Hypersonic Force Measurement System

Asa Guldbrandsen, Maxwell Gjevre, Alexander Lee, Luke Herter, Miles Owens
University of Rochester, Hajim School of Engineering and Applied Sciences
Department of Mechanical Engineering

MELIORA

Problem Statement

A research group at the Laboratory for Laser Energetics (LLE) studies the interactions of lasers with materials in hypersonic flow. Currently, the group does not have a method of directly measuring applied force by pulsed lasers hypersonic environment. Commercially available load cells do not have the combined sample rate, resolution, and robustness required to measure such a short, intense deposition of energy in the extreme conditions seen during hypersonic flight. This project aims to design, manufacture, and test a prototype device capable of measuring pulsed laser effects on a body in hypersonic flow.

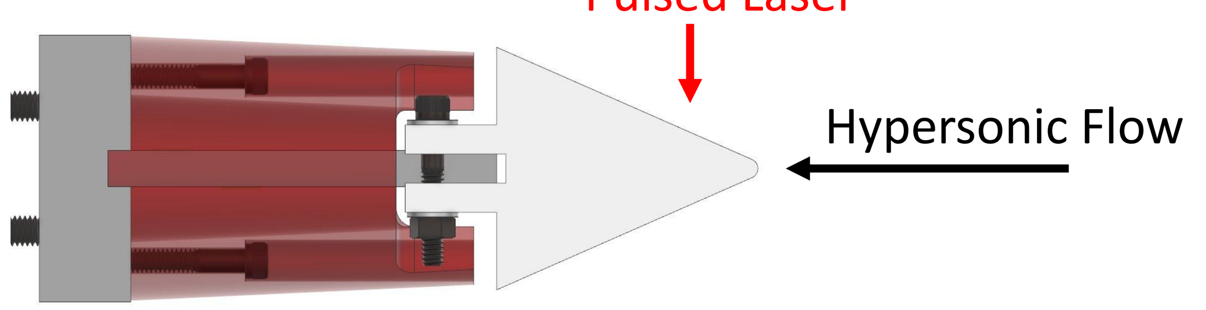

Figure 1: Hypersonic flow and pulsed laser diagram

Requirements and Specifications

TABLE 1
REQUIREMENTS AND SPECIFICATIONS

	Value	Specification
1	10 FoS	Minimum factor of safety for mount and hardware
2	1 DoF	Minimum data collection axis
3	300 kS/s	Minimum sampling rate
4	0.2 lb_f	Minimum resolved load from impulse hammer
5	500 lb_f	Minimum acceptable flow load
6	1 ft^3	Maximum design envelope (cube)
7	48 in	Maximum flow diameter
8	1 kHz	Minimum natural frequency

	Requirement
1	Must not experience mechanical failure when subject to hypersonic flow
2	Must be compatible with the diagnostics known to the PLE group
3	Must be able to resolve impulse load applied via pulsed laser

Due to the immense forces experienced during hypersonic flow, the group set a factor of safety value of 10 for all the mounting hardware. Furthermore, the group calculated that with a factor of safety, the minimum acceptable load due to hypersonic flow was 500 lb_f. This value aimed to avoid any permanent deformation in the prototype after testing. Additionally, based on background research, the group determined that a 300 kS/s sampling rate would be sufficient. To ensure the prototype would fit in the wind tunnel, the basic design envelope was defined in specification 6 and 7. Finally, the first vibrational node value, 1 kHz, was selected to avoid vibration in the sting that would severely impact any of the diagnostics.

TABLE 2
ANALYSIS OF SPECIFICATIONS

	Value	Specification	V.1 Pass?	V.2 Pass?
1	10 FoS	Minimum factor of safety for mount	Y	Y
2	1 DoF	Minimum data collection axis	Y	Y
3	300 kS/s	Minimum sampling rate	Y	Y
4	0.2 lb_f	Minimum load from impulse hammer	N	Y
5	500 lb_f	Minimum flow load	N	N
6	1 ft^3	Maximum size	Y	Y
7	48 in	Maximum flow diameter	Y	Y
8	1 kHz	Minimum natural frequency	N	N

Concept Development

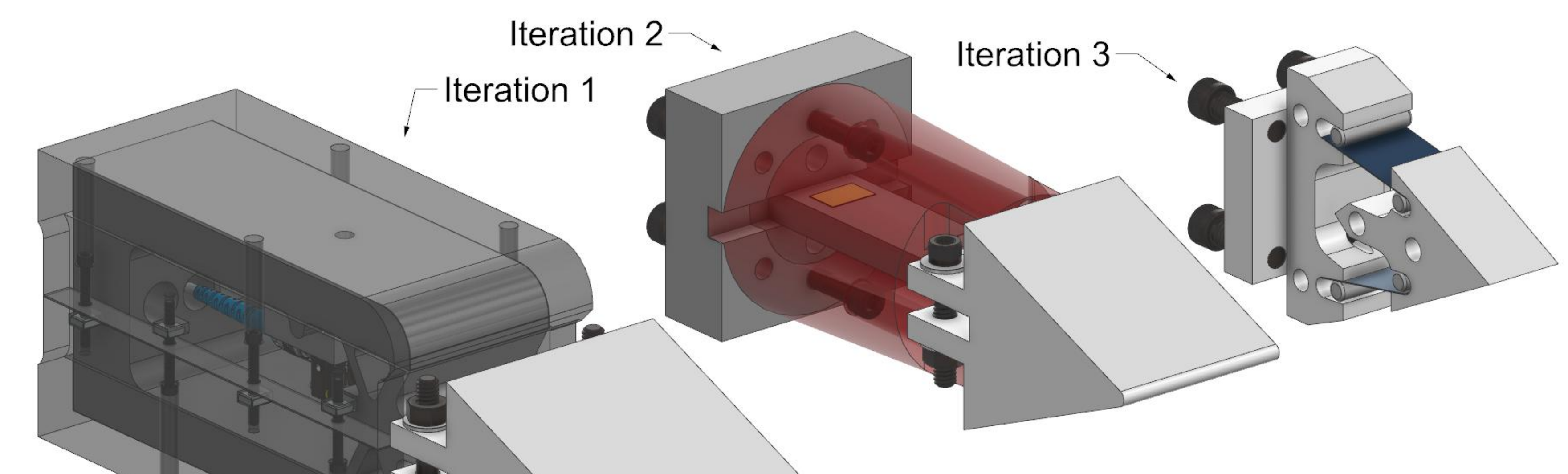

Figure 2: All three iterations of the sting

The first iteration utilized an "X-mechanism", allowing for a small amount of rotation about a specified point. This allowed the interferometry system to measure the angular deflection on the back face of the diving board and strain gauges to measure the deflection of the X-webs. After testing, the group determined that this design was too stiff and pivoted to a second iteration that was orders of magnitude more flexible. Using a cantilever beam and strain gauges, the expectation was for the applied load to result in a measurable amount of deflection in the beam. After testing the second iteration, it was determined that the design was still too stiff, which led to the development of a highly flexible, spring steel flexure design concept. This iteration was not manufactured, but the group believes this iteration could result in valuable results.

Analysis

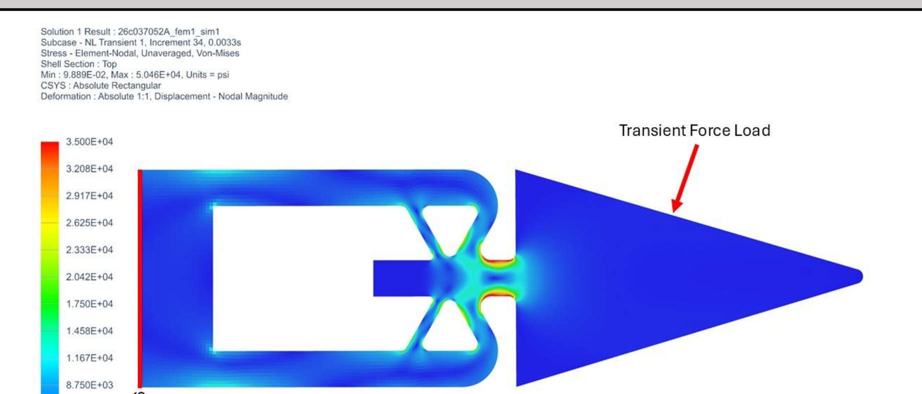

Figure 7: FEA Results with applied constraint and force position.

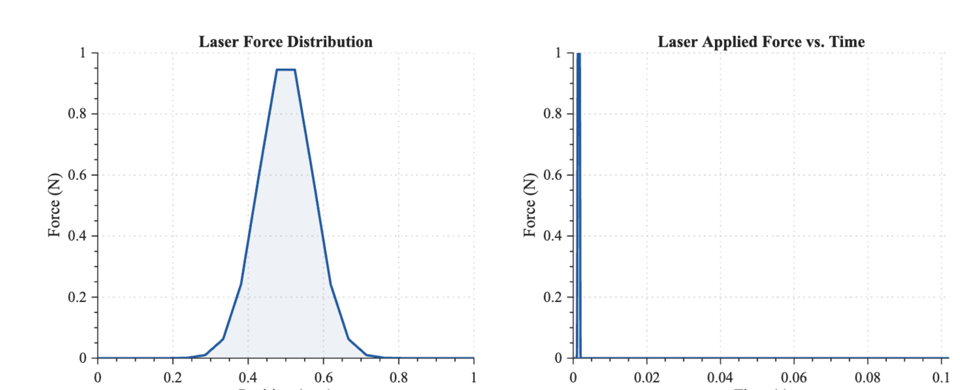

Figure 8: Spatial and Temporal Load Distributions

The FEM model can be seen in Figure 7. A 2" thick paver CQUAD4 mesh was applied to a two-dimensional profile of the compliant mechanism with an element size of 0.05" within the main body and a reduced element size of 0.0025" at points of interest. The model has a fixed constraint along the rear face and uses the load case described by the plots in Figure 8 above. SOL129 with a time step of 1 microsecond was used to study the nonlinear transient response of the body. In deciding what material to make the mechanism from, stress was the first thing considered. The FEA found that there is a max stress of 44.25 ksi at the fillet connecting the compliant mechanism to the wedge connector, as seen in Figure 7. This value exceeds the yield stress for 6061 aluminum, so 1018 HR Steel was considered next. 1018 HR Steel has a yield strength of 50 ksi, which results in a factor of safety of 1.13.

Manufacturing

The main body of the first iteration is 1018 steel and was made using wire EDM and outsourced to Machine Craft II. The wedge is the same across both design iterations and cut out of 6061 aluminum using CNC machining. Finally, the collimator mount bracket, 6061 aluminum, was machined on a manual mill. In the second design iteration, the beam section, 1018 steel, was made on a manual mill and welded to the mount flange, 1018 steel, which was also made on a manual mill.

Figure 11: Manufactured first iteration

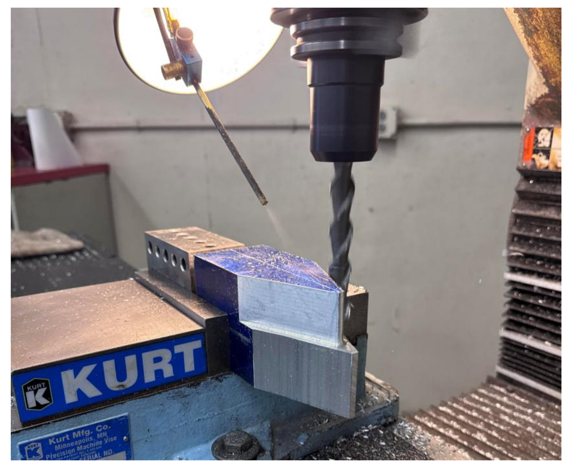

Figure 9: Wedge machining

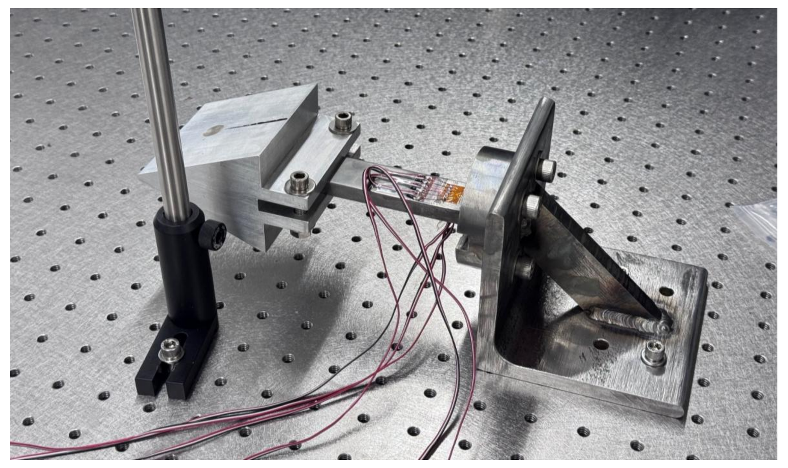

Figure 10: Iteration two with strain gauges

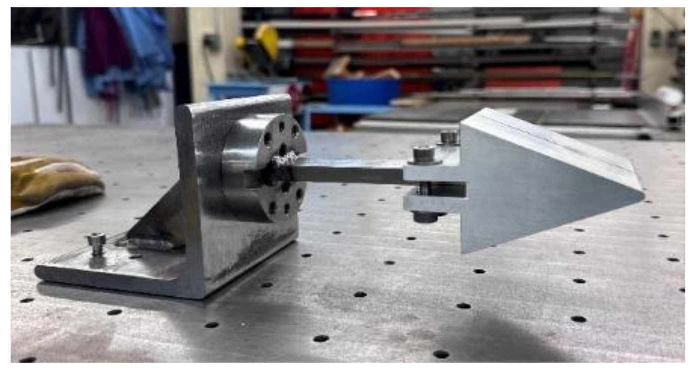

Figure 12: Manufactured second iteration

Testing

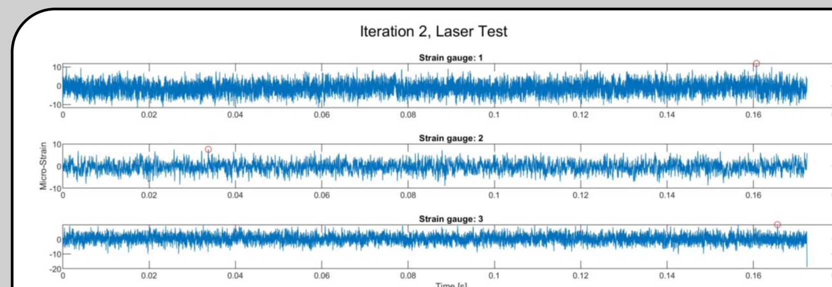

Figure 3: Iteration two: laser testing noise output

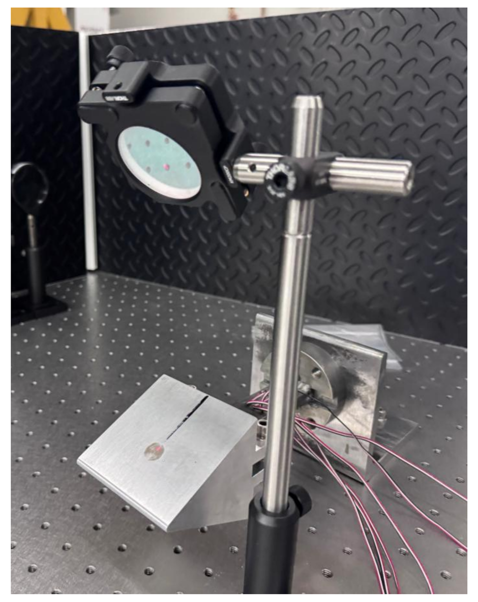

Figure 4: Laser testing, iteration two

In order to quantify the prototypes' ability to detect and resolve a pulsed laser shock, the group shot both deign iterations multiple times with a 2.2 Joule pulsed laser. The laser pulse lasts roughly 6 ns. In both design iterations, the pulse was lost in the noise.

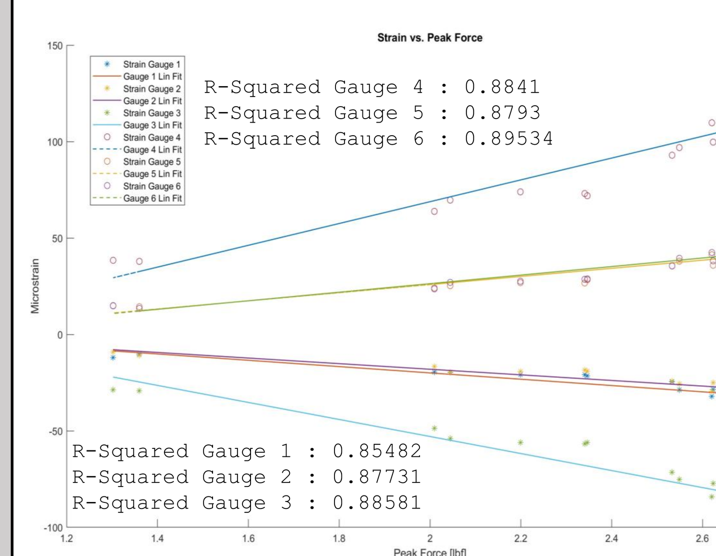

Figure 5: Calibration plot for design iteration two

In addition to laser testing, the group focused on calibration and tuning the system such that we could accurately determine the peak force applied on the face of the wedge. As seen in Figure 5, the second iteration design provided a relatively linear response showing an accurate characterization of impulse loading.

Data collection (Figure 3) using the HBK, GEN3i high speed data collection system. Micro-Measurements, quarter bridge, rosette strain gauges were used.

TABLE 3
DAQ AND STRAIN GAUGE VALUES

Gain	1 K
Bridge Factor	1
Gauge Factor	2.09
Excitation Range	+/- 1.5 V
Impedance	10 MΩ
Filter Frequency High	5 KhZ
Sampling Rate	500 kS/s
Strain Gauge Resistance	120Ω
Gauge Length	0.120"
Strain Range	+/- 3%
Matrix Size	0.62 X 0.42"

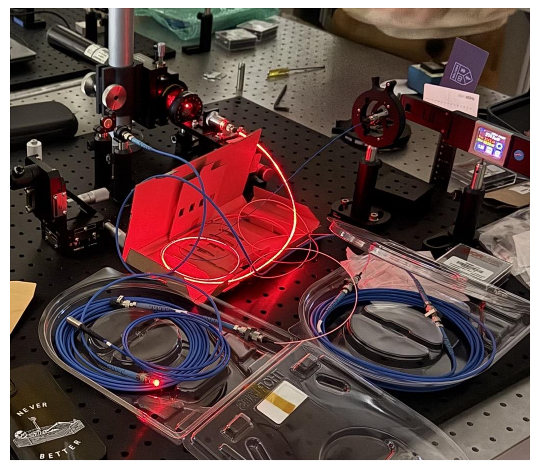

Figure 6: Interferometer

The group created a custom, fiber Michelson interferometric system (Figure 6) that utilized a red HeNe laser and fiber optic cables. This system gives high resolution and sampling rate.

Future Work

Going forward, the group recommends further analysis and testing of strain gauges to better understand their ability to characterize pulsed laser effects. The use of a Photon Doppler Velocimetry (PDV) system to measure the intensity of the laser shock is a promising path forward for detecting and characterizing laser-applied force.

Acknowledgements

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