightforward to collect at multiple locations with several channels. Maximum measurable velocity depends upon the speed of the oscilloscope and instrumentation, and PDV's that can measure in excess of 10km/s have been demonstrated. This equipment can also be easily packaged for use in electromagnetic forming facilities that are even in industrial environments, because only a thin fiber optic line (with an inexpensive probe on the end) needs to run between the instrumentation and the target. A schematic of the PDV system is shown in Figure 1.

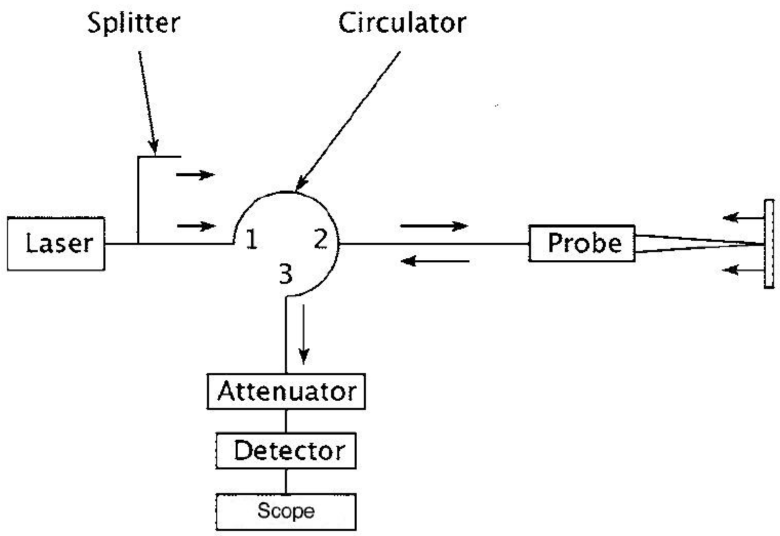

***Figure 1**: Schematic diagram of a Photon Doppler Velocimeter (PDV) system.*

This approach has been adopted at Ohio State University and the key components of the OSU PDV system include:

Laser — The heart of the system is a erbium high power fiber laser that has a very narrow spectral linewidth. The OSU system is based on an NP Photonics 1550 nm, 1000 mW output power fiber laser with a linewideth of <5kHz.

Splitters — Divide laser output to several fiber optic ports for multi channel operations or phase comparison.

Circulators — Directional fiber optic device guides light from the laser out to the probe and reflected light from the probe to the detector. We use a 1 watt JDS Uniphase device.

Detectors — Short rise time biased photodetector, high bandwidth comparable to oscilloscope. Newport model 818s detectors are used in the OSU system.

Probes — Collimating or focusing with built in reference partial reflection surface. Many types are available and used.

Oscilloscope — A 1 GHz, 5 GS/s, LeCroy Wavesrufer 104MXs with 4 channels is used in this system. This Oscilloscope has a relatively large amount of data storage, of 10 Mpts on each channel. This allows storage for periods up to 2 ms at full speed on each of the 4 channels.

The basic physics of the PDV are actually relatively simple, a moving surface produces Doppler shifted light, which is then recombined with the incident light signal to produce a beat frequency. This beat frequency is proportional to the velocity of the moving surface, and can be analyzed with modern digitizing equipment to yield velocity vs. time profiles with good accuracy. Though the principles are simple, the actual measurements are non-trivial, and require very modern electronics.

In regards to data analysis, there are multiple methods that are possible. A full beat cycle is observed for every 775 nm of sample motion (one half of the incident wavelength, i.e. 1550/2 nm), so a simple velocity calculation can be done from the raw data (i.e. velocity = distance/time, so velocity = 775 nm/(period of one beat cycle)), also, a Fourier Transform can be performed to analyze the changes in beat frequency in order to generate velocity vs. time profiles. Due to the Nyquist limit, the minimum sampling rate is twice the bandwidth and or good analysis, it about a minimum of 5 sampling points are required for each oscillation of the beat wave. By these considerations, the basic capabilities of the OSU system are that it can measure 4 independent velocity channels at velocities from zero to about 775 m/s over a period of up to 2 ms. This can correspond to a displacement of about 1.5 m for the maximum speed acting over 2 ms. Typical measured displacements are on the order of millimeters to centimetres, as is shown in the following examples

3 Ring Expansion and Constitutive Determination

There is a great need for data on the mechanical behavior of metals at high strain rates. This is not only importan for understanding high strain rate forming processes, but also for machining, crashworthiness, armor and anti-armor studies as well as for basic scientific understanding. The Hopkinson-Kolsky bar method is the dominant approach, but this method is difficult to run in true uniaxial tension and the process of testing and data analysis is rather time consuming.

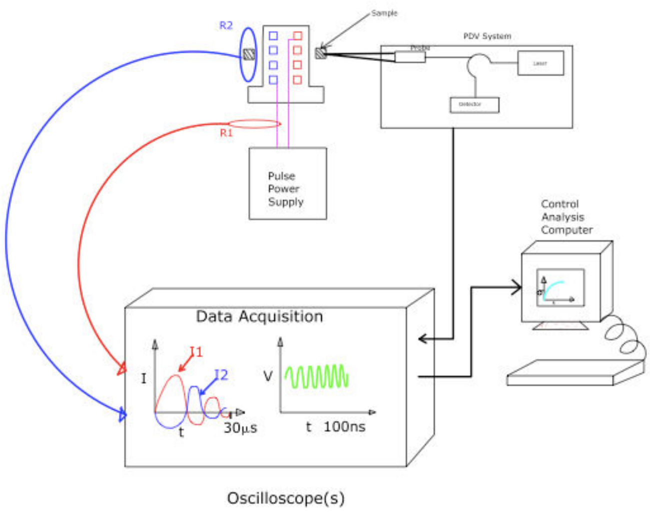

***Figure 2**: Schematic of the instrumented dynamic ring expansion test that is being developed for the measurement of tensile stress-strain relations at high strain rate.*

The electromagnetically driven expanding ring has been proposed as a test for high strain rate tensile testing by Niordson [3]and was developed to a fairly high degree of sophistication by Gourdin ([4,5]) This is a very elegant test in that it provides true uniaxial tension and can drive to strain rates over 10^4 s^{-1}. It is also a very useful test in studying high strain rate ductility and fragmentation behavior [6, 7]). This test never became widely used for a few principal reasons: 1) The Velocity Interferometer Systems for Any Reflector (VISARs) that were used to measure expanding ring velocity (and deceleration) were very difficult to use routinely, 2) To keep the boundary conditions simple when determining constitutive tests, only very sender rings were used in testing. This limited the strain rates that could be achieved, as resistive heating is very strong in slender rings, and 3) Experimental analysis, particularly using VISAR's is rather time consuming and not typically straightforward. This section makes the case that with some modifications to Gourdin's essential test system and by using modern instrumentation and analysis, the expanding ring test can be a very efficient and effective test for acquiring high strain rate mechanical strength data in tension. In addition this test is able to work easily over a wide and controlled range of strain rates and temperatures.

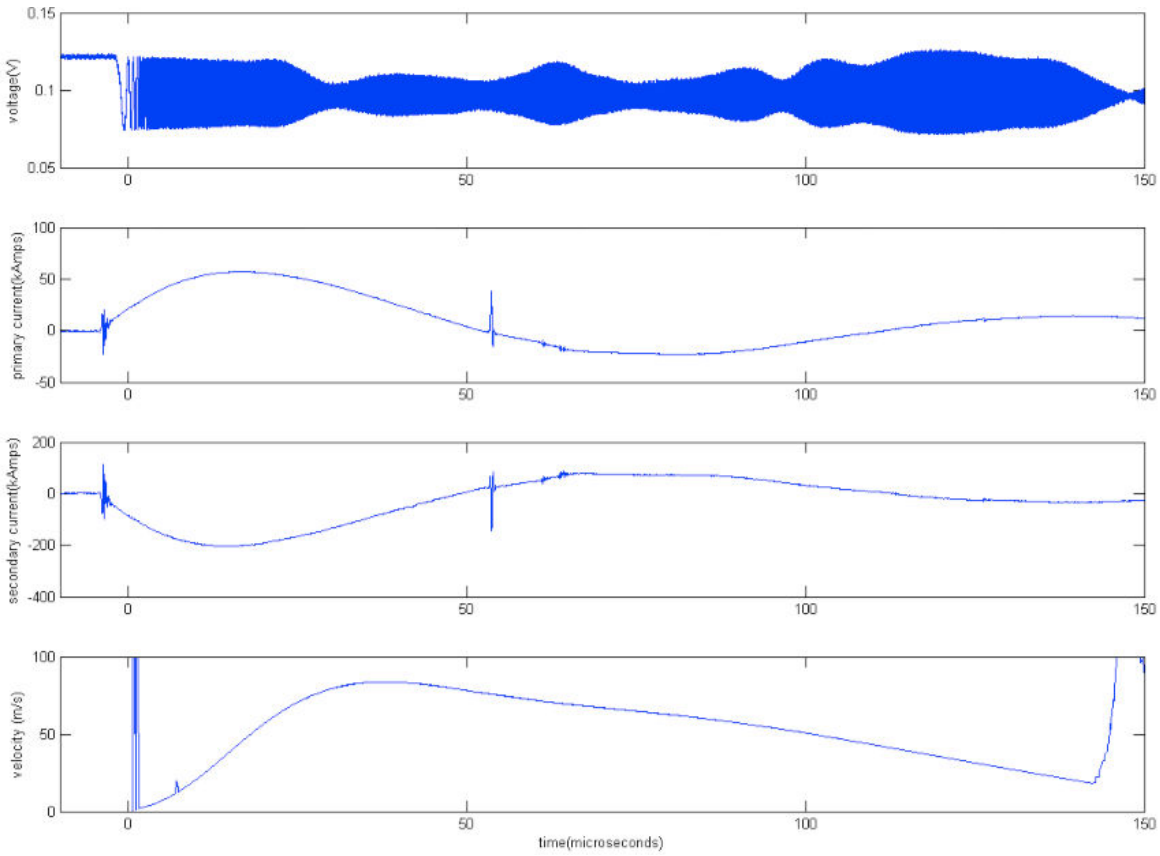

Figure 3*. Raw data from an experiment in expanding an annealed short copper tube with a 1.44 kJ electromagnetic pulse. From top to bottom the curves respectively show: 1- the raw optical amplifier signal, 2- the primary current in the 5-turn coil, 3- the induced current in the ring and 3- the measured ring velocity as a function of time.*

The basic approach for the experiment is shown in Figure 2. Standard electromagnetic ring expansion driven by capacitor bank discharge is used to expand the test ring form a fixed solenoid coil. The instrumentation used allows precise measurements of a number of quantities with exceptional temporal resolution during the experiment. A standard commercial Rogowski coil allows measurement of the primary current. A second Rogowski coil made from fine wire loops directly around the sample ring allowing direct measurement of the induced current with time. The PDV system gives sample position with time with temporal resolution on the order of nano-seconds and spatial resolution on the order of microns. This data can be singly or doubly differentiated with time to give velocity or acceleration with time for the ring.

The resulting data from an example launch of an annealed copper ring from a 5-turn coil at a 1.44 kJ launch is shown in Figure 3. Here the raw signal from the light detector is shown in the top graph primary and secondary currents are shown in the next two graphs and the ring velocity with time is shown in the last graph. The ring velocity is measured based on the period of each optical oscillation. Thus, this plot contains literally thousands of independent measurements of ring velocity, so acceleration values can be estimated very well. Automated methods are now being developed to turn these data into stress-strain curves for the rings.

There are two ways to analyze the deformation of the ring to determine the stress versus strain behavior of the metallic workpiece. The ring can be considered to be slender and a one-dimensional analysis can be used or for more complex situations full numerical analysis can be used. Let us consider the simpler one-dimensional approach first. The basic geometry of a short tube and the forces that act on it are shown in Figure 3. The important balance is between the magnetic pressure created by the electrical discharge and the hoop tension in the ring. Inbalance causes acceleration of the ring. The basic governing equation for this is:

$$\frac{dV_r}{dt} = \frac{P(t)}{\rho h(r)} - \frac{\sigma\left(\varepsilon\left(r\right)\right)}{\rho r} \tag{1}$$

Where t, r, h, and ρ are time, ring radius, ring width, and ring density, respectively. V_r is radial velocity. P(t) is the time-varying magnetic pressure. Ring flow stress as a function of strain is written as $\sigma(\varepsilon(r))$. When volume conservation of the ring is included, the equation can be re-cast as:

$$\frac{dV_r}{dt} = \frac{P(t)r}{\rho h_o r_o} - \frac{\sigma\left(\varepsilon\left(r\right)\right)}{\rho r} \tag{2}$$

What is important here is that every term, except for the ring flow stress can be explicitly measured or estimated at each time step. Thus, by using the kinds of data in Figure 3, each term except for the flow stress can be very closely measured or approximated and then the only remaining term, the ring flow stress, can be solved for. At each short time increment the flow stress and ring strain can be calculated and a traditional stress-strain curve can be displayed.

The approach above is largely Gourdin's original method. He strived to use very slender rings so that the equations would be nearly one-dimensional. Modern simulation software provides another method. As described in a previous publication by L'Eplattenier and co-workers [8]. Data of the type in Figure 3 can be used as input finite element simulations of ring expansion to coupled by LS-OPT and from this, the parameters for a constitutive equation can be optimized for.

This general approach offers many advantages for developing high strain rate constitutive behavior. The tests are carried out in pure tension. Tensile ductility parameters are recovered. Constitutive relations are revealed. And the geometries need not be simple. By varying the cross section of the ring, for example, the amount of heat generation can be varied at a given strain rate. These tests are thus done under conditions that are quite faithful to those seen in electromagnetic forming.

4 Flyer Launch from the Uniform Pressure Actuator

Recently the Uniform Pressure actuator has been conceived, analyzed and shown useful for several applications [9, 10]. To present only analytical estimates of the sheet acceleration and velocity have been available and impact velocity is one of the most critical parameters in this kind of forming. Figure 4 shows schematically how a PDV system has been added to the Uniform Pressure actuator system to launch 1mm thick aluminum sheet. In these particular experiments the probe could only measure to a distance of under about 400 µm. However the example data shown in Figure 5 shows that UP actuator is able to reach velocities in excess of 50 m/s over an acceleration distance of under 400 µm, in a manner that is spatially uniform. In the future this capability will be routinely used with the UP actuator system to measure sheet-die impact velocities.

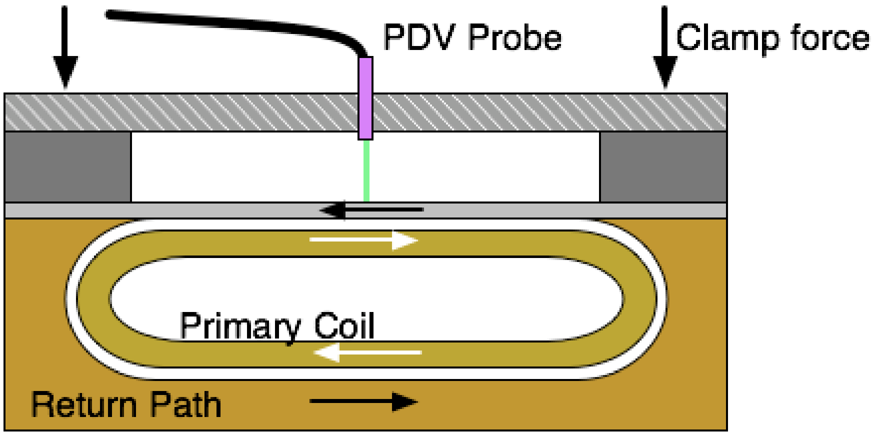

Figure 4*: Schematic diagram of use of the PDV system to measure velocity and acceleration of a metal sheet launched using the uniform pressure actuator. The white arrows show the current in the primary coil and the black arrows shown the induced current in the return path.*

5 Flange Impact

One application of electromagnetic impulse that has received considerable attention recently is impact seam welding. The recent work of Aizawa and Kore [11-14] and their respective colleagues have shown that this can give high strength welds, can weld dissimilar metal combinations that cannot be welded by fusion and most significantly, Aizawa's work has shown that very modest energies (about 2kJ) are able to create welds in aluminum or aluminum to steel with sheet thicknesses on the order of 1mm and joint lengths of about 10 cm. This low energy requirement makes commercialization of this technique quite simple.

From work in collision welding driven by explosives (explosive welding) it is well known that collision welding takes place when the flyer and target have an sufficiently high impact velocity (usually between 100 and 500 m/s) and an appropriate impact angle (typically 10° - 20°). Figure 6 shows schematically how sheet collision welding can be carried out in a well-packaged and efficient manner and how the PDV can be used to measure impact speed and collision angle. In this example either short focal distance or columnator probes are used and they are spaced at known distances. Since the probe signal can be analyzed both for displacement and velocity, at any time the position and velocity at each of the 3 spatial coordinates spaced along the X direction is known. Thus the impact velocity and angle can be explicitly known and compared to numerical models. Work integrating measured impact parameters with numerical models and interface microstructure development is underway currently at Ohio State.

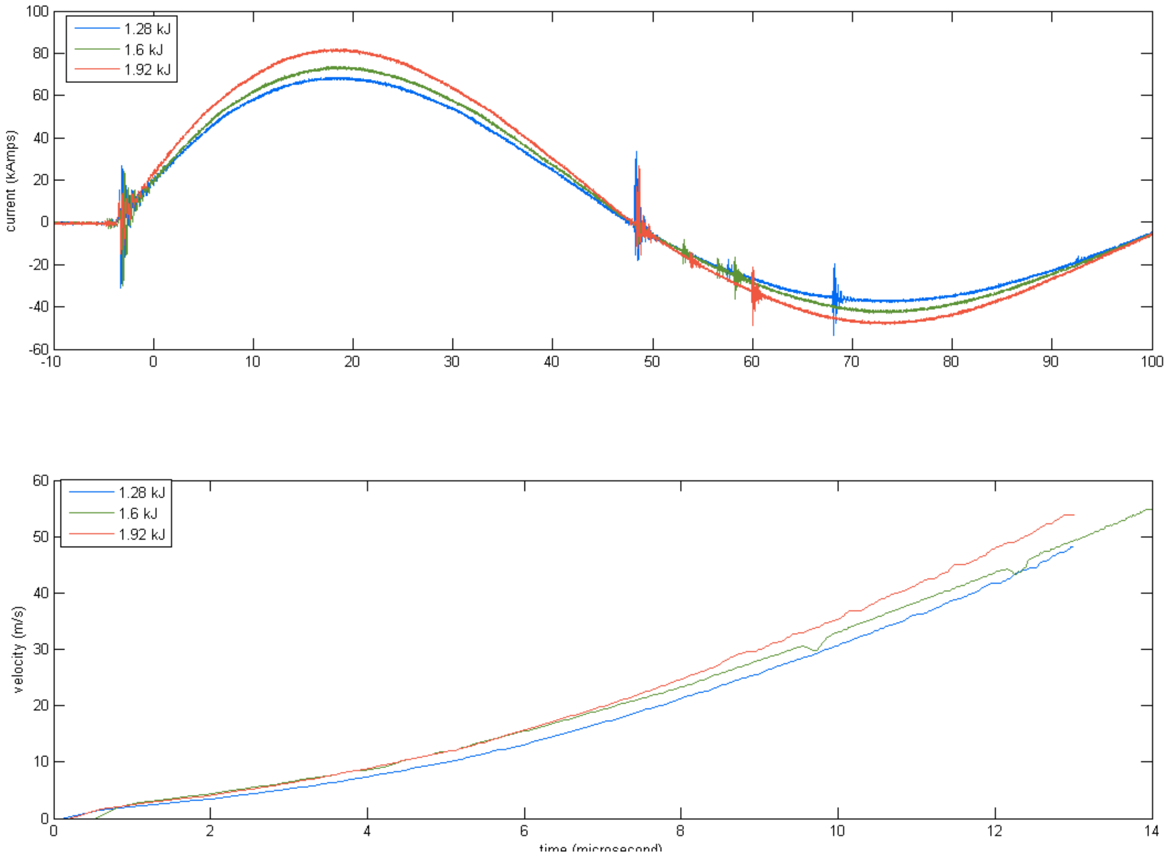

***Figure 5**: Induced current and measured velocity in the launch of a 1mm thick copper sheet from a uniform pressure actuator at launch energies of 1.28, 1.6 and 1.9 kJ respectively.*

The PDV system has been used to measure the impact velocity on one of the magnetic pulse welding actuators. A preliminary velocity profile is shown in Figure 7, which indicates the impact velocity is around 300m/s. At present signal analysis techniques are being improved. The very encouraging aspect of this is that despite the fact the flange bends and distorts in flight, a good optical beat signal can be obtained through the entire period of the experiment.

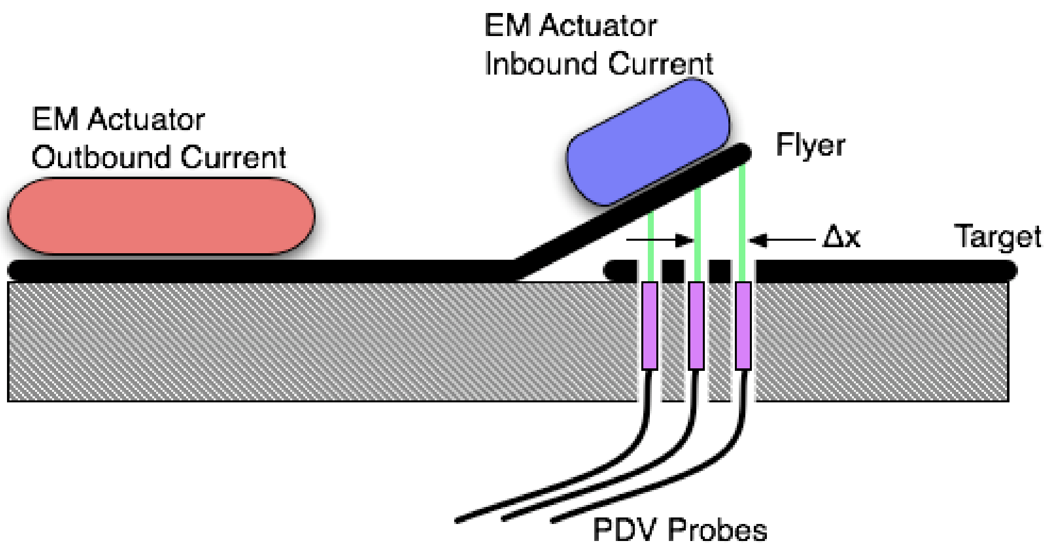

Figure 6: *Implementation of the PDV to study impact seam welding.*

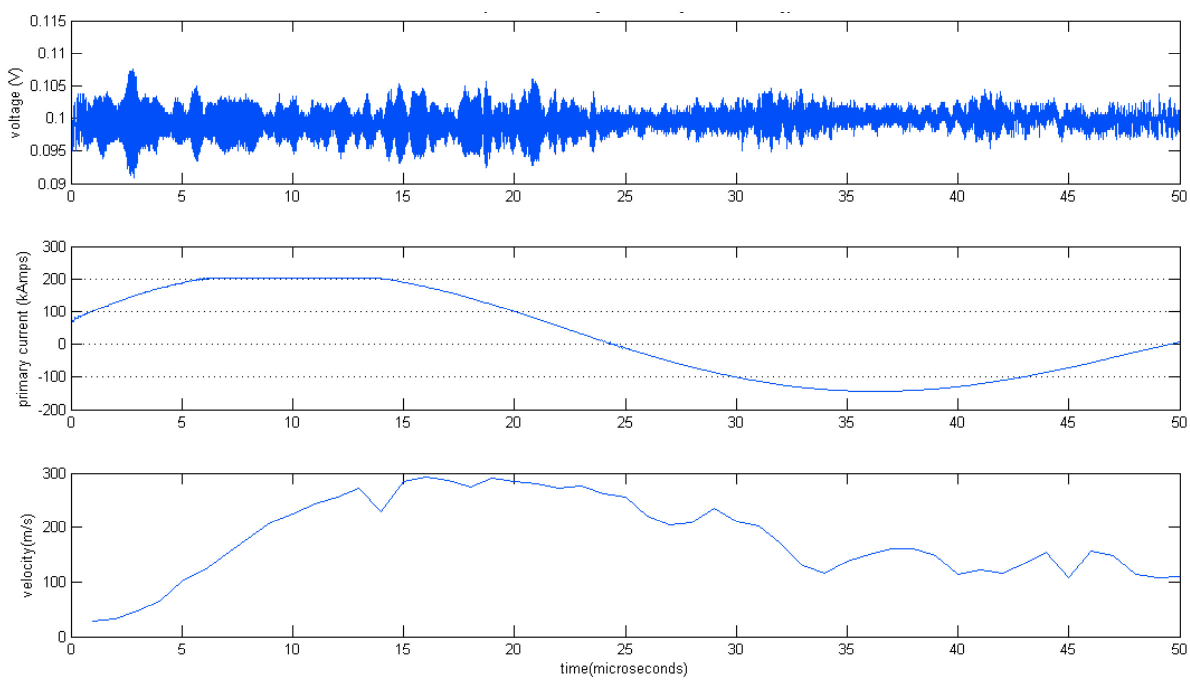

Figure 7: *Primary current and impact velocity profile on magnetic pulse linear seam welding system. The launch energy is 4.8kJ and the stand off distance is 5.7mm.*

6 Summary / Concluding Remark

This paper details the development of a relatively low-cost, robust and easily configured photon doppler velocimeter (PDV). This device can give exceptionally precise and accurate measurements of local velocities, displacements and accelerations in electromagnetic forming experiments. Its use has been demonstrated in several practical embodiments of electromagnetic forming.

This diagnostic tool can provide better estimates of material constitutive behavior in relevant rages of strain rates and temperatures, provide measurements of velocities and contact angles in processes such as welding and provide data sets for critical evaluation of numerical models.

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