# Dynamics of shocks in laser-launched flyer plates probed by photon Doppler velocimetry

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**Abstract**. We investigated the launch and impact with glass targets for four different thicknesses of Al laser-launched flyer plates by monitoring the flight with photon Doppler velocimetry (PDV). The amplitudes and damping times of the reverberating shocks in the flyers, created by short laser pulse launching, were investigated as a function of pulse duration using 10 or 20 ns laser pulses. The shorter pulse duration showed a surprisingly more efficient damping process in the thicker flyers. The durations of the supported shocks in the glass targets were also measured as a function of flyer thickness. The supported shock durations were significantly shorter than the common picture of shock round-trip transit time in the flyer.

## 1. Introduction

Thin flyer plates launched by lasers provide a convenient method to rapidly acquire shock data. Our laser-driven flyer plate apparatus generates up to hundreds of shots per day. However thin flyer plates provide shock durations that are only nanoseconds, so shocks may not be in steady state and slower processes such as chemical reactions may not be triggered. Short laser pulse launching creates reverberating shocks in the flyer during launching. If the reverberations do not die out before impact, multiple velocities will be present in the flyer that complicate the characteristics of the shocks in the targets. In this study we investigate the ringing in thin Al foil flyer plates 0.001-0.004” thick (approximately 25-100 μm) using two different launch pulse durations, and we measure the durations of steady shocks in glass targets.

There are two ways to deal with the laser-generated reverberations in the flyers. The flight path can be made long enough for the reverberations to die out, or the laser launch pulse duration can be increased. Longer flight paths provide opportunities for the flyer to twist and tilt, and may compromise planar 1D impacts. Longer-duration laser pulses reduce the peak energy experienced by the flyer, providing a more gradual impetus that reduces the sudden shock to the flyer. But with high-energy lasers such as Nd:YAG, creating pulse durations longer than 10 ns may require costly modifications such as complicated cavity-stretching systems or special oscillator-amplifier combinations. In this study, we lengthen the pulse durations by passing the pulses through an external-cavity reflective pulse stretcher.

When a flyer impacts a target, counterpropagating shocks are launched in the target and in the flyer. The duration of the shock in the target has frequently been approximated as the round-trip time in the flyer, with some claims that it should be even longer [1-6]. The round trip is about equal to the time for the shock in the flyer to travel from the target to the back surface of the flyer plus the time for the rarefaction created there to reach the sample. One issue in such discussions is how to define the shock duration. Here we define the duration as the time interval when the material velocity in the target remains constant. That time interval defines what is termed a "fully-supported" shock. Of course the shock front will continue to propagate with less than full support for a while after the material velocity begins to decline, and that is the cause of ambiguities in shock duration definitions. In the present study, we use PDV to monitor the speed of the flyer surface as it moves in contact with a glass target. This speed is the speed of the flyer/target interface and it is equal to the material velocity in the target. We then directly measure the time intervals where the flyer plates create steady, constant-speed motion of these interfaces. Because the shock durations are nanoseconds, we have developed analysis techniques to maximize the temporal accuracy of data from our PDV apparatus.

## 2. Experimental
Our experimental apparatus has been explained in detail elsewhere [5], and is briefly explained here. A schematic is shown in figure 1.

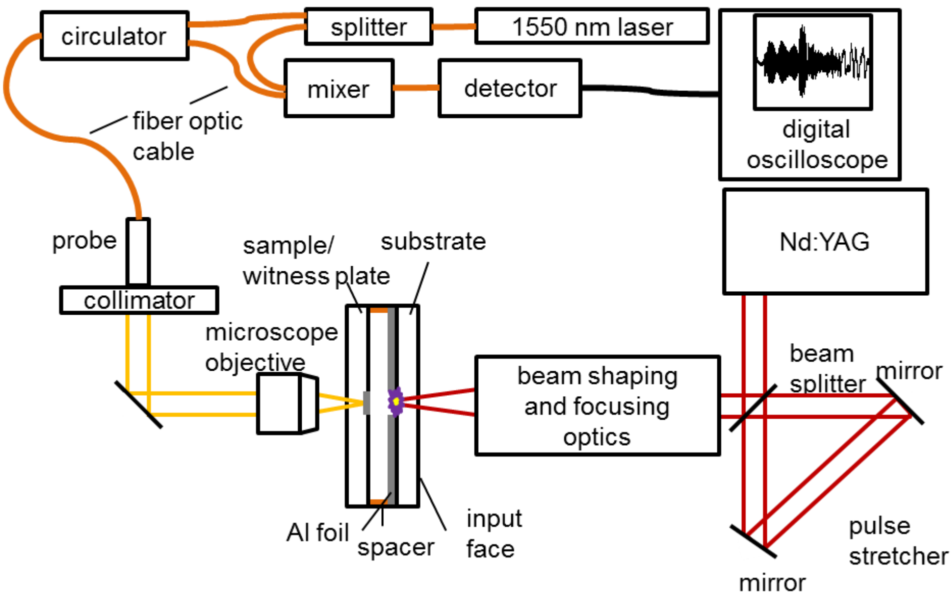


**Figure 1** Laser launching and PDV detection apparatus

We launched flyers using a Nd:YAG laser (Quanta-Ray Pro 350 from Newport Corp.) that produced 10 ns pulses with up to 2.9 J energies. The pulses were sent through shaping optics to provide a flat-top spatial profile with a focal diameter of ~700 μm. When the laser pulses were incident on the foil, a rapidly-expanding plasma was created that launched the flyer. The flyer plates were launched across a nominal 375 μm gap before impacting the glass target (witness plate). The reflective pulse stretcher was a recent addition that provides a stretch factor of two, so we can easily switch from 10 ns to 20 ns pulses by inserting or removing the beamsplitter [7].

Our PDV system was based on the design of Weng {Weng, 2008 #2882}, with a few modifications. The fiber collimator created an 800 μm beam of the 1550 nm laser that was then focused onto the flyer using a 10X microscope objective. The focused PDV beam was measured to be 70 μm in diameter using a 90:10 razor-edge technique. This focused beam was collimated over 5 mm. The PDV signals were detected using a 20 GHz detector from Miteq and an 8 GHz Tektronix digital oscilloscope.

Flyer plates were prepared using epoxy (Eccobond 24, Emerson and Cummings) to cement the approximate 25-100 μm thick flyers to glass substrates. The Al foil supplier (Alufoil) cites a 10% uncertainty in the foil thicknesses. The substrates and targets were 2x2" squares, ¼" thick of heat-resistant borosilicate glass from either McMaster-Carr or Chemglass.

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## 3. Results and discussion

*3.1 Flyer launch and the effects of pulse duration*

Figure 2 shows velocity profiles from launching 25 and 100 μm thick flyers at ~1.4 km/s across a nominal 375 μm gap, with either 10 or 20 ns pulses. The ringing was smallest in the thinner flyers with the 20 ns launching pulses, as expected. In the 100 μm flyers, the ringing was substantial. The modulations in the flyer surface velocity were as large as 0.5 km/s. With the 100 μm flyers and the 20 ns launching pulses (figure 2b), the ringing was in the form of a damped oscillation, where the oscillations had almost vanished by the time (~320 ns) the flyer impacted the target. A very interesting phenomenon was seen with 100 μm flyers and 10 ns launch pulses (figure 2d). This was the case where the reverberations would be expected to be the most extreme. Immediately after the first velocity oscillation maximum, an unexpectedly efficient damping process came into play, such that the reverberations were entirely gone before the flyers impacted the targets. In figure 2b, each oscillation maximum can be associated with the arrival of the reverberating shock front at the flyer front surface. The first return to the front surface occurs at ~60 ns. Figure 2d shows that with the 10 ns drive pulses, at the expected time of the first return there is no velocity modulation whatsoever. Such a velocity profile is typical for spallation, but no change in the shock duration occurred that would indicate the mass loss that should accompany spallation. We do not yet have a complete understanding of the enhanced damping mechanisms, and we intend to investigate them in more detail in the future.

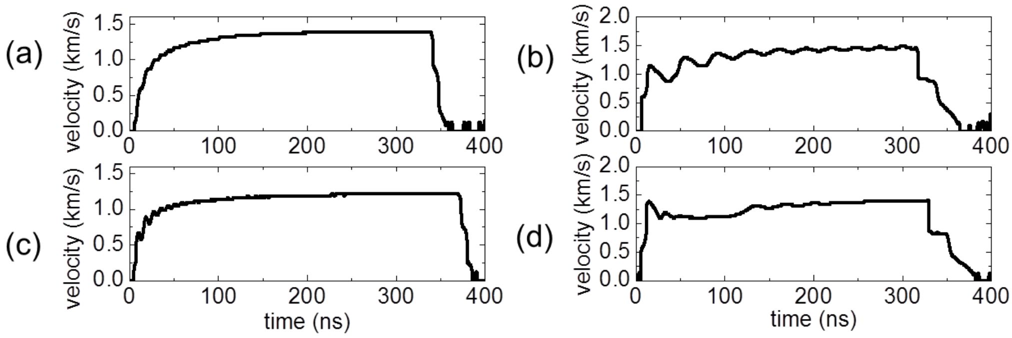


**Figure 2** Velocity profiles of flyers launched across a nominal 375 μm gap onto glass targets. (a) 25 μm thick flyer with 20 ns pulse. (b) 100 μm thick flyer with 20 ns pulse (c) 25 μm thick flyer with 10 ns pulse. (d) 100 μm thick flyer with 10 ns pulse.

*3.2 Supported shock duration after impact*

PDV interferograms are often analyzed using a short-time Fourier transform (STFT), but the apparent duration of an event using this analysis method is highly dependent on the time window used in the transform. An alternative method used fringe-counting methods in the time domain [8]. In the fringe-counting method, a cubic-spline fit was used to identify the maxima and minima of each fringe. The distance represented by adjacent extreme was 0.388 μm, one-fourth of the PDV laser wavelength of 1.55 μm. Figure 3 compares data obtained with a 50 μm flyer impacting glass at 1.17 km/s analyzed by different methods: STFT with two different frequency resolutions, and fringe counting. Immediately after impact, the flyer/glass interface moves at a steady speed $U_p$ = 0.75 km/s. Different shock durations were obtained with each method.

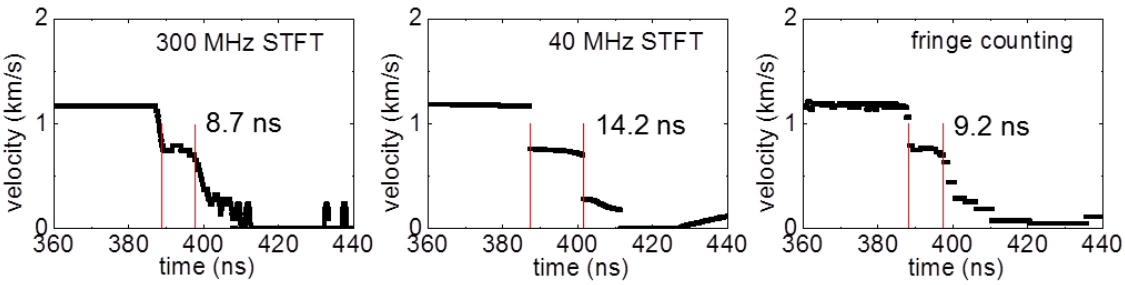


**Figure 3** A data set analyzed with three methods to determine the steady shock duration.

To determine the most accurate analysis method for measuring steady shock durations, a signal in the time domain was simulated with a known shock duration of 10 ns and then analyzed using these three methods. The results were similar to what was seen in figure 3, and only the fringe-counting method provided the correct result.

Measuring the supported shock duration of hundreds of aluminum flyers impacting glass showed that the shock duration was significantly shorter than a shock round-trip in the flyer. All of the shots reported for this study had impact velocities from 1-3 km/s, but no statistically significant change in the shock duration for this velocity range was observed. Table 1 shows results from an average of 30 shots for each flyer thickness with 95% confidence bounds calculated from two standard deviations in the collected data. Also shown are our predicted durations, as will be discussed shortly, with error bars based on the 10% thickness uncertainty.

**Table 1.**

| Flyer Thickness | Shock Duration (ns) | Predicted Duration (ns) |
|---|---|---|
| 0.001” | 4.7 ± 0.7 | 4.8 ± 0.5 |
| 0.002” | 9.9 ± 1.3 | 9.7 ± 1.0 |
| 0.003” | 15.2 ± 1.3 | 14.5 ± 1.5 |
| 0.004” | 19.4 ± 2.4 | 19.4 ± 1.9 |

We considered the possibility that the flyers were thinned substantially by laser ablation before reaching the targets. To test this supposition, we created a multilayer protected flyer assembly consisting of an opaque 2.5 μm thick Al launch layer, an epoxy layer and 75 μm flyers. The 2.5 μm layer was sacrificial and insured that laser pulses never reached the 75 μm flyer. There was no significant difference in the durations produced with protected flyers. In fact five shots with protected flyers gave an shock average duration of 14.7 ns, slightly shorter than with unprotected flyers, but within the 10% uncertainty in foil thickness. These additional experiments confirmed that shock durations were significantly shorter than what was predicted by a round-trip transit time.

The durations reported in table 1 match what would be predicted from the amount of time it took the shock front to transit the flyer only once, from the flyer/target interface to the back surface of the flyer. To calculate the shock velocity in the flyer requires a correction from what is reported in the Hugoniot tables [9] because of Eulerian velocity constraints [10]. The Hugoniot tables describe shocks in target materials, but the shocks in flyers are moving against the direction of the material velocity. In this case the shock velocity is reduced by the material velocity. Once this correction was made to the shock velocity in the flyer, the duration of the steady shock was predictable by simply dividing the thickness of the flyer by its shock velocity.

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