Characterizing the Vibrational Response of a Fuel Injector

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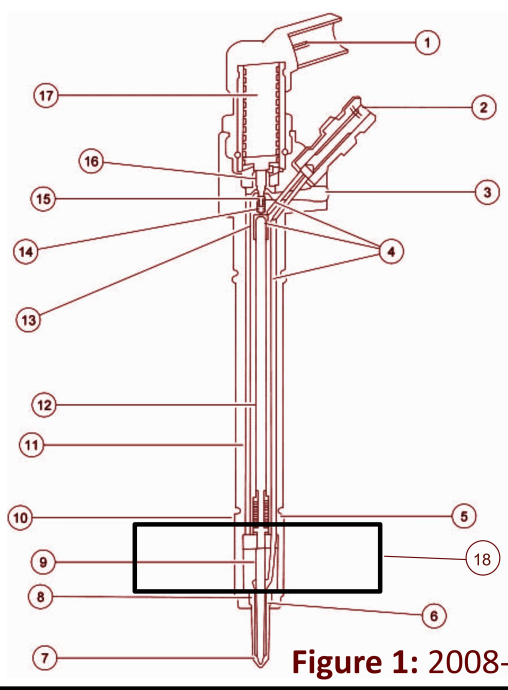
Introduction

Fuel injectors are electronically actuated mechanical devices which operate under high hydraulic pressures. The nozzle is designed to deliver fuel to an engine as a spray in a cylinder's combustion chamber. Although vibration is typically avoided due to mechanical stress and noise, it can also be a useful diagnostic tool. In fuel injectors, cavitation collapse, fluid hammer, turbulent flow, acoustic waves, and needle actuation are all plausible causes for vibration[1]. In this study, a laser vibrometer method is used to examine the cantilever vibration of a fuel injector to discern the void fraction of gas or vapor.



1: Electrical harness connector
2: High pressure fuel in from fuel rail
3: Fuel return chamber
4: High pressure fuel
5. Needle control spring
6. Steel combustion gasket
7. Spray holes
8: High pressure chamber
9: Nozzle needle
10: O-ring
11: Fuel return passage
12: Control piston
13: Control piston chamber
14: Fuel injector valve return spring
15: Fuel injector valve
16: Valve piston
17: Piezo actuator
18: Mount

Figure 1: 2008-10 Ford 6.4L diesel fuel injector[2]

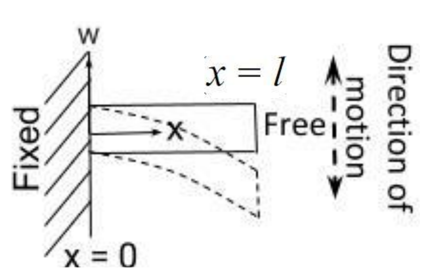
Theory

Flexural (Cantilever)

Equation 1a: Free vibration equation

$$\frac{\partial^2 w(x,t)}{\partial t^2} + c^2 \frac{\partial^4 w(x,t)}{\partial x^4} = 0 \; , \; c = \sqrt{\frac{EI}{\rho A}}$$

c = flexural wave speed
E = Young's Modulus (measures stiffness)
I = moment of inertia
ρ = density
A = cross-sectional area



$w(x=0)=0$
$w(x=l)=$ free boundary conditions

Figure 2: Illustration displaying direction of cantilever oscillations

Longitudinal (Acoustic)

Equation 1b: Acoustic vibration equation

$$c^2 \frac{\partial^2 P}{\partial x^2} - \frac{\partial^2 P}{\partial t^2} = 0 \; , \; c = \sqrt{\frac{\beta}{\rho}}$$

c = speed of sound
ρ = density
P = pressure
β = bulk modulus

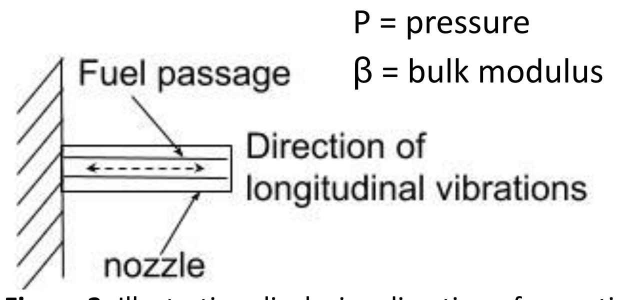


Figure 3: Illustration displaying direction of acoustic oscillations

Mode Frequency:

Equation 2: (a)Mode Frequency equation for flexural oscillations (b)Mode Frequency equation for longitudinal oscillations

$$\text{(a)} \quad f_n = \frac{\xi_n^2}{2\pi}\frac{1}{l^2}\sqrt{\frac{EI}{\rho A}} \qquad \text{(b)} \quad f_n = \frac{nc}{2l}$$

n	1	2	3	4	5	6
Flexural Frequency(Hz)	2.366×10^4	1.483×10^5	4.152×10^5	8.136×10^5	1.345×10^6	2.009×10^6
Longitudinal Frequency of air(Hz)	1.056×10^4	2.112×10^4	3.168×10^4	4.224×10^4	5.280×10^4	6.336×10^4

Table 1: Calculated theoretical frequencies. Measured length as 16.24mm. Approximated inner radius as 2.84mm. Used Young's Modulus and density for stainless steel.

Mode Shape:

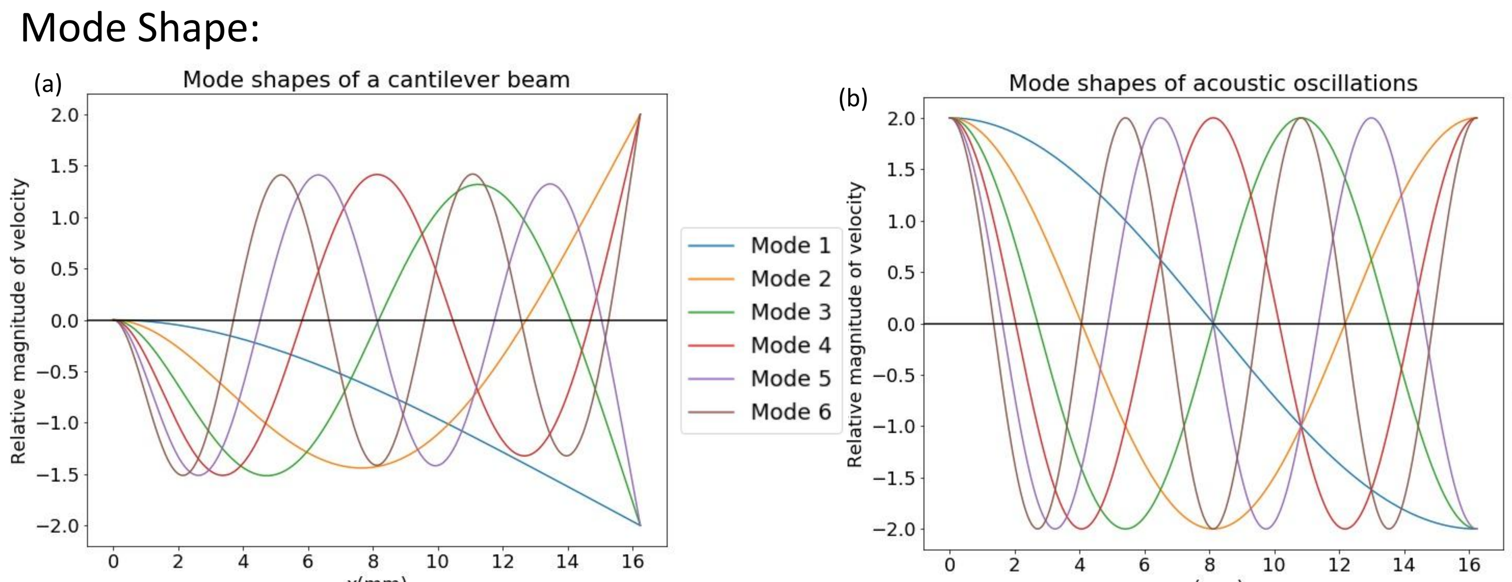


Figure 4: (a)Mode shapes of flexural vibrations (b)Mode shapes of longitudinal vibrations

Results

Figure 9: Timeseries of velocity near tip of nozzle
(a)Data collected from empty fuel injector (b)Data collected from filled fuel injector

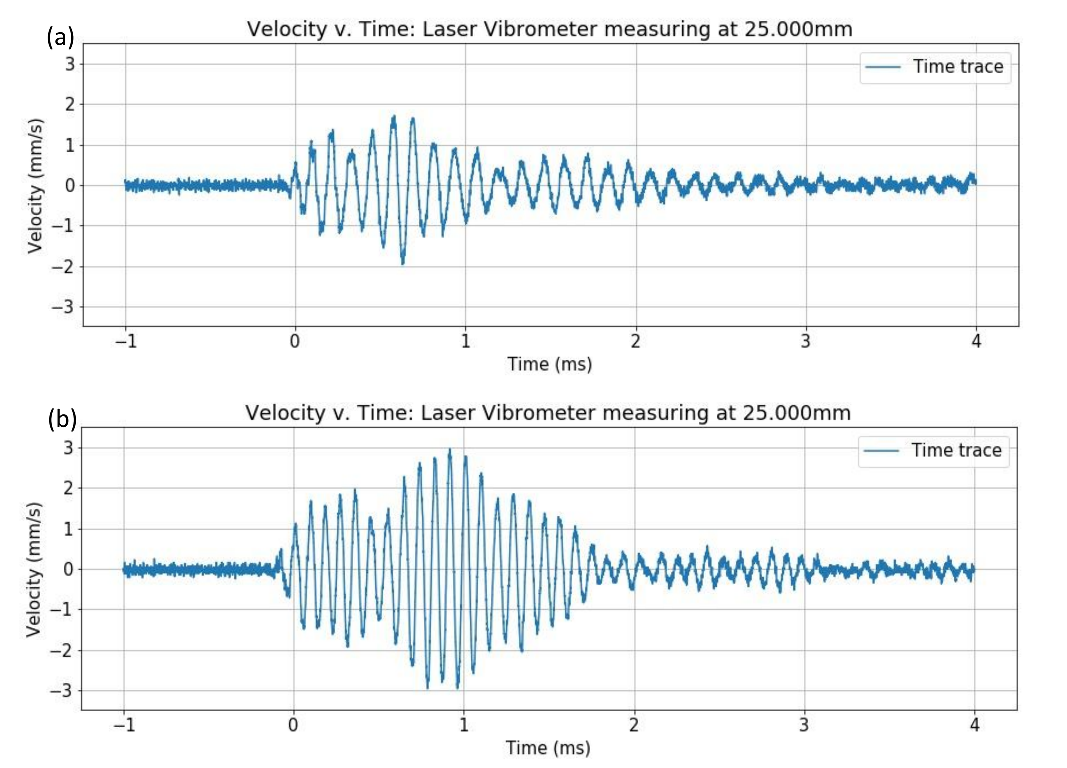
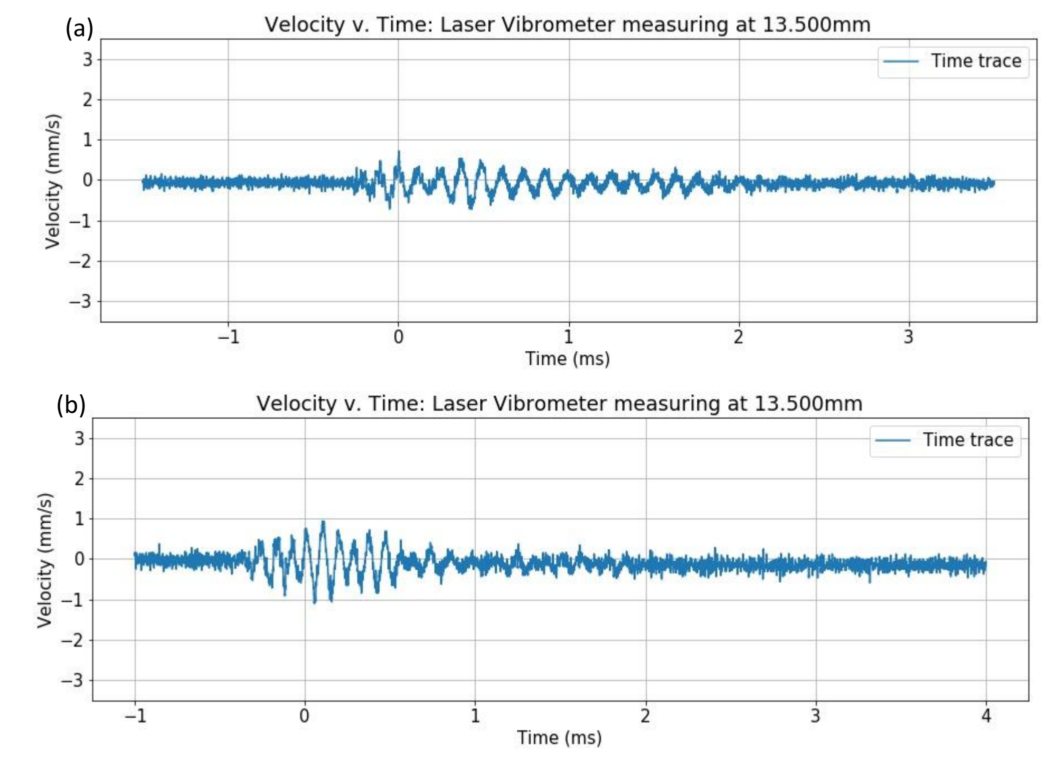


Figure 10: Timeseries of velocity near base of nozzle
(a) Data collected from empty fuel injector (b)Data collected from filled fuel injector



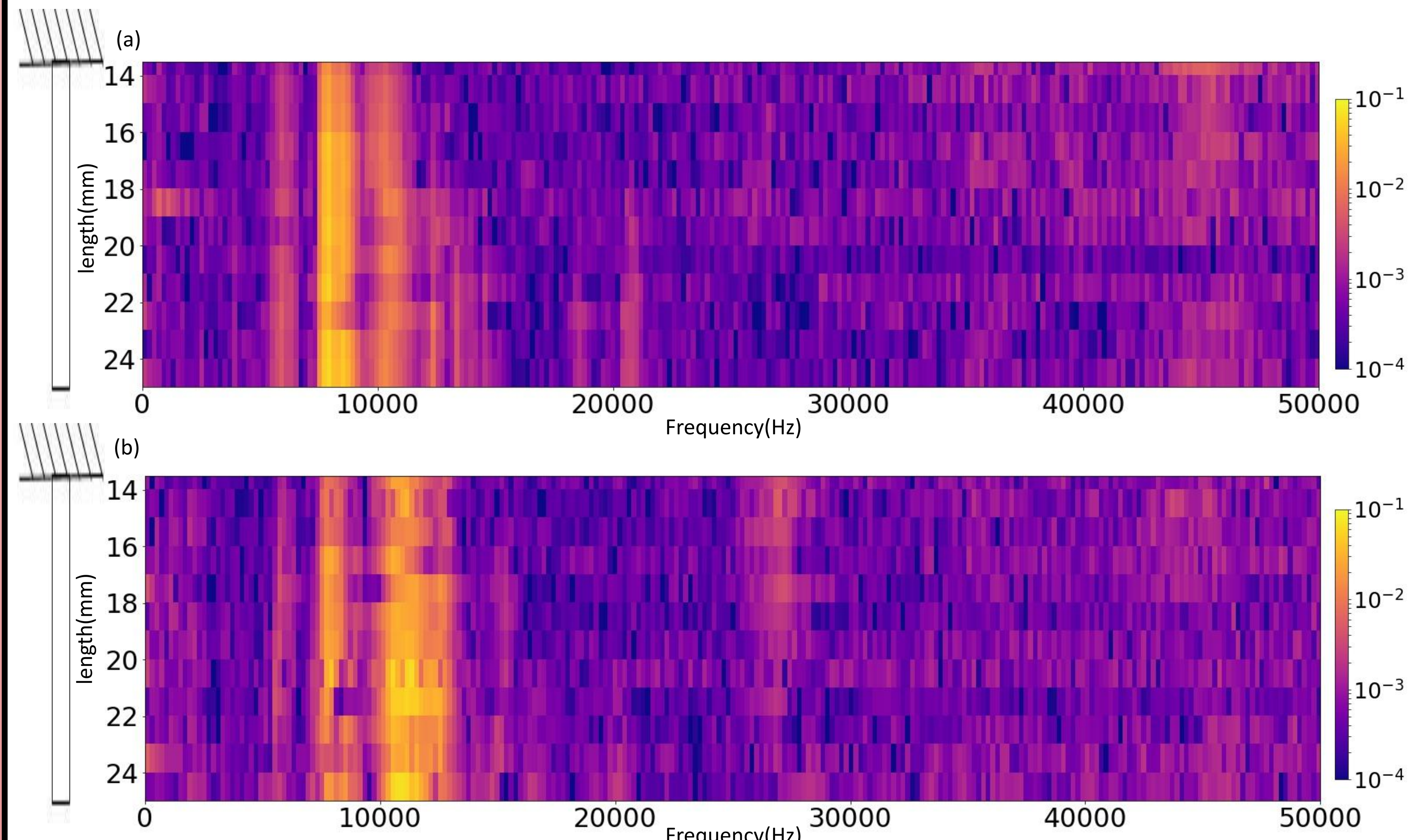


Figure 11: (a)Spectrogram for empty fuel injector (b)Spectrogram for full fuel injector

Conclusions

What frequency peaks are observed?
- Empty: 9000±200Hz
- Full: 11000±200Hz

Why does frequency increase as mass increases?
- In a simple spring-mass system, as mass increases, frequency decreases.
- In this study, the frequency increases as mass increases suggesting effects other than cantilever oscillations are occuring.

Which mode is occuring?
- The measured frequencies correlate more closely with the theoretical frequencies from longitudinal theory. However, longitudinal theory predicts maxima pressure at the base and tip and minimum pressure in the middle that are not observed. But according to the data, velocity is at its maximum at the tip but not at the base which correlates to cantilever oscillations.
- It is possible that cantilever vibrations are being driven by acoustic vibrations occurring in the air inside the fuel injector. However, the coupling isn't strong enough to display cantilever modes.

How to explore further:
- Excite the fuel injector in other methods — e.g. external impulse response or measuring driven frequency response
- Analyzing system with a computational model
- Flow fluid through the nozzle and study response

References

[1]Do, H. Cavitation detection and characterization for small scale nozzles and fuel injectors. Masters thesis, Boston University, 2018.

[2]Ford Diesel Diagnostics https://oregonfuelinjection.com/services-repair/diesel-diagnostics-repair/ford-diesel-diagnostics/#2008 (accessed Jul 3, 2018).

[3]Basic principles of vibrometry https://www.polytec.com/us/vibrometry/technology/$laser-doppler-vibrometry/$single-point-vibrometry/(accessed Jul 31, 2018).

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Methods

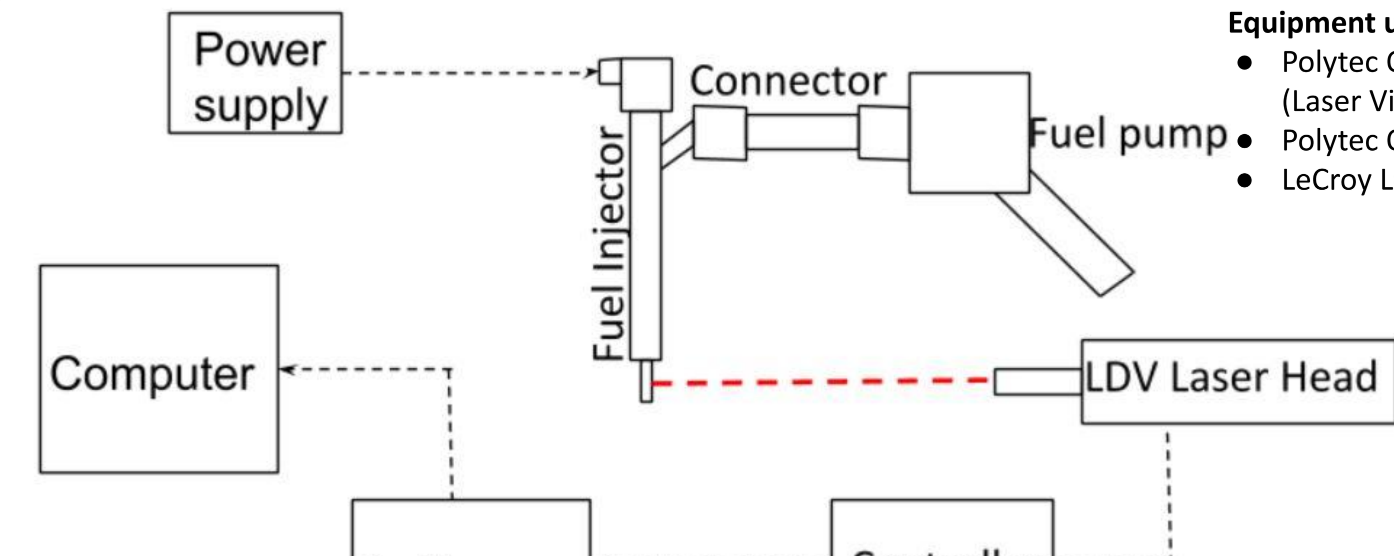

Figure 5: Block diagram of experimental setup

Equipment used:
- Polytec OFV 303 Sensor Head (Laser Vibrometer)
- Polytec OFV 3001 controller
- LeCroy LC334A oscilloscope

Data Collection:
1. Polytec OFV 303 Sensor Head focused on tip of nozzle.
2. Fuel injector actuated with high voltage (~90V) which excites the pintile.
3. The impulse response is measured by the LDV, the signal is then converted by the oscilloscope, and finally recorded by the computer.
4. Repeated along the length of the nozzle with 0.500mm steps

This procedure was first executed with the fuel injector empty, then it was filled with water.

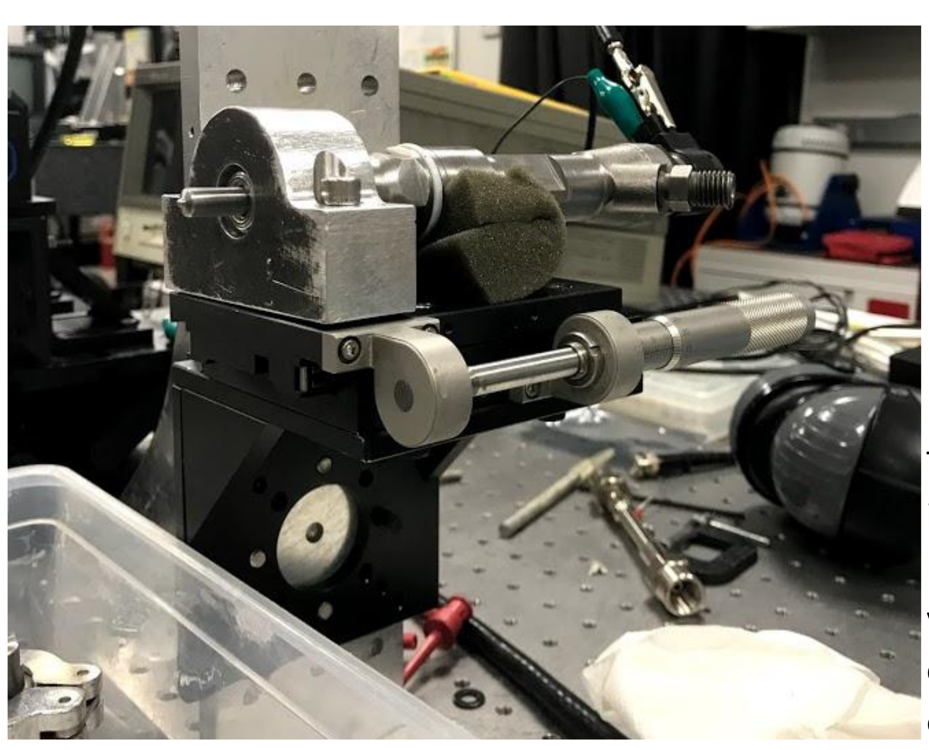

Figure 6: Mounted fuel injector

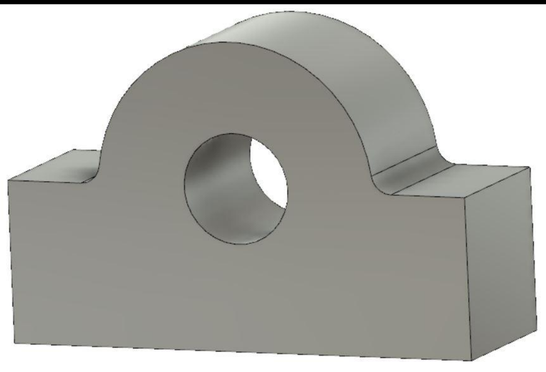

Figure 7: CAD part for fuel injector mount. The mount for the fuel injector was machined at BU Engineering Product Innovation Center.

The laser vibrometer utilizes interferometry and the Doppler effect to measure displacement and velocity on vibrating surfaces. The Doppler effect, the change in frequency of moving source observed from a stationary reference, is expressed with **Equation 3**[1]:

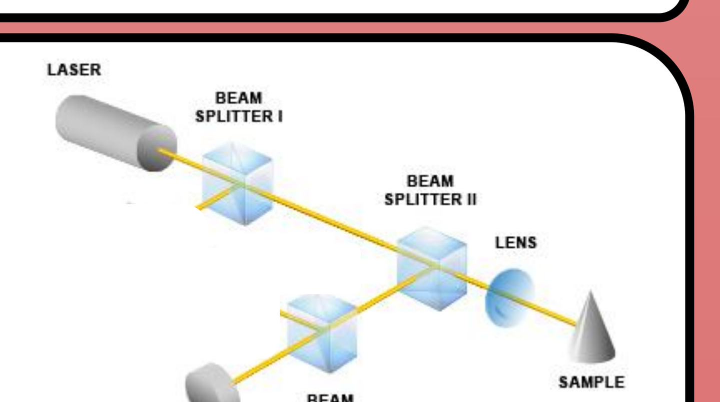

Figure 8[3]: Principle of Laser Vibrometer operation
The LDV system splits the beam of the laser into a reference beam and a measurement beam. The measurement beam is then reflected off the fuel injector and combined with the reference beam. The LDVs are capable of measuring both displacement and velocity, however, in this study, velocity is utilized because it is better suited for higher frequencies.[3]

Equation 3: Doppler effect

$$f_{obs} = f_{source}\frac{a+v}{a}$$

Where:
f_{obs} = observed frequency
f_{source} = frequency of the source
a = speed of wave
v = speed of source