

SIMULATING HEAT GENERATION IN THE MONOBLOCK LASER USING
FINITE ELEMENT ANALYSIS

by

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ABSTRACT

Under photonic pumping Nd:YAG (Neodymium Yttrium Aluminum Garnet) generates a significant amount of heat as a result of quantum deficit and non-radiative absorption sites, this excess heat results in thermal deformation and a shift in the index of refraction of Nd:YAG causing a net change in Optical Path Length (OPL). Finite Element Analysis (FEA) techniques provide a powerful approach for digital design and analysis of complex thermo-mechanical systems; unfortunately, finite element software packages do not use light as a traditional loading mechanism nor track optical properties. This research has sought to establish a methodology to interface thermal loading as a result of photonic conversion with traditional FEA practices and track the resulting optical effects. The ABAQUS software package interfaced with a python driven input procedure has been used to develop a representation of photonic loading in the FEA environment. This modeling method has been calibrated utilizing interferometry imaging of a pulsed Nd:YAG system tracking the resultant OPL and comparing these results to FEA predictions. FEA predictions were developed that matched experimental measurements within 0.5 waves at the 1064nm laser line for Nd:YAG.

INTRODUCTION

Motivation

Laser systems were born in 1960 with the creation of the first ruby laser [1]. Since their creation lasers have become an essential part of modern life. Lasers exist in almost every setting ranging from simple low power barcode scanners at grocery stores to extremely high power laser defense systems developed by DARPA [2]. As part of the lasing process heat generates in the laser medium [3]. In the case of very high power lasers this high internal heat generation can lead to fracture of the solid state gain media [4]. Even for lower power systems heat generation can lead lensing effects[5]. System heating can lead to a change in operational efficiency of the system[6]. Additionally heating results in expansion and changes system geometry and optical properties [7]. All of these problems associated with heating can lead to laser failure and must be mitigated to ensure laser operation.

Spectrum Lab in Bozeman Montana has developed a Mid-IR wavelength laser capable of operation as a remote sensing laser source [8]. This system has applications in public safety as a detection method for methamphetamine effluents. It also has applications in environmental monitoring as a CO₂ detector. This laser system utilizes a diode pumped Nd:YAG (Neodymium doped Yttrium Aluminum Garnet) laser sold under the name Monoblock . This laser is produced by Scientific Materials Corporation of Bozeman, Montana. Problematically this system is currently limited in operational power and repetition rate due to failure of the Monoblock laser as result of internal heating.

This thesis describes development of a modeling approach using the finite element package ABAQUS to predict heat generation associated with lasing in the Monoblock laser. Modeling methods were calibrated using interferometry measurements of optical path length in Monoblock system during operation.

Laser Basics

Laser is an acronym for Light Amplification by the Stimulated Emission of Radiation. Lasers are class of optical devices that emit monochromatic (single color) light that is highly directional. The laser was first executed in the form of a solid-state ruby laser in 1960 [1] and later that year in the form of a gas Helium Neon laser [9]. Lasers consist of three basic components(Figure 1): 1) A gain medium, 2) A pump source, and 3) A pair of mirrors forming an optical cavity

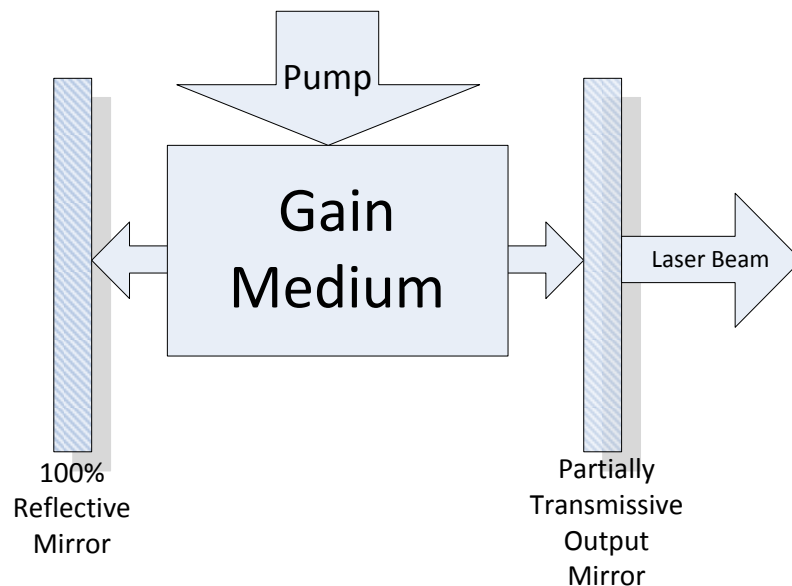


Figure 1: Block Diagram of a Laser

Laser Pumping

The laser pump is an energy source that causes the population inversion in the gain medium. Population inversion is a process by which a majority of atoms in a thermodynamic system are raised from a ground energy state (E_1) to an energy state above the thermal equilibrium (E_2), note that E_1 must be greater than E_2 . The difference in energy between the ground state and the excited state is a characteristic energy required to excite the atom. Using Planck's constant (h) equation 1 relates the characteristic energy required to excite a system (ΔE_{12}) to the characteristic frequency of light (ν_{12}) Planck's constant has a value of $6.626069 \times 10^{-34} \text{Js}$ [10].

$$\Delta E_{12} = E_2 - E_1 = \nu_{12}h \quad \text{equation 1}$$

The Planck relation (equation 2) can be used to relate light frequency to wavelength, where λ is wavelength and c is the speed of light ($2.9997 \times 10^8 \text{ms}^{-1}$).

$$\lambda_{12} = \frac{c}{\nu_{12}} \quad \text{equation 2}$$

Combining equation 1 and equation 2 allows it to be said that a single photon of wavelength λ_{12} characterizes the energy in transition from ground state to excited state (equation 3).

$$\Delta E_{12} = \frac{ch}{\lambda_{12}} \quad \text{equation 3}$$

When a photon of wavelength λ_{12} is imparted into a system three results are of interest: Absorption, Spontaneous Emission, and Stimulated emission [10]. For a system at

thermal equilibrium the addition of λ_{12} has a probability of causing atoms in the system to be excited from E1 to E2 this process is known as absorption Figure 2.

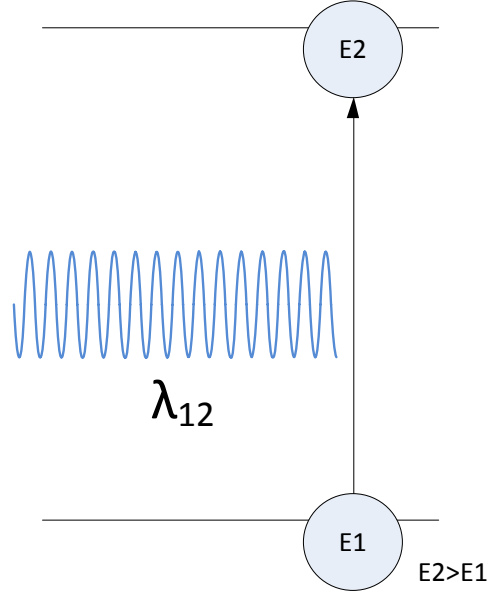


Figure 2: Block Diagram of Absorption

All materials behave as absorbers at thermal equilibrium, the distribution of atoms in the states E1 and E2 is described by the Boltzmann distribution (equation 4) where N_1 and N_2 refer to populations in the excited and ground state respectively, E_2 and E_1 refer to energy levels of the excited and ground state respectively, k_B is the Boltzmann constant ($1.368 \times 10^{-23} \text{ JK}^{-1}$) and T is absolute temperature in Kelvin.

$$\frac{N_2^e}{N_1^e} = \exp\left(\frac{-E_2 - E_1}{k_B T}\right) \quad \text{equation 4}$$

Note that equation 4 implies that $N_2 < N_1$. Also note that atoms in the excited state E2 will tend to spontaneously decay to the lower energy ground state emitting a photon of wavelength λ_{12} . This photon is emitted in random direction, polarization and phase; this

Process of emission is called spontaneous emission (Figure 3). Spontaneous emission can be thought of as the inverse of absorption.

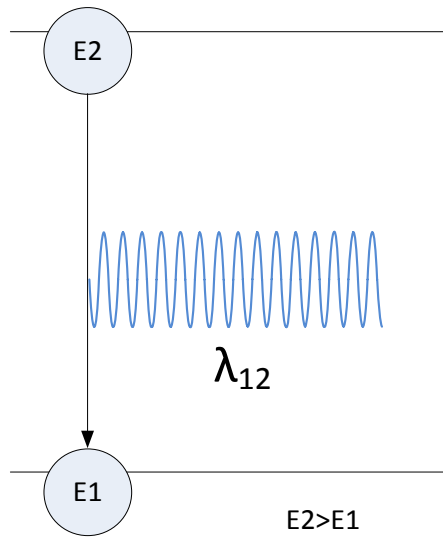


Figure 3: Block Diagram of Spontaneous Emission

Lastly stimulated emission is a process by which an atom in an excited state interacts with a photon of wavelength λ_{12} and as result drops to the ground energy emitting a second photon with wavelength λ_{12} (Figure 5).

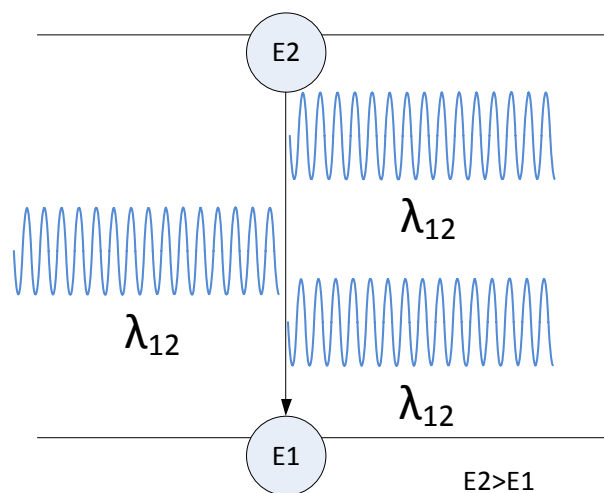


Figure 4: Block Diagram of Stimulated Emission

Photons emitted in this process have the same properties as the parent photon; i.e. phase, polarization, wavelength; resulting in a pair of monochromatic highly directional photons.

Population Inversion

Population inversion occurs in a system when there is a majority of atoms in excited energy states. This majority atoms in an excited state means that emission dominates over absorption and there is an amplification of light. For a system consisting of only two energy levels input of λ_{12} causes an increase in the population of N_2 and a decrease in N_1 , as this process continues stimulated emission will begin to occur and eventually equilibrium will be reached where N_1 and N_2 are equal. When N_1 and N_2 are equal the system is optically transparent. For two level systems it is impossible to achieve steady state population inversion and amplification of the input light λ_{12} because N_1 will be equal to N_2 in steady state operation. Population inversions can occur if additional energy levels are added to the system. The addition of an another level or levels allows population inversion because stimulated emission causes decay out of the excited state to an intermediary level and that will eventually decay to the ground state allowing repopulation of the excited state. The most common energy level systems in lasers are three and four level systems, Figure 5.

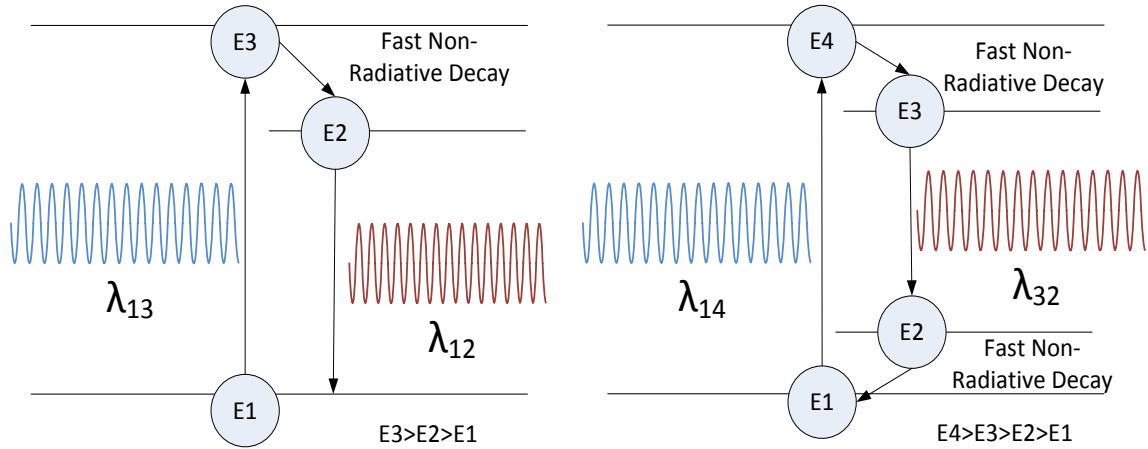


Figure 5: Block Diagrams of Three Level (left) and Four Level (right) Laser Systems

Because of the rapid decay between the highest excited state and the intermediary states it is possible to achieve population inversion between the ground states and the intermediary and thus light amplification of the secondary wavelength λ_{12} or λ_{32} .

Gain Mediums

Laser gain mediums are a class of materials that are capable of light amplification via the process of population inversion as discussed previously. Lasers can be categorized by the type of gain medium utilized. Four of the most common types of laser are: Gas, Solid-State, Semiconductor, and Dye. Gas gain media utilize a contained gas pumped via an electrical discharge to produce stimulated emission. Two of the most common examples of gas laser media are the helium neon laser (HeNe) and carbon dioxide (CO₂) laser. Solid-State laser media are ion doped glasses that utilize optical energy to excite the dopant ion resulting in spontaneous and stimulated emission. Common solid state lasers include glasses doped with rare earth ions such as neodymium (Nd³⁺), erbium

(Er^{3+}), holmium (Ho^{3+}), and chromium (Cr^{3+}) [11]. Semiconductor Lasers are a special class of solid-state lasers that utilize a semiconductor as the parent material and are electronically pumped rather than optically pumped [12]. Dye lasers utilize organic dye suspended in a solvent and are optically pumped in a manner similar to solid state lasers [13].

Pump Sources

The source of the input energy is referred to the pump. There are a variety of pump sources depending on laser type and design. Optical pumping with broad spectrum flash lamp pumps like krypton flash lamps; provide the advantage of relative simplicity at the cost of low efficiency because not all light pumped into the system contributed to population inversion. The improvement of light emitting diodes has increased the availability of narrow spectrum diodes for optical pumping that provide the advantage of narrow band emission at the cost of complexity and financial cost. As lasers and improved and been developed for a diversity of wavelength they have also found use as optical pumps for other gain mediums. Additionally gas and semiconductor lasers can utilize electrical discharge to produce population inversion. This project focuses on the diode pumping process and future discussion will be oriented around the specific case of diode pumping Nd:YAG.

Optical Cavity

In order to achieve laser operation a pumped gain medium of a laser must be placed between mirrors forming an optical cavity. The paired mirrors cause light

generated via spontaneous and stimulated emission to propagate between the two mirrors repeatedly passing through the gain media. Repeated reflection along the laser axis through the gain medium stimulates further photon emission and amplification for each pass. The directional nature of the reflection ensures that only photons emitted parallel to the laser axis remain in the cavity and are amplified and thus the output beam has a uniform direction. If both mirrors are fully reflective no light is allowed out of the system, as result one mirror must be fully reflective and one partially transmissive. The transmissive or partially reflective mirror is referred to as the output coupler. The portion of light that is transmitted through the output coupler is the light that constitutes the actual laser beam and is a function of the transmission of the output coupler (Figure 6).

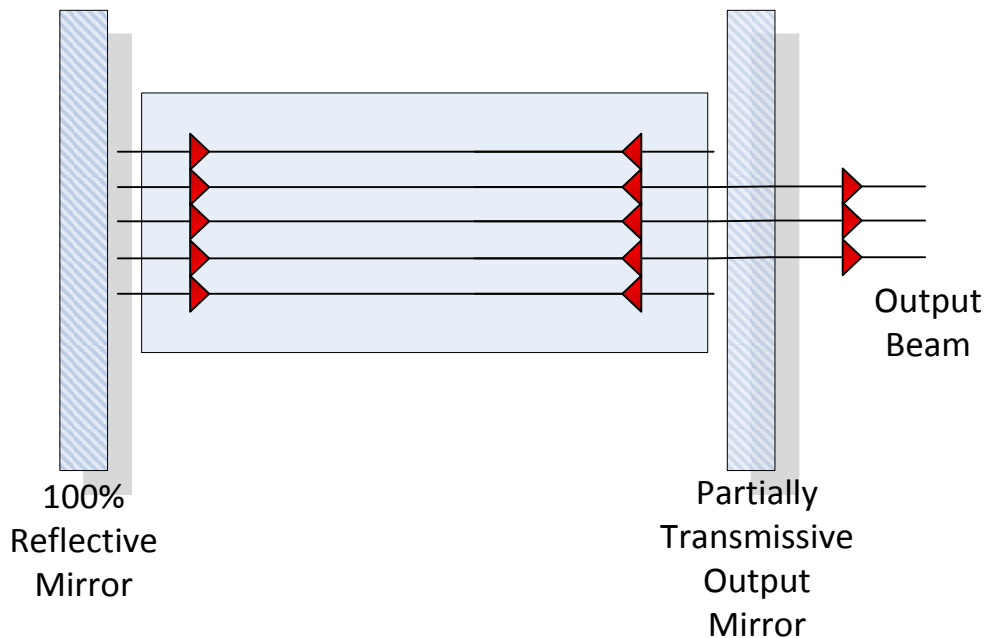


Figure 6: Simple Flat-Flat Laser Cavity Block Diagram

For a cavity to lase the gain produced by stimulated emission must be greater than the losses produced by transmission through the output coupler as well as the losses produced by any scattering or transmission out of the cavity. If losses exceed gain the number of photons will continually decrease until zero. If gain of the cavity is greater than the total losses in the cavity the laser is said to have exceeded the threshold condition and lasing will result.

LITERATURE REVIEW

Diode pumping was first demonstrated by Ross using Nd:YAG illuminating the efficiency and narrow band output advantages of diode pumps [14]. Byer provides an excellent summary of the early history and the associated improvement of solid state lasers with improving diode pump sources [15]. Additionally Fan and Byer further summarize the transition to diode pumped lasers and the associated difficulties of diode pumping[11]. Koechner solved the differential heat transfer equations associated with lamp pumping Nd:YAG for a finite length rod of Nd:YAG with convective boundary conditions and the associated lens effect produced in a laser system [16]. This solution assumed a uniform heat input; assuming radial symmetry and no axial heat transfer allowed for a closed form solution to the temperature distribution at steady state. Innocenzi et. al [17] improves upon Koechner's solution by incorporating Beer's law to include non-uniform heat generation. Both Innocenzi and Koechner only consider the temperature effects on index of refraction and neglect the coupled mechanical problems associated with thermal expansion. Weber et al. provides a key study introducing finite element analysis allowing inclusion of mechanical coupling between the thermal and structural effects for a continuous diode pumped Nd:YAG laser rod [18]. Several subsequent studies extended these methods to other laser media. Pollnau et al. published studies of erbium lasers [19]. Tilleman further expands on the heat generation problem including effects of stress on steady state operation and providing a closed form solution for simplified rod and slab geometries [20, 21]. Recently Li et. al have extended these

methods to solve for temperature distribution resulting from extremely fast pulsed operation pulsed operation (in excess of 100 Hz) of various rod shaped laser glasses [22].

YAG PROPERTIES

The Monoblock's monolithic construction of doped and un-doped YAG crystals necessitates a consideration of mechanical and thermal properties YAG. YAG is particularly attractive as a laser host material because it is a homogenous regular array allowing consistent dispersion of the rare earth ions associated with lasing. The mechanical properties (high thermal conductivity, high hardness, and high fracture limit) of YAG also lend it to use as a laser gain media [13].

Crystalline Structure

Materials with highly ordered structure are referred to as crystalline. Crystals are categorized based on the type of structure they exhibit, specifically the location and arrangement of the atoms. A system of points is used to describe this structure called lattice points. A lattice point is an ordered point in space with neighboring points continuing to infinity, where each point has a consistent periodic spacing and orientation [23]. Connecting these points with lines produces the unit cell (Figure 7).

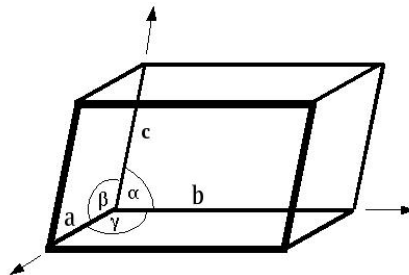


Figure 7: General Unit Cell [24]

Six parameters are used to fully define the unit cell: the lengths of the unit cell edges (a , b , c) and the corresponding angles between each edge (α , β , γ). Most crystal structures contain some form of symmetry and can be classified based on the extent of that symmetry. Because identical molecular units must be packed in a repeated order to produce the unit cell, only limited forms of symmetry are possible. The following types of symmetry are possible: pure rotation (folds), translational rotation (screw axes), mirror planes, translational planes (glide planes), and inversion centers [24]. The result of these symmetries produces seven types of crystal structures (Table 1).

Table 1: Types of Crystal Structures [24]

Crystal Structure	Dimensional Constraints
Triclinic	none
Monoclinic	$\alpha=\gamma=90$ degrees
Orthorhombic	$\alpha=\beta=\gamma=90$ degrees
Tetragonal	$a=b$, $\alpha=\beta=\gamma=90$ degrees
Trigonal	$a=b$, $\alpha=\beta=\gamma=120$ degrees
Hexagonal	$a=b$, $\alpha=\beta=\gamma=120$ degrees
Cubic	$a=b=c$, $\alpha=\beta=\gamma=90$ degrees

YAG crystals have a Body Centered Cubic (BCC) structure [25], and the rest of this section will focus on the BCC structure. A body centered cubic structure consists of one atom at each lattice point of the body centered cubic unit cell and one additional atom in the center (Figure 8).

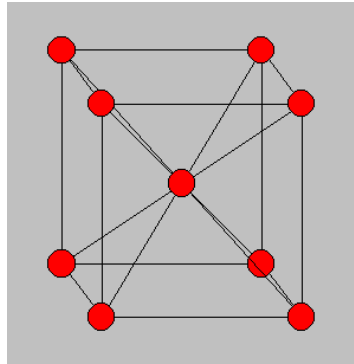


Figure 8: Body Centered Cubic Lattice, red circles represent atoms [26]

The red circles in Figure 8 represent locations of atoms, each of the corner atoms are shared by the eight adjacent cubes of the repeating lattice. Due to the symmetry of the cubic structure only one lattice parameter, the length of the unit lattice (a , b , c), is needed to describe the cubic unit cell. In the case of YAG this value is approximately 12 Å, though some variation is shown in published values see references [25], [27], [28], [29], [30]. YAG crystals consist of Yttrium, Aluminum and Oxygen in the form of $\text{Y}_3\text{Al}_5\text{O}_{12}$. The unit cell consists of 160 atoms or 8 YAG molecules per unit cell (Figure 9) [25]. The unit cell of YAG is a series of base cubic cells repeated where aluminum and yttrium are the repeating central atoms surrounded by 8 shared oxygen atoms.

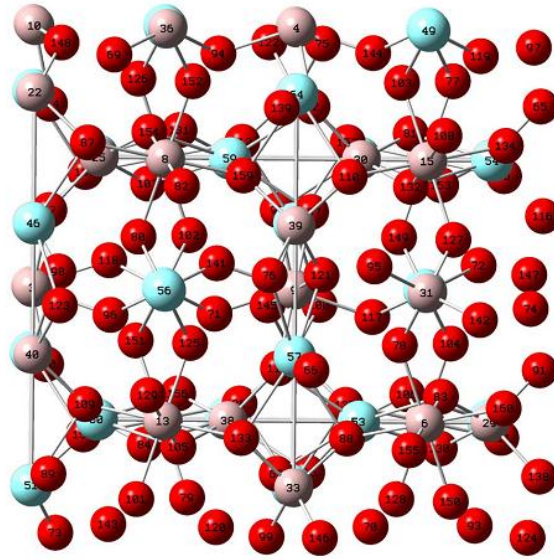


Figure 9: Unit cell of bulk YAG, red spheres represent oxygen, pink aluminum, and teal yttrium [28]

Elastic Constants

The elastic constants (C_{11} , C_{12} , and C_{44}) for YAG have been calculated by several different research groups with similar results see references, [30] [31], [32], [33] [34] [35]. For a derivation of cubic symmetry and the associated parameters see Appendix A cubic symmetry derivation. The change in each of the three elastic constants (C_{11} , C_{12} , and C_{44}) for YAG is nearly linear for temperatures in the range of 150K-300K. Alton and Barlow examined the change below room temperature noting that the change was only approximately ~5% over the entire range[34]. Of note the isotropy factor A decreases from 1.033 at 300K to 1.027 at 150K, this decrease implies that the change in C_{ij} is not proportional for each constant. For values above 300K Stoddart *et. al.* examined the change in the elastic constants [35]. For the 1200 degree range studied the maximum

change in each constant was 11% and the change was linear with temperature. At high stresses YAG crystals' elastic constants cease to be linear and show dependence on stress [30].

Table 2: First derivatives of C_{ij} for YAG at room temperature [30]

$\frac{\partial C_{11}}{\partial P}$	$\frac{\partial C_{12}}{\partial P}$	$\frac{\partial C_{44}}{\partial P}$
6.31	3.51	0.62

For this project our YAG systems are near room temperature and only deviate by less than 30 degrees Celsius given values published in literature the change in modulus over that small of a range will be on the order of 1-5 GPa as result no temperature dependence will be used in further modeling efforts. Given the nearly isotropic behavior of YAG at room temperature ($A \sim 1.03$) and the added complexity associated with modeling non-isotropic materials YAG will be treated as an isotropic solid for this project. Additionally, considering the low stress associated with the CTE matched system inclusion of the pressure effects will also be omitted as the impact of low stresses on the system are negligible.

Index of Refraction and Coefficient of Thermal Expansion

Index of refraction varies linearly with temperature. The values for Nd:YAG are well known and have been confirmed by several research groups, Tilleman's two recent publications [20] and [21] provide an excellent summary of published values for both index of refraction and the first derivative with respect to temperature. Tillman's publication also consolidates several groups' measurements of thermal expansion as well.

Ultimately because Scientific Materials publishes material properties for the Nd:YAG it produces those values were chosen for the simulation parameters those parameters are summarized in Table 3: Material Properties for Nd:YAG published by Scientific Materials [36] .

Table 3: Material Properties for Nd:YAG published by Scientific Materials [36]

Property	
Index of Refraction (n)	1.8283
dn/dT	7.8E-6 K ⁻¹
Coefficient of Thermal Expansion (α)	8.2E-6 K ⁻¹
Poisson's Ratio	0.28
Young's Modulus (E)	8.25 GPa
Thermal Conductivity (k)	11.2 Wm ⁻¹ K ⁻¹
Specific Heat (c_p)	0.59 Jg ⁻¹ K ⁻¹

MODELING ABSORPTION IN Nd:YAG

Absorption is the first step in the lasing process. As light passes through an optical glass the glass will absorb light as a function of wavelength. This absorption can be modeled mathematically allowing calculation of absorption distribution and intensity. This distribution can then be converted to a thermal load on the system and included in a finite element model of the laser system.

Beer-Lambert Law

Absorption is often described using the Beer-Lambert law given in equation 5. The Beer-Lambert law (Beer's Law) predicts absorption as a function of the path length (x), the wavelength dependent absorption coefficient ($\alpha(\lambda)$), and the initial light intensity (I_0).

$$I(x) = I_0 e^{-\alpha(\lambda)x} \quad \text{equation 5}$$

Beer's law is useful in calculation of the distribution of absorption sites in Nd:YAG [37]. This formulation defines absorption as a function of a material parameter (α), a spatial parameter (x), and a system input parameter (I_0).

Alpha is an intrinsic material property that is a result of distributed absorbing ions in a host lattice. Alpha can be calculated by the product of the number density of the absorption ion (N) and the absorption cross-section of that ion ($\sigma^{abs}(\lambda)$), equation 16[10].

$$\alpha(\lambda) = N \sigma^{abs}(\lambda) \quad \text{equation 6}$$

The number density has units of inverse volume (m^{-3}) and is a function of how many absorbing ions exist in the parent lattice. In the case of Nd:YAG with the molecular

formula $\text{Nd}^{3+}:\text{Y}_3\text{Al}_5\text{O}_{12}$ there are three replacement sites because neodymium ions are replacing the yttrium in the parent YAG lattice. By comparing the density of YAG to the mass of a single unit cell of YAG and multiplying that by the doping concentration of neodymium the number density can be calculated. equation 16 [38] gives the resultant number density, where ρ_{YAG} is the density of YAG, M_Y is the atomic mass of Yttrium, M_{Al} is the atomic mass of Aluminum, M_O is the atomic mass of oxygen, M_{proton} is the mass of a proton, and P_{Nd} is the percentage of neodymium replacing yttrium in the glass.

$$N = \frac{3\rho_{\text{YAG}}}{(3M_Y + 5M_{\text{Al}} + 12M_O)M_{\text{proton}}} P_{\text{Nd}} \quad \text{equation 7}$$

The Absorption cross-section ($\sigma^{\text{abs}}(\lambda)$) has units of area (m^2) and can be interpreted as the effective area seen by a perpendicular incident beam of pump light. The absorption cross section is a material property [39] that changes with wavelength as result the absorption coefficient alpha is also a wavelength dependent parameter and the dependency is shown in Figure 10 see. Note that the absorption peak is $\sim 9.5\text{cm}^{-1}$ at the pump wavelength 808nm.

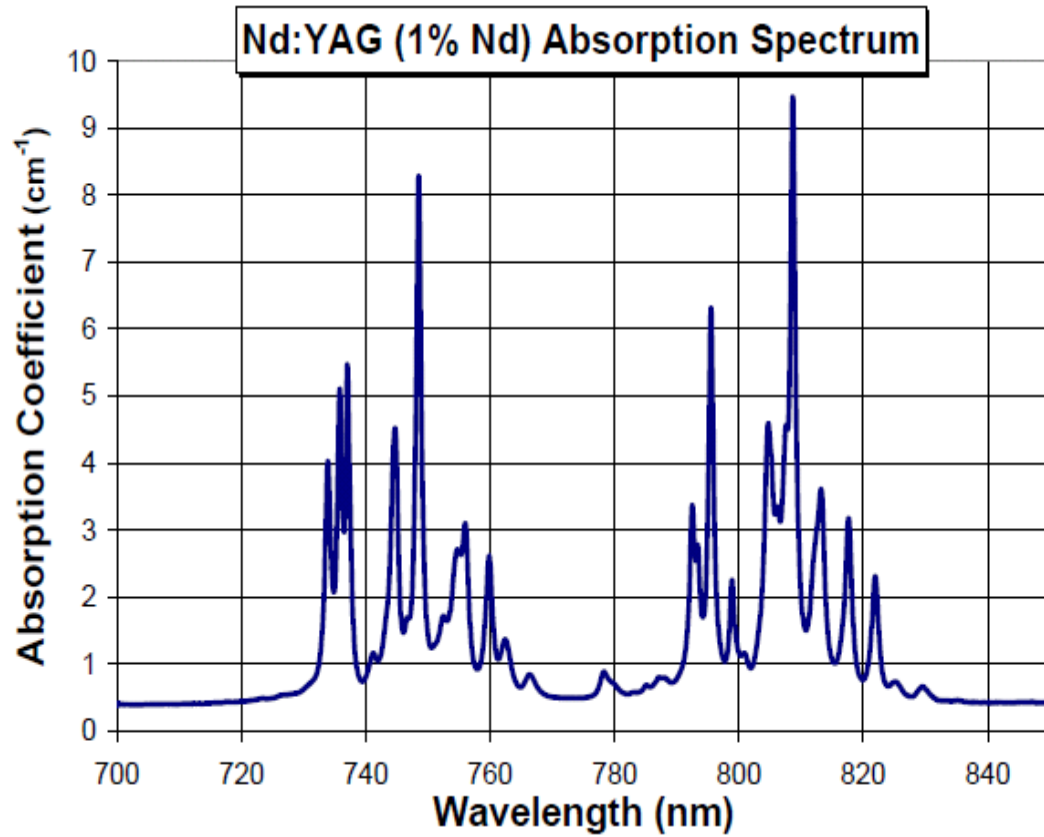


Figure 10: Absorption Coefficient of 1% doped Nd:YAG Versus Wavelength [40]

Figure 11 shows absorption predicted by Beer's law as a function of normalized length for Nd:YAG with an alpha coefficient of 9.5cm^{-1} equivalent to a pump wavelength of 808nm. It is apparent that when pumped at the absorption peak for Nd:YAG absorption is a rapid process in regards to the path required to absorb the input light.

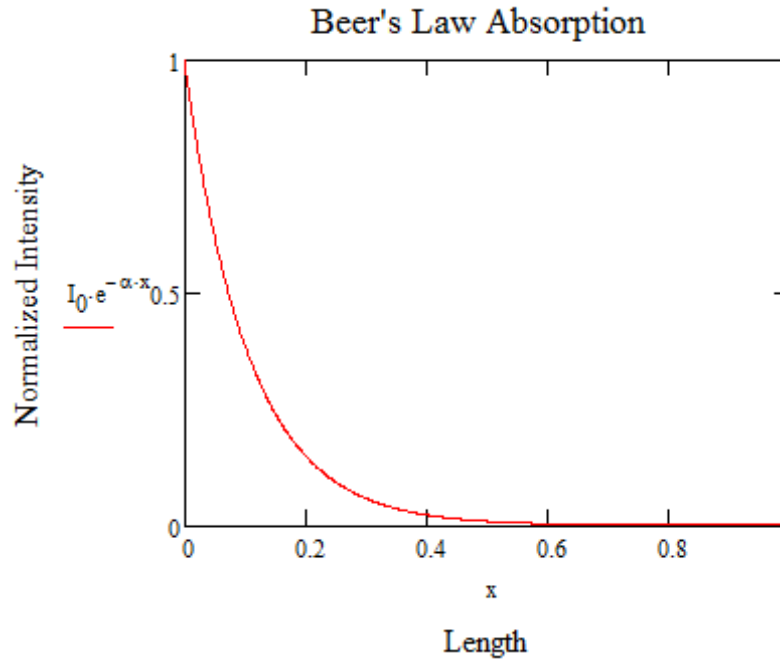


Figure 11: Predicted Absorption Using Beer's Law and an Alpha Value of 9.5cm^{-1}

Photonic Conversion and Absorption Efficiency

Photonic conversion following absorption is not a lossless process. The conversion of pump photons in Nd: YAG results in a deficit in energy between the input photons of the pump and the output emission photons. Using equation 2 the photon energies can be calculated for both the pump wavelength of 808nm and the laser wavelength of 1064nm (Table 4). If the energies are compared it is apparent that for all input energy at the pump wavelength only ~76% of the input energy is converted to light at the laser wavelength.

Table 4: Pump and Laser Photon Energies and Percentage of Energy Maintained in Laser

Pump Photon Energy	2.458 E -19 J
Laser Photon Energy	1.866 E -19 J
Percentage of Energy Remaining in Laser Photon	75.94

This deficit in energy is referred to as the quantum deficit. This energy manifests in the form of non radiative phonon interactions and ultimately heat [19, 41]. The four level laser system of YAG results in heating at each of the absorption sites described by Beer's law (Figure 12).

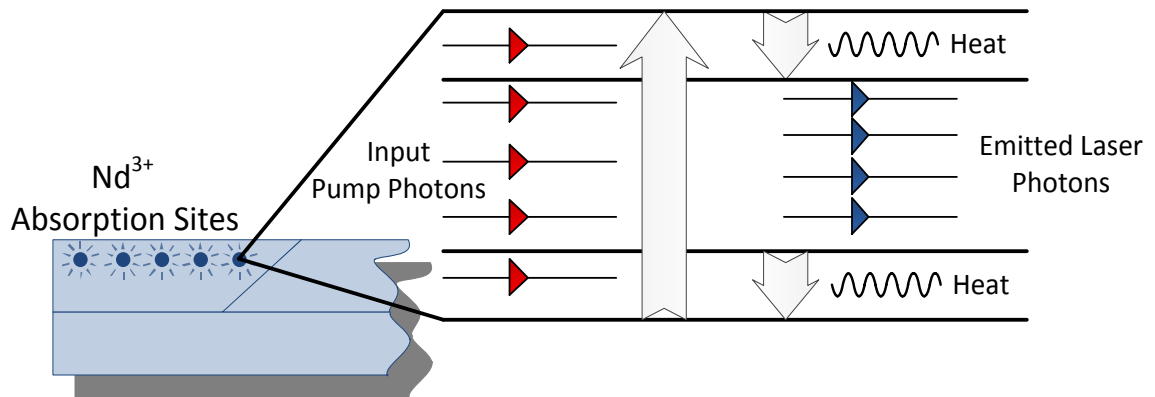


Figure 12: Diagram of Four Level Laser System and Resulting Quantum Deficit in the Nd:YAG

In addition to the deficit in photon energies not all neodymium sites in the YAG lattice emit phonons after absorption. These 'dead sites' will absorb input photons and not decay via a radiative emission but rather relax to the ground state via a non radiative phonon interaction. This additional non radiative decay further increases the heat load beyond the ~24% due to the quantum deficit. Fan et. al studied this phenomenon in both

lasing and non lasing Nd:YAG systems and noted that depending on the distribution of dead sites and the lasing conditions this thermal efficiency can range from 37-43% of the input energy [3]. Fan et al also notes that the higher values of thermal efficiency occur under non lasing conditions. If this thermal efficiency term is applied to equation 5 a heat load can be calculated as a function of path length through the system (equation 8).

$$I_{heat}(x) = \eta_{heat} I_0 e^{-\alpha(\lambda)x} \quad \text{equation 8}$$

This unfortunate correlation results in a snowball effect where an unstable pulsed laser can miss an emission pulse resulting in an instantaneous spike in heat generation and an intensification of thermally induced errors. These thermal errors include lens effects from the change in index of refraction associated with increased temperature[42], lens effects the change in physical length associated with increased temperature[19], stress induced changes from expansion at boundaries[5]. These papers are focused on lensing effects on beam quality and the resulting output powers of slab and rod geometry lasers.

MONOBLOCK LASER

Scientific Materials Corporation (SMC) of Bozeman [43] produces a solid state pulsed laser source the moniker Monoblock. The Monoblock is unique because of its small size (Figure 13) and low cost (~\$1600). The Monoblock laser is a solid-state laser based around a neodymium doped yttrium aluminum garnet (Nd:YAG) gain medium. The Monoblock laser is capable of producing high energy pulses ($>15\text{mJ}$) with pulse durations less than 10 ns. The Monoblock was developed by Army Night Vision Labs for use as a range finder [44]. As produced by SMC the Monoblock contains an optical parametric oscillator (OPO) and produces $1.5\mu\text{m}$ light pulses, personnel at Spectrum Lab and Bridger Photonics have modified the system and removed the OPO resulting in light pulses of 1064nm [8]. The resulting footprint of the Monoblock is approximately $3''\times0.25''\times0.25''$ and is shown in Figure 13.

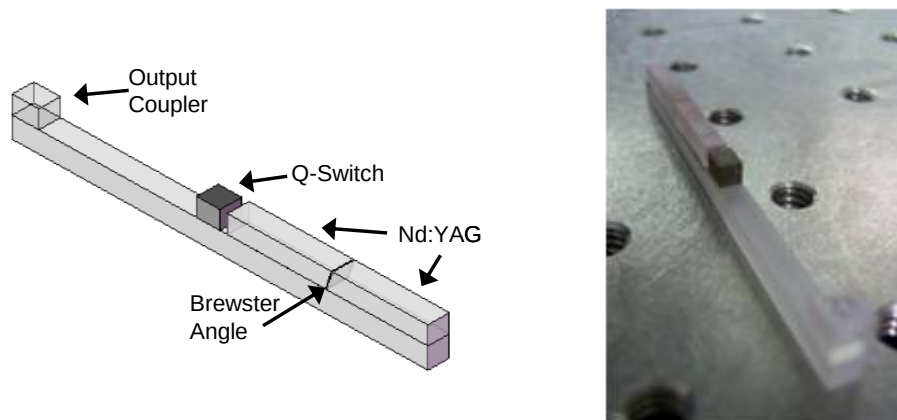


Figure 13: Monoblock Laser, Labeled SolidWorks drawing of Monoblock Construction (left), Image of Monoblock on optical table with 1 inch hole spacing to show relative size (right)

Construction

The Monoblock utilizes a unique construction allowing operation across a wide temperature window[37]. Each of the individual optical components of the Monoblock laser is constructed from doped or un-doped YAG making it a monolithic construction. The Monoblock laser cavity is a flat-flat configuration formed by a pair of reflective coatings on the gain region and output coupler, a cut in the gain region at the Brewster polarization angle for 1064nm light rejects all but a single polarization of light. An intracavity chromium doped YAG (Cr:YAG) parallelepiped acts as a passive Q-Switch producing pulsed behavior (Figure 14).

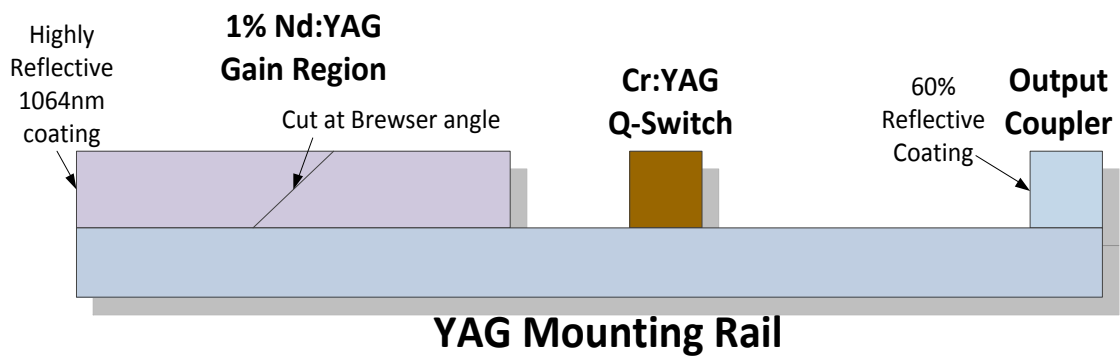


Figure 14: Monoblock Constituents

By mounting the components of the laser on a continuous piece of YAG the Monoblock has no mismatch in the coefficient of thermal expansion (CTE) among components. A lack of CTE mismatch allows each of the individual components to move uniformly with temperature changes and the alignment of the optical cavity can be

maintained at various temperatures. The prismatic nature of the optical components also allows for ease of manufacture and low cost.

Laser Failure

The Monoblock was originally developed as a flash lamped system for 0.33Hz pulse rate operation [44]. Flash lamp systems provided the advantage of low cost simplicity but lacked ability to scale to higher pulse rates. To transition to a higher repetition rate a diode system was chosen as the pump source. The diode system provided advantages in both repetition rate as well as monochromatic input increasing the overall efficiency of the optical pump [8]. Two pumping configurations were possible pumping the gain region on the side opposing the mounting rail (Top Pumping) and pumping the back reflective face of the gain region (Back pumping) Figure 15.

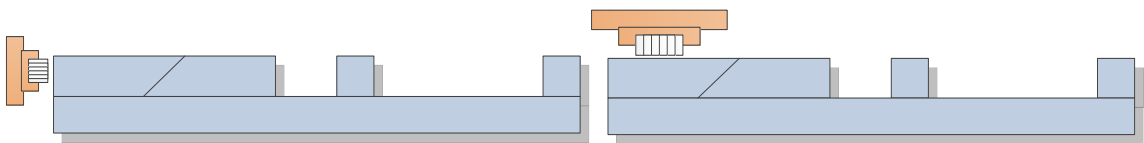


Figure 15: Diagram Showing Diode Back Pumping (Left) and Diode Top Pumping (Right) of the Monoblock

As diode repetition rate increased laser performance became unstable. Diode pumping the Monoblock was resulting in expansion of the pumped gain region as result of thermal expansion. The reflective surface at the back of the gain acts as one of the mirrors forming the optical cavity this means that if the gain region moves the highly reflective mirror of the optical cavity also moves. The mounting method of the gain

region resulted in a non uniform expansion of the back face; the bottom of the gain is glued to the base YAG rail while the top is unbound and free to expand. In the case of top pumping this was compounded by the absorption profile of the YAG; high absorption at the top of the gain and thus high heat generation. These two effects worked in tandem to produce an angled face that resulted in reflected light moving off axis of the Monoblock (Figure 16).

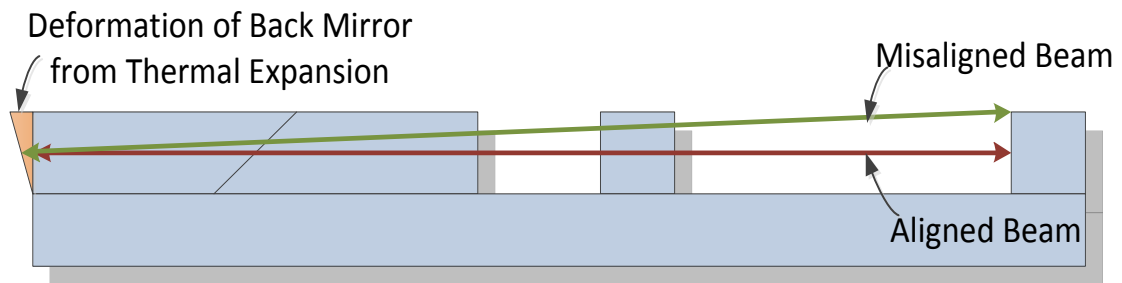


Figure 16: Diagram Showing Misalignment (green) of the Monoblock as Result of Thermal Expansion

Using the dimensions of the Monoblock and simple right angle trigonometry angular deflection in excess of 0.015 degrees will result in the reflected beam missing the face of the output coupler and laser failure. Thermal loading of the system at higher repetition rates was producing an optical misalignment of the laser cavity. Monoblock systems began to intermittently lase between 3 and 4 Hz diode pulse rates and cease all together above 4 Hz. It became apparent that the Monoblock though robust at low repetition rates exhibited a systematic failure as repetition rate increased. Switching from a top pumped configuration to a back pump configuration would alleviate some of the

asymmetry associated with the system but heat generation still poses a problem for high repetition laser operation.

EXPIERMENTAL VALIDATION

As discussed, alignment of the optical cavity in the Monoblock is one of the most important parameters ensuring continued operation of the lasing system. If FEA is to be used as a design tool for improvement and optimization of the Monoblock system or any Nd:YAG laser system simulation results must be validated against experimental testing. Experimental testing over the course of this project measured the effect diode pumping has on length of the Monoblock optical cavity.

Interferometry

Interferometry takes advantage of the wave nature of light and uses superposition of two monochromatic optical waves to measure distance or in our case change in distance. Superposition of waves produces constructive and destructive interference that results in a change of in intensity. Constructive interference occurs when intensity peaks are in phase and produces net increase in intensity; destructive interference is the inverse both are diagramed in Figure 17.

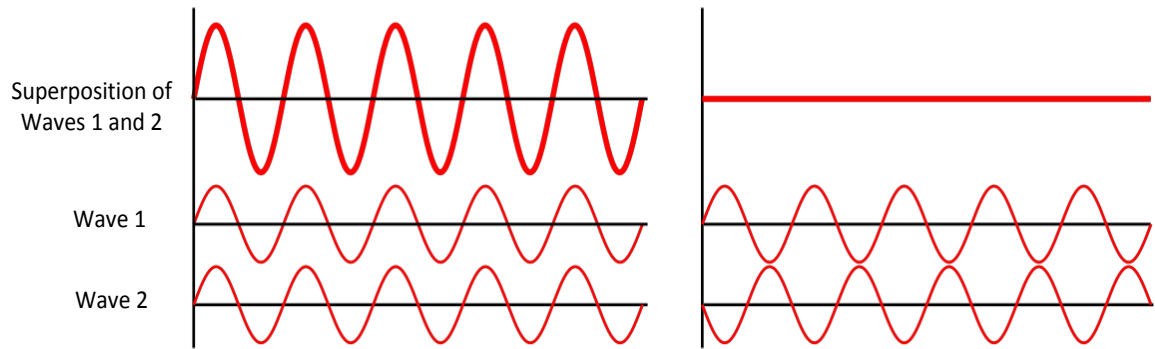


Figure 17: Constructive Interference of Two Sinusoidal Waves Perfectly In Phase (left)
Destructive Interference of Two Sinusoidal wave 180 Degrees Out of Phase (right)

Relative phase among two waves will vary as a function of the path each wave takes. If two waves begin with identical phase and travel different distances after to reach the same point, one of the two waves will have traveled a distance equal to more wavelengths than the other. If the waves go through a reflection and the waves started out in phase, they will no longer be in phase at their destination. They will be out of phase by the fractional number of wavelengths that fit in the path length difference. For the simple case shown in Figure 18 wave 1 and wave 2 differ by in phase by 4.5 wavelengths and are no longer in the same phase.

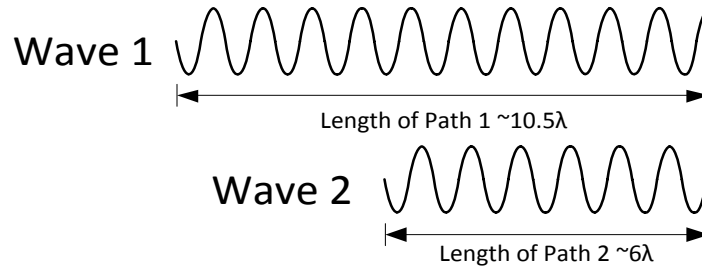


Figure 18: Block Diagram Demonstrating Phase Shift Due to Difference in Path Length

When considering an optical path we also must consider the medium that light is moving through. The speed of light in a vacuum is a constant, but for most other mediums light travels at a slower rate. The ratio of the speed of light in any given medium and the speed of light in a vacuum is referred to as the index of refraction (n). Changing the index of a path while maintaining the geometric length will produce a phase shift in the same manner that changing the geometric length, it is therefore useful to consider a new term optical path length (OPL). For a uniform medium OPL is the product of index of refraction (n) and geometric length (L) and is the apparent length seen by light (equation 9)[10].

$$OPL = nL \quad \text{equation 9}$$

Any change in either index of refraction or geometric length will produce a change in the OPL and thus a phase shift of light moving through that path. For an object whose temperature changes, length as well as index of refraction, both of these properties will affect the OPL of a beam traveling through the object. For a uniform temperature change the change in length can be calculated by the product of the coefficient of thermal

expansion (α), the change in temperature (ΔT), and the original length (L) (equation 10) [45]. Alpha has units of $\frac{m}{m^{\circ}C}$ and is an intrinsic property of the material.

$$\Delta L = \alpha L \Delta T \quad \text{equation 10}$$

The change in index of refraction can be calculated similarly by multiplying the change in temperature (ΔT) by the rate change in index with respect to temperature (dn/dT) [10].

$$\Delta n = \frac{dn}{dT} \Delta T \quad \text{equation 11}$$

The change in optical path length for a uniform temperature change can then be calculated by combining equation 9, equation 10 and equation 11 this expanded form is shown in equation 12. The effect of a temperature change is summarized in Figure 19.

$$\Delta OPL = \left(n\alpha + \frac{dn}{dT} + \alpha \Delta T \frac{dn}{dT} \right) L \Delta T \quad \text{equation 12}$$

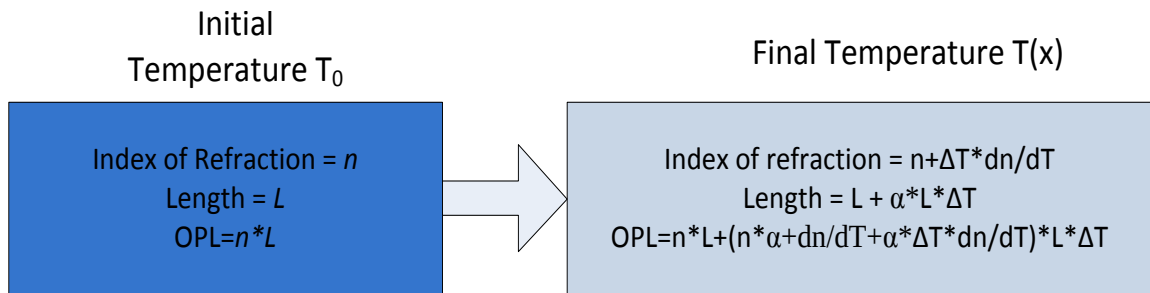


Figure 19: Summary of Temperature Effect on Optical Path Length

For a non uniform temperature distribution ($T(x)$) along a path equation 12 can be extended to a differential equation and integrate along a path to yield the final optical path length.

$$OPL = \int n + n\alpha(T(x) - T_0) + \frac{dn}{dT}(T(x) - T_0) + \frac{dn}{dT}\alpha(T(x) - T_0)^2 dx$$

equation 13

Michelson Interferometer

In a Michelson Interferometer a laser source is split into two beams of the same phase; these two beams can each then be sent a separate paths (arms) and then recombined and interfered to produce a measureable change in intensity.

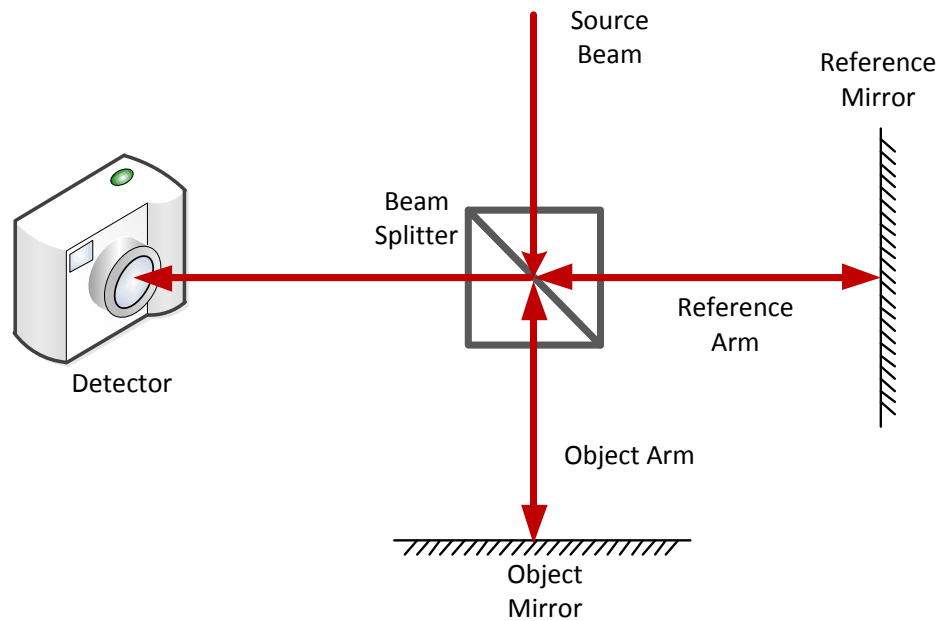


Figure 20: Block Diagram of a Michelson Interferometer

If the OPLs of the arms are equal the beams will remain in phase and when interfered will result in a uniform maximum or minimum output depending on the phase of the initial phase of light. If the arms are of differing OPLs the intensity will vary depending on the phase shift produced by differing OPLs. Typically one arm is held at a constant OPL and the second arm is allowed to vary and produces the change in output intensity.

Experimental Method

A modified version of the Monoblock laser that had the output coupler and Q-switch removed was used in a Michelson interferometer (Figure 21). The highly reflective back face of the gain region acted as the reflective mirror of the object arm. As the diode was pulsed a CCD camera was used to capture changes in the interference pattern for later analysis via MATLAB.

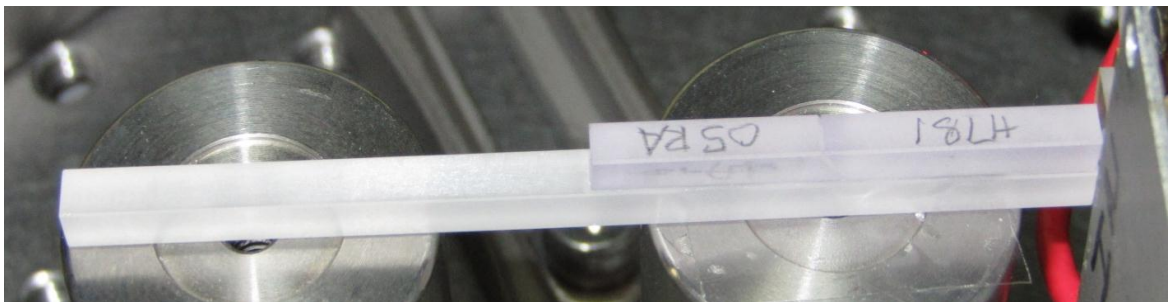


Figure 21: Monoblock Test Sample Showing Removed Output Coupler and Q-Switch

A 1060nm fiber coupled distributed feedback (DFB) laser (Qphotonics model QFBGLD-1060-40) was used as the source beam in the Michelson. The DFB was mounted in a ThorLabs butterfly mount (model LM14S2) and temperature stabilized using an ILX

Lightwave temperature controller (model LDT-5412). The laser was current driven by an ILX Lightwave precision current source (model LDX-3207B). Output of the DFB was collimated into a 1mm diameter beam and passed through a pair of lenses acting as a beam expander. The object lens was a 50mm focal length bi-convex lens, the image lens was a 200mm bi-convex lens that was placed at 200mm from the focus of the of the object. This pairing of lenses created a Kepler type beam expander (Figure 22) that expanded the beam by a factor of 4 to a 4mm diameter beam [46].

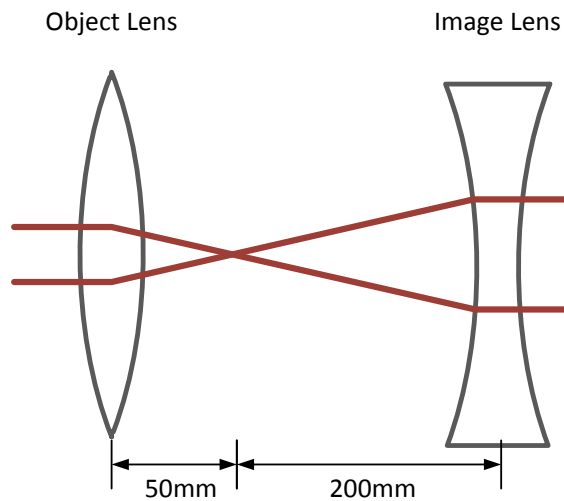


Figure 22: Block Diagram of a Kepler Type Beam Expander

After expansion the beam entered the Michelson interferometer, where a beam cube was used to split the beam into the object and reference arms. A silvered flat mirror was used for the reference mirror and the highly reflective back face of the Monoblock gain was used for the Object mirror. A ThorLabs CMOS camera (model DCC1645C) was used to capture the interference pattern produced by the superimposed beams. A Lasertel

808nm diode (model LT-5500-01-1897) was used as the pump source for the Monoblock. The diode was driven by an Omnipulse pulsed current source (model PLDD-200-12-20), the diode was pulsed 300 microseconds at 74 amps and 17.7 volts , producing 720 watts of optical power. A Stanford Research Systems delay pulse generator (Model DG535) was used to produce pulse trigger and duration. The pump diode was temperature stabilized at 23 degrees Celsius via a thermoelectric cooler (TEC) controlled by a Wavelength electronics temperature controller (model WTC3293-14001). Figure 23 shows a diagram of the overall optical Layout.

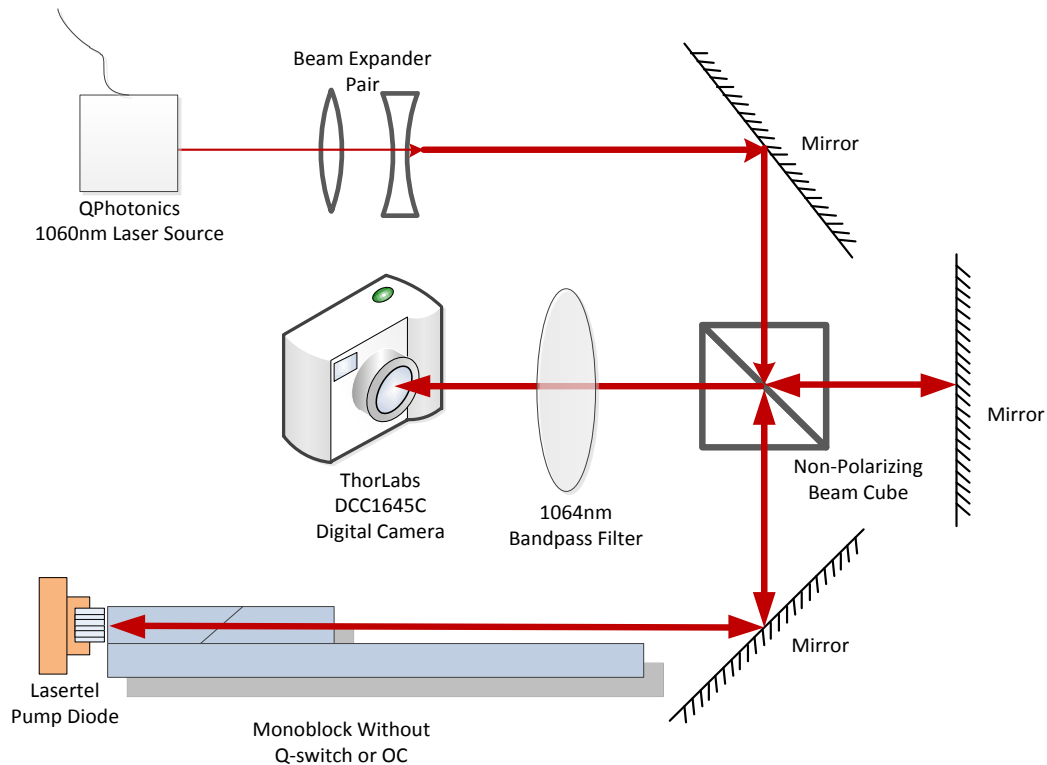


Figure 23: Diagram of Optical Components Creating a Michelson Interferometer for Measurement of the Monoblock OPL Changes as Result of Diode Pumping

The modified Monoblock was mounted with Scotch 3M permanent double stick tape on two 3 inch stainless steel optical pedestals (Figure 24).



Figure 24: Mounting Method for Monoblock Interferometer Tests

Tape was only used on the rear region of the Monoblock to insure that the system would expand forward from the reflective surface. The forward region of the pedestal was not taped and merely provided support under the bottom rail. The optical system was aligned such that a perturbation of the reference mirror caused a uniform change in intensity over the entire rectangular image captured by the camera; Figure 25 shows a series of typical patterns produced by diode pumping the Monoblock in the Michelson interferometer.

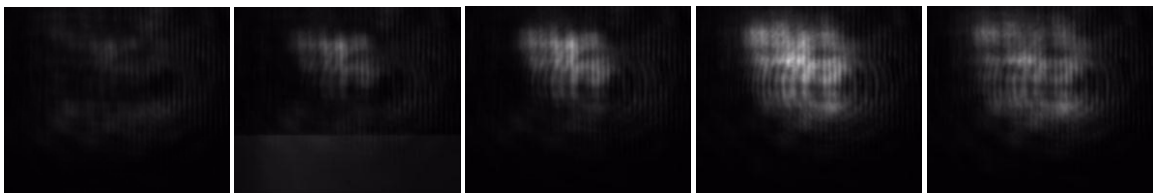


Figure 25: Series of images showing change in intensity produced in the Michelson interferometer as result of diode pumping

Data Capture

Image data was captured using ThorLab's UC480 image acquisition program in tandem with the DCC1645C CMOS camera. The camera capture rates and resolution were set such that the camera captured at 33.66 frames per second (fps). This rate was chosen because it was 1.5 times greater than the Nyquist rate for the fastest testing at 10Hz ensuring there was not aliasing in the Interferogram data. The Nyquist rate is the minimum sampling rate that can be used and produce an alias free data. Aliasing in this case would be the detection of a fringe change when no fringe change had actually occurred. Capture at this rate resulted in an image size of 640x512 pixels and was dependent on the capabilities of the camera; images were captured in *.avi video format.

Tests were performed for repetition rates from 1-10 Hz increasing by 1 Hz per test, 3 tests were performed at each repetition rate. The testing procedure was as follows: Begin capturing video of the steady state system, trigger diode pulse at desired repetition rate, capture diode pulses for ~12,000 frames at 33.66fps, turn off diode trigger, continue capturing frames until total frame number is ~20,000 frames. Frame capture numbers were determined from previous tests and chosen because ~12,000 frames was approximately the time necessary for a 10 Hz test to reach steady state.

Data Processing

Video files for each test were processed using MATLAB video and image processing capabilities. Each test video was imported into MATLAB using the multimedia reader command *mmreader()*. Mmreader creates a MATLAB readable object from the *.avi video file. Following object creation each of the individual frames was read using the *read()* function which produces a data matrix corresponding to the RGB values of each of the pixels of the video frame. This matrix was then converted into a grayscale image using the function *rgb2grey()*. This converted image represented the intensity of each of the pixels from 0-1, with 0 being black and 1 being white. Now that the image was converted to an intensity plot it could be divided into regions for later comparison with simulation results. Each of the images was subdivided into eight vertical regions (80x64pixels) to match the mesh size used in the simulation the intensity of these regions was then averaged for each frame; Figure 26 shows the subdivision and averaging scheme for a single frame. The frame read and conversion procedure resulted in an intensity data set that could be plotted with reference to frame number representing the change in intensity as a result of diode pumping the Monoblock; Figure 27 shows an example plot for a single intensity region. See Appendix B for complete import code.

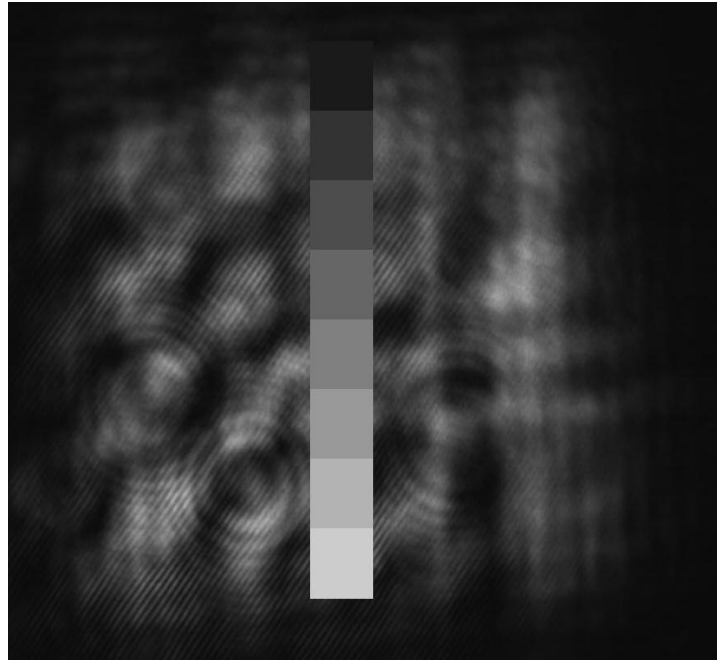


Figure 26: Picture showing the Subdivision averaging scheme for of Each Interferogram Frame of the Video

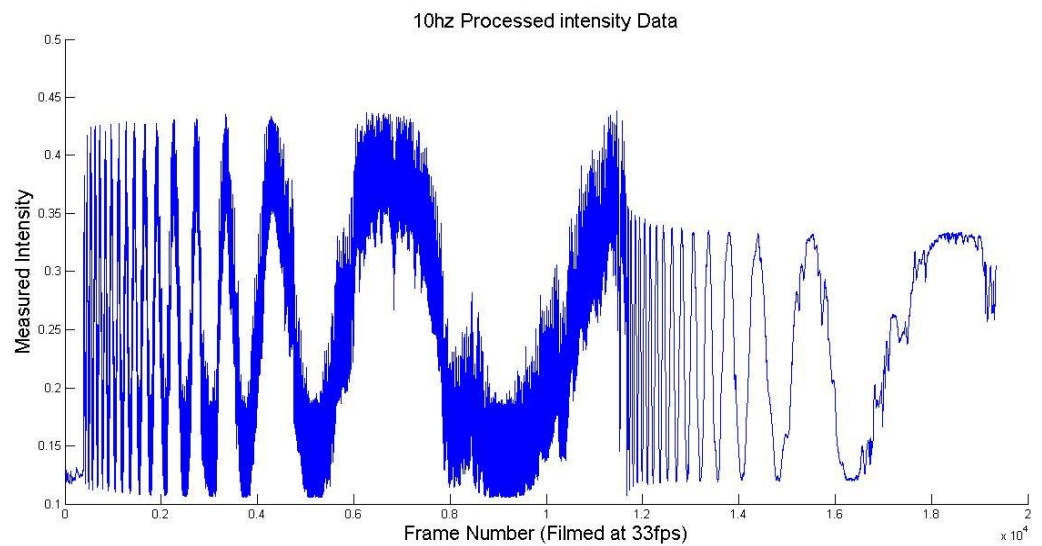


Figure 27: Example of Intensity Plot from Video File at 10 Hz Diode Pulse rate

After plotting it became apparent that during diode operation the diode was saturating the camera over a portion of the image causing an artificial inflation in the measured intensity. Figure 28 shows an example of both the effect of the diode saturation on the image captured by the camera and the resulting intensity inflation in the extracted data, the peaks in the right of Figure 28 show frames that had saturation as a result of diode pulses.

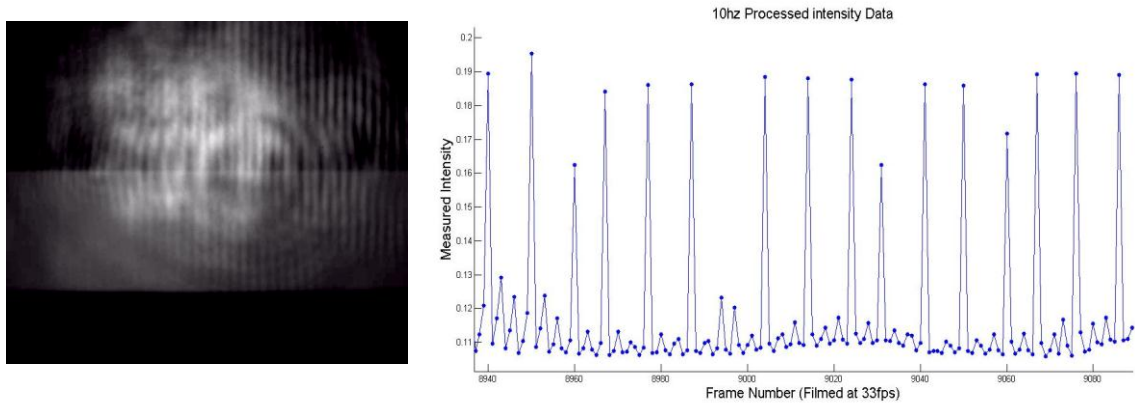


Figure 28: Effect of diode light on interferometer intensity, Image showing Camera Saturation (Left), Intensity plot at Steady State Operation shown diode effect (Right)

To remove the artificial effect of the diode pulse the intensity data was post processed to remove artificial pulses. The intensity data produced from the captured videos was first smoothed using MATLAB's integrated smoothing algorithm *smooth()* with a 10 point moving average. This smoothed data was used as a reference to compare the raw data and find outliers produced by diode pulses. The quadratic mean (RMS) was then calculated for the data set (equation 16), where *Data* is the captured intensity data for a given test.

$$RMS = \frac{Norm(Data)}{\sqrt{length(Data)}} \quad \text{equation 14}$$

The raw data set was then searched for data points differing from the averaged set by 1.25 times the RMS, 1.25 was chosen after inspecting the data by hand and noting that the minimum deviation of the outliers was approximately 25 percent. The outliers were then replaced by the average of the two data points on either side of the outlier. Figure 29 shows a plot of both the raw uncorrected data (blue) and the corrected data (red) for a single 10 Hz test. Appendix C shows the entire MATLAB code used to process each data set.

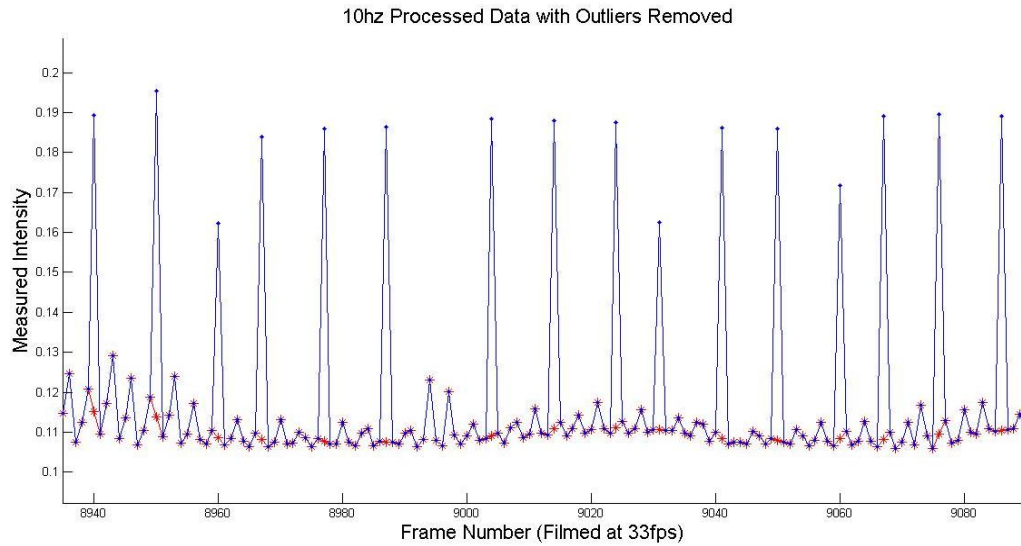


Figure 29: Plot of Interferogram Intensity Data with Both Raw Intensity Data with outliers (Blue), Data Post Processed to Remove Outliers (Red)

After the outliers were removed from the data sets the data was converted from an intensity plot into a plot of unwrapped phase. The change in intensity captured by the camera actually corresponds to the phase angle in radians of the incoming light and is a periodic function. The periodic phase change can be ‘counted’ and transformed into a total phase change, this is termed unwrapping the phase or unwrapping. MATLAB has built in functions for performing unwraps of captured data. Before the intensity data can be unwrapped it must be centered about the x-axis. By subtracting the mean of the data series it can be centered about the x-axis, the Hilbert transform was then used to calculate the instantaneous phase of the data[47]. The *angle()* function was used to transform the Hilbert output into a phase angle. Finally the phase angle was unwrapped using the built in unwrapping function that collects the total phase change of the data [48]. equation 16 shows the necessary operations to produce the unwrapped data, where *data* refers to the post processed data with outliers removed.

$$\text{unwrapped data} = \text{unwrap}(\text{angle}(\text{hilbert}(\text{data} - \text{mean}(\text{data})))) \quad \text{equation 15}$$

The unwrapped data is the total change in phase angle of the light detected by the interferometer as a function of time (Figure 30).

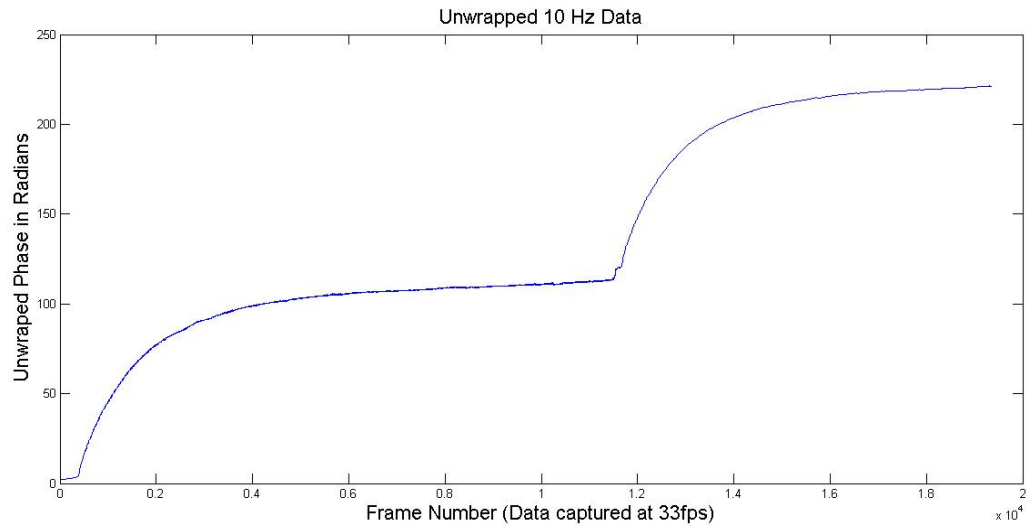


Figure 30: Example of Unwrapped phase data for a 10Hz test

Note that the second rise shown in Figure 30 at approximately frame 12,000, this second rise is a result of when the diode was turned off and the system began to cool. The raw data shows that it is an additive effect but it is actually a subtractive effect because the system had begun to cool and contract. The unwrap function has no way of detecting whether a fringe change is additive or subtractive so some knowledge of the processes occurring in the system must be used to interpret the results.

To convert the unwrapped phase from phase angle to optical length the unwrapped data must be divide by two pi to convert from radians to number of waves, multiplied by the wavelength of the source beam, and divide by 2 because the light is passing though the medium twice, once for the initial pass and once for the reflection pass (equation 16).

$$\Delta L = \frac{\text{unwrapped data}}{2\pi} \left(\frac{\lambda_{\text{source}}}{2} \right) \quad \text{equation 16}$$

Figure 31 is a plot of a single 10 Hz test after processing to remove outliers, unwrap, and convert to optical path length.

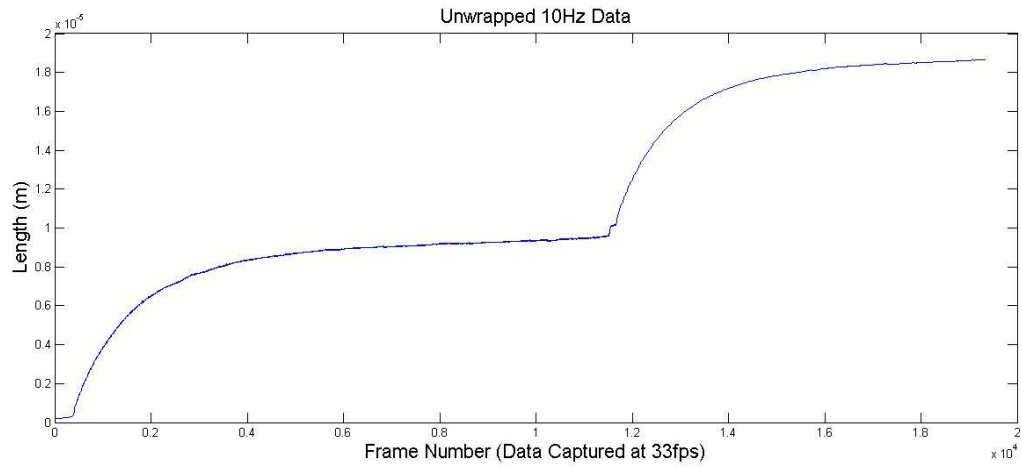


Figure 31: Example of processed 10 Hz Data, Showing Unwrapped Optical Path Length as a Function of Frame Number

Sources of Error Experimental Data

There are three primary sources of error that were considered in collected data: noise errors, drift noise and unwrap errors. Noise errors are errors that are systematic for the method of data collection and are present in all systems. Noise can be result of vibrations of buildings, air currents, variance in camera performance and a myriad of other causes. To analyze the level of noise in this system the unwrapped portions of the

data when the diode was off were studied. If a steady state portion of those tests is examined closely roughness in the data is apparent. Figure 32 shows location of noise analysis plot examined in Figure 33.

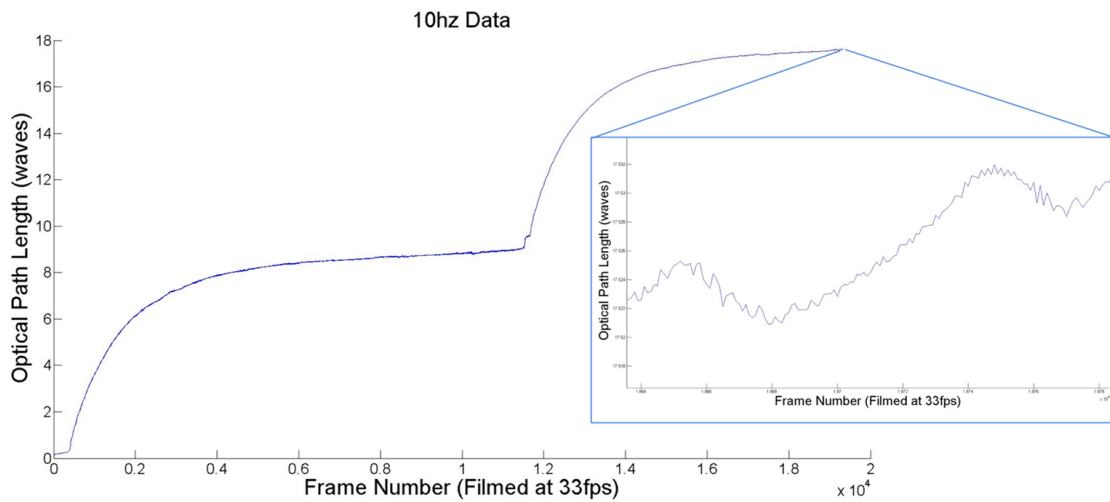


Figure 32: Typical noise error in waves for a 10 Hz test

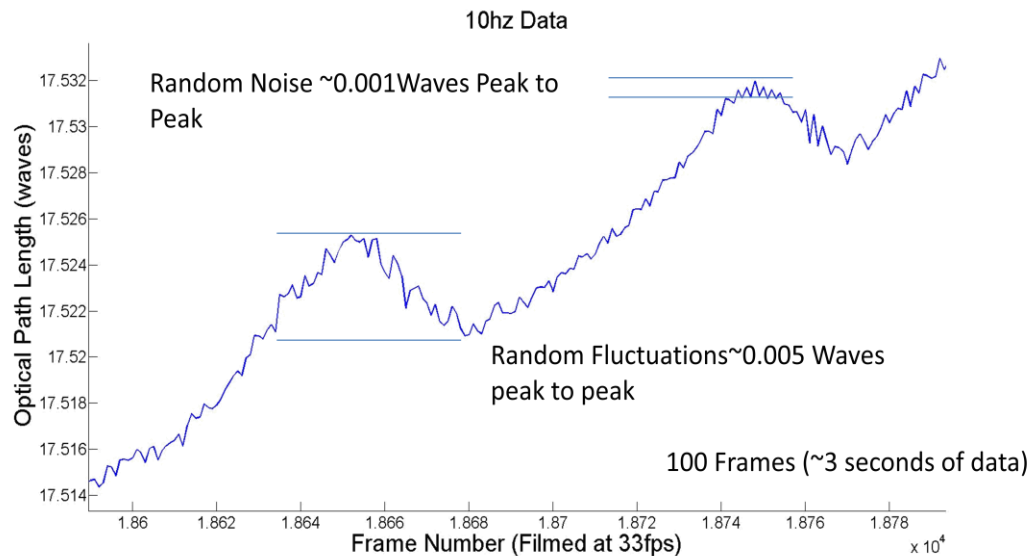


Figure 33: Noise analysis Plot for Steady State Diode off 10 Hz test

If the noise in plot in Figure 32 is measured as a peak to peak error, the data has a typical noise error of 0.001 waves, and a random fluctuation error of 0.005 waves at the laser line of Nd:YAG 1064nm. If the noise error is converted to a physical length the resulting error is on the order of 1-5nm. The error shown in Figure 33 is typical of the error seen in all the tests and it is a reasonable claim that measurements by the system are accurate to 0.01 waves.

The second error of concern is stability of the system or temporal drift. Drift will result in the measurement of a steady state system changing over time when the system is in fact stable. To calculate drift the unwrapped portion of data with the diode off is again used. A liner fit to what should be flat steady state data was performed and the slope of the line was considered the drift of the data. Figure 34 shows a plot of typical drift error across all tests.

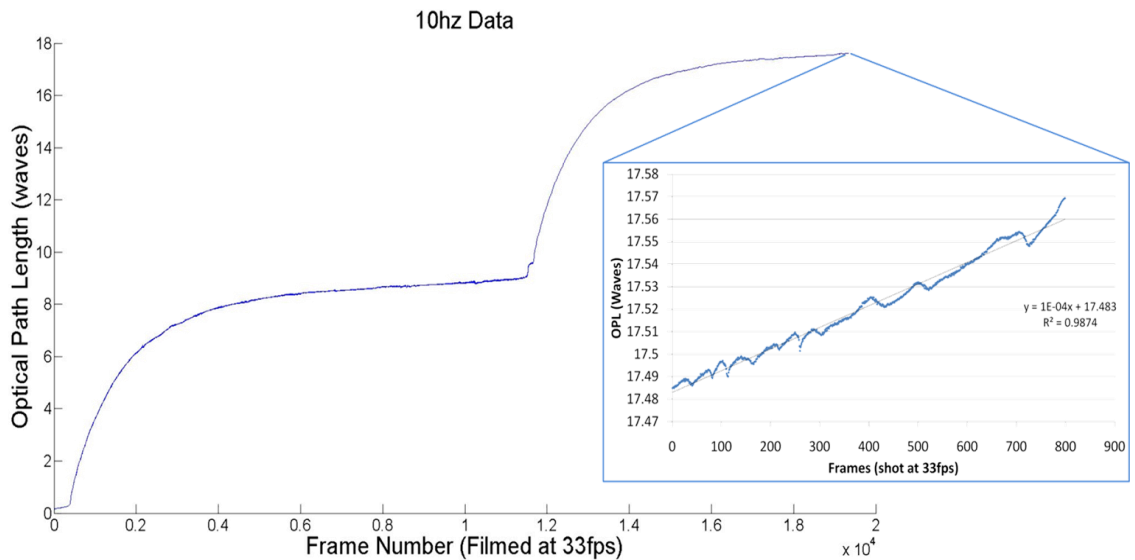


Figure 34: Typical Drift Error for a 10 Hz test

Drift error for all tests was on the order of 1×10^{-3} waves per second or 1×10^{-9} meters per second. This small error implied that a full wavelength of error would occur approximately every 1000 seconds or 17 minutes of operation, three times longer than the test duration. The sum of both the noise and drift error implies that final steady state results should be accurate to approximately 0.3 waves.

Lastly the most significant errors of the measurement technique were errors caused by the unwrap algorithm. The unwrap function is effective for data with a rapid change in frequency but the algorithm can introduce factors of π (half wave length) error in data with slower frequency changes. For this project the lower pulse rate tests, primarily 1-5 Hz, exhibited errors as a result of the unwrap function. Figure 35 is a plot of both the unwrapped data (top) and the RMS corrected data (bottom) showing a typical unwrap error producing a sudden jump in phase that is not representative of the actual phase change of the system.

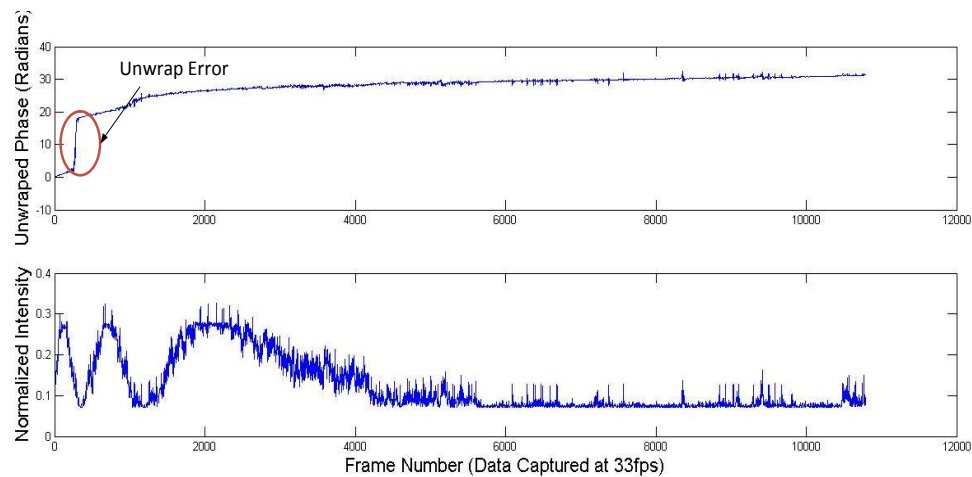


Figure 35: Example of Unwrap Error in a 2 Hz test case, Unwrapped data (Top), RMS Corrected Intensity Data (Bottom)

These unwrap errors introduce an offset in the data but do not affect slope. After many attempts we were unable to remove these errors while still maintaining the integrity of the data, it is apparent when unwrap errors exists and we must rely on the ability of a human to distinguish these errors from actual data.

EXPERIMENTAL RESULTS

Three data sets were taken at 1 Hz intervals ranging from 1 to 10 Hz. Four of these test sets were corrupted in video file creation. To ensure that each data set is referenced to zero the mean was taken for the first 10 data points and subtracted from the set to ensure that the set is beginning at zero. The heating process is of primary interest to the project so each set was plotted for only the heating portion of the total experiment. Additionally data sets that showed unwrap errors as after the system reached steady state were only plotted up to those errors. Figure 36 plots all of the data taken for the heating portion of the diode pulses. Dark blue represents the lowest repetition rate (1 Hz) and red the highest repetition rate (10 Hz). The individual repetition sets are also plotted in Appendix D: Plots of Unwrapped Experimental Data.

Steady State Results

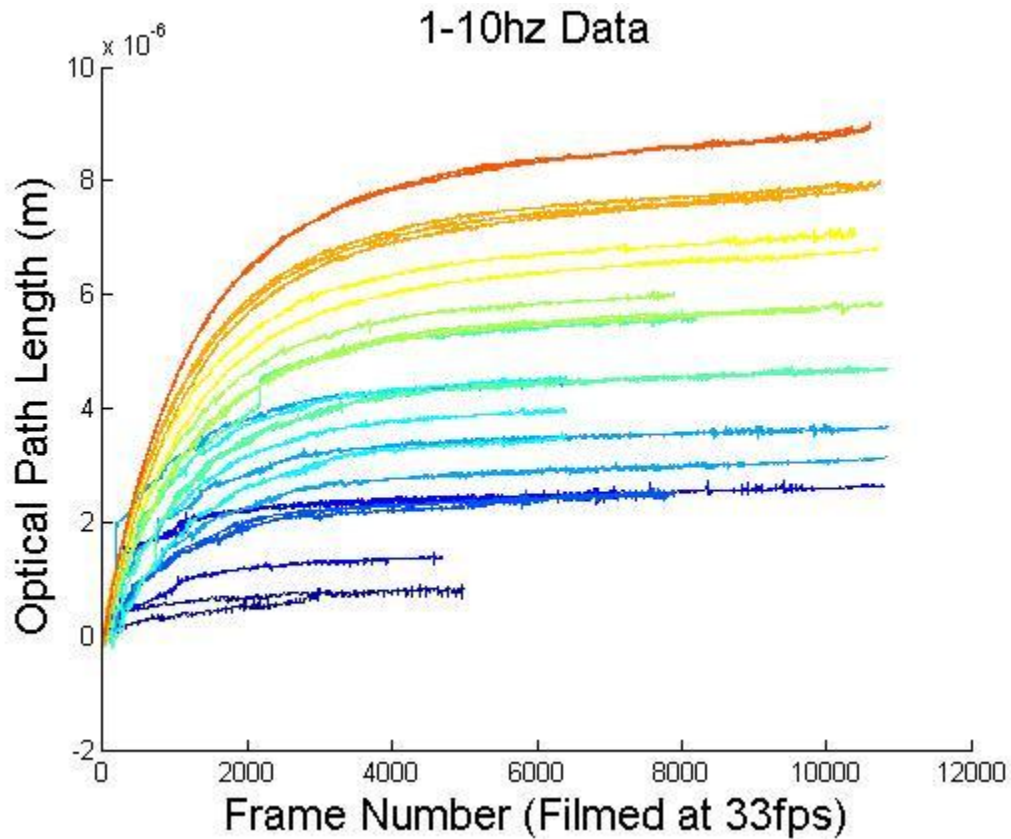


Figure 36: Plots of all Test Data at Steady State

To measure the final OPL of each test the mean of the test set was calculated for the final 100 data points of the test. This mean was compared across tests and is tabulated in Table 5 as well as the percent that the total range deviates from the average across the tests. In the case of tests that showed large unwrap errors the error range is significant and the percent change when compared to the average for the test set can exceed 50%. This large error is attributed to unwrap errors.

Table 5: Final Steady State OPL, Units are Meters

Repetition Rate	Test 1	Test 2	Test 3	Range	Range in Waves	Average	Average in Waves	Range Over Average
1 Hz	7.46E-07	8.08E-07		6.18E-08	0.058	7.77E-07	0.730	7.95%
2 Hz	1.37E-06	2.64E-06	2.52E-06	1.26E-06	1.189	2.18E-06	2.046	57.92%
3 Hz		2.39E-06	2.50E-06	1.14E-07	0.107	2.44E-06	2.296	4.67%
4 Hz	4.45E-06	3.12E-06	3.66E-06	1.33E-06	1.257	3.74E-06	3.519	35.61%
5 Hz	3.96E-06	3.50E-06	4.52E-06	1.02E-06	0.966	3.99E-06	3.753	25.65%
6 Hz	5.56E-06	4.69E-06	4.68E-06	8.85E-07	0.834	4.98E-06	4.677	17.78%
7 Hz	5.99E-06	5.82E-06	5.74E-06	2.58E-07	0.243	5.85E-06	5.498	4.42%
8 Hz		7.08E-06	6.80E-06	2.73E-07	0.257	6.94E-06	6.521	3.94%
9 Hz	7.85E-06	7.94E-06	7.75E-06	1.94E-07	0.183	7.85E-06	7.375	2.47%
10 Hz	8.92E-06	8.93E-06		1.20E-08	0.011	8.92E-06	8.386	0.13%

FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) or the finite element method (FEM) is a numerical approach to solving complex differential equations like stress or temperature distributions. The method utilizes the premise that a complex system can be approximated by subdividing the system into a subset of simpler problems represented by a set of linear equations. These simpler problems can then be solved using standard matrix algebra techniques resulting in an approximation of the larger system. As the number of subsets increases the approximate solution will converge to the exact solution for the complex system. FEA is a multi step process that can be divided into three general steps: preprocessing, analysis, and post processing. In the Preprocessing step a model of the system of interest is created and then divided into smaller subsets or 'elements' these elements will have conditions applied to them to replicate system being modeled. These elements represent a set of linear equations; the sum result of this step is called the input file. During the analysis step a numerical method is applied to solve the set of linear equations defined by the input file created in the previous step. Finally in the post processing step the solutions to the linear equations are combined to provide a solution to the complex system being modeled. Modern FEA packages provide a convenient graphical user interface and well developed algorithms for computation and processing of FEA information.

Evolution of Modeling Method

Creation of a modeling method was an evolutionary process of adding complexity and trying to better capture the physics of heat generation as result of the lasing process.

The first attempt at system modeling used a surface flux applied for the duration of a diode pulse on the top surface of the Monoblock. This surface flux was set to the magnitude of the pumping power multiplied by a thermal efficiency as discussed in Fan et al [3]. This surface flux was then followed by a relaxation step that represented the time between pulses (Figure 37). This process was then looped to produce a series of pulses and relation steps that replicated diode pumping of the Monoblock system.

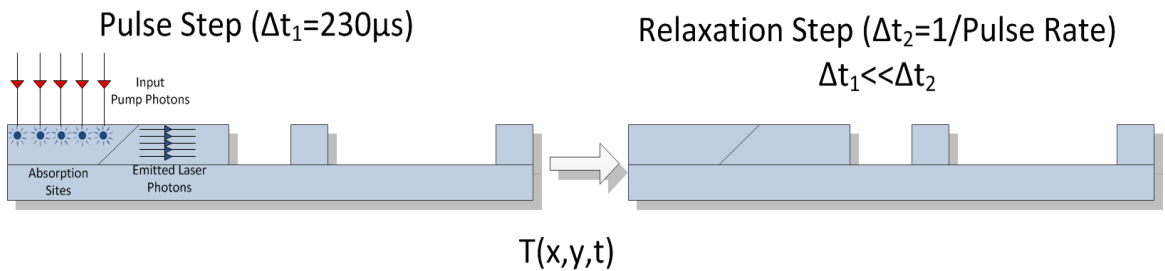


Figure 37: Pulsed Simulation Method

This early model was used to develop an understanding of the FEA environment and establish an automation method for creation of a large number of loading steps to represent the pulsed operation of the Monoblock. The automation method established to create a number of pulsed Monoblock loads is summarized in Figure 38. The procedure required using the Abaqus GUI environment to create a model representing a single pulse and a single relaxation step. This model was then exported into a text input file and read using the Python programming language. The load and relaxation steps were then replicated producing a new input file with a large number of pulse steps simulating the continued pulsed operation of the diode. This new input file was then imported back into Abaqus and solved, finally relevant data was exported into excel to process.

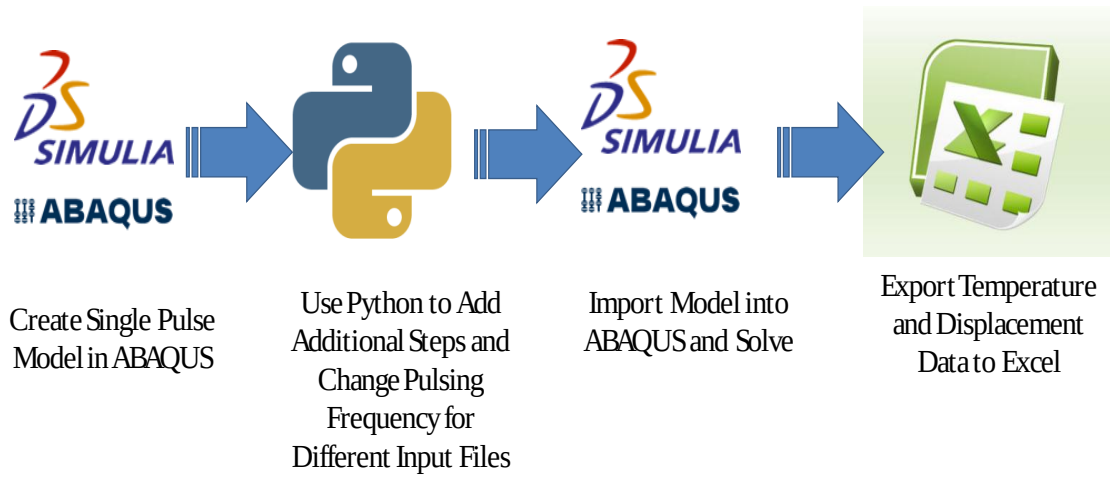


Figure 38: Modeling Procedure for Creation of Pulsed Load Input Files

The results of the first modeling effort are shown in Figure 39.

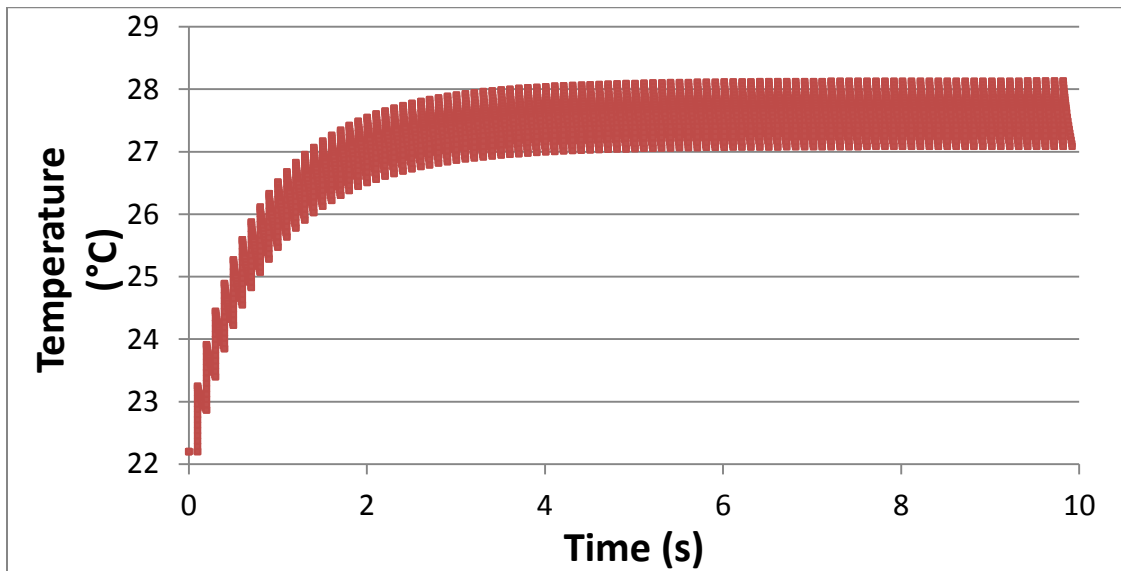


Figure 39: First Modeling Attempt Using Surface Flux and Repeated Pulse Steps, plot shows temperature at the Centroid of the gain region

The results associated with Figure 39 demonstrated the viability of the modeling procedure that was developed and allowed further refinement of the flux load and loading

method. This surface flux was then replaced by a body flux associated with the absorption predicted by Beer's law.

Load Creation

To generate the internal heat load associated with laser Beer's law absorption was used in conjunction with the thermal efficiency range published by Fan et. al developed in [3]. Abaqus has a native script interface utilizing the python programming language. Using this script interface a group of elements in the gain region was selected and grouped into a subset designated by the depth from the pumped face. This set creation was continued for the entire gain region in either the vertical direction (top pumping) or horizontal direction (back pumping) (Figure 40).

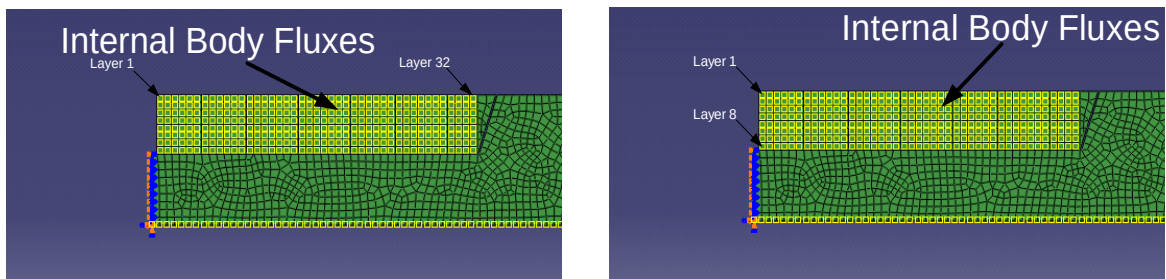


Figure 40: Diagram of Layer Subdivision for Body Flux Division in FEA model

These regions could then each be assigned a load based on the parameters of Beer's law and the associated thermal efficiencies. Load creation relied on calculation of four terms, the percent absorbed in each layer, the corresponding power in that layer, the volumetric flux corresponding to that power and finally the time average of that flux. The percentage of input energy absorbed in each layer is defined in equation 17 where alpha

is the absorption coefficient discussed previously, n is the absorption layer number and e_{size} is the thickness of the layer.

$$Percent_{abs}(n) = e^{-\alpha*(n-1)*e_{size}} - e^{-\alpha*n*e_{size}} \quad \text{equation 17}$$

From equation 8 the heat in each layer can be calculated based on the thermal efficiency (η), the input power (P_{pump}), and the pulse duration (t_{pulse}) as shown in equation 18.

$$Heat(n) = \eta * P_{pump} * t_{pulse} * Percent_{abs}(n) \quad \text{equation 18}$$

The result of equation 18 is the total energy per pulse that manifests in the form of heat in each layer. For use in the finite element model this energy needs to be transformed into a body flux by dividing by the volume of the absorption layer which is simply the height of the gain (H_{gain}) multiplied by the width of the gain (W_{gain}) and the element size (e_{size}) shown in equation 19.

$$Flux(n) = \frac{Heat(n)}{H_{gain} * W_{gain} * e_{size}} \quad \text{equation 19}$$

A second subroutine was written in python using equation 17 through equation 19 to assign loads to each of the sub divided layers of the gain region. This subroutine creates the loads for the entire gain region based on four input parameters: Pulse duration, Absorption coefficient, Diode Power, and Thermal Efficiency. The result of a single calculation for a back pump configuration is shown in Figure 41 along with the exact volumetric flux predicted by Beer's law.

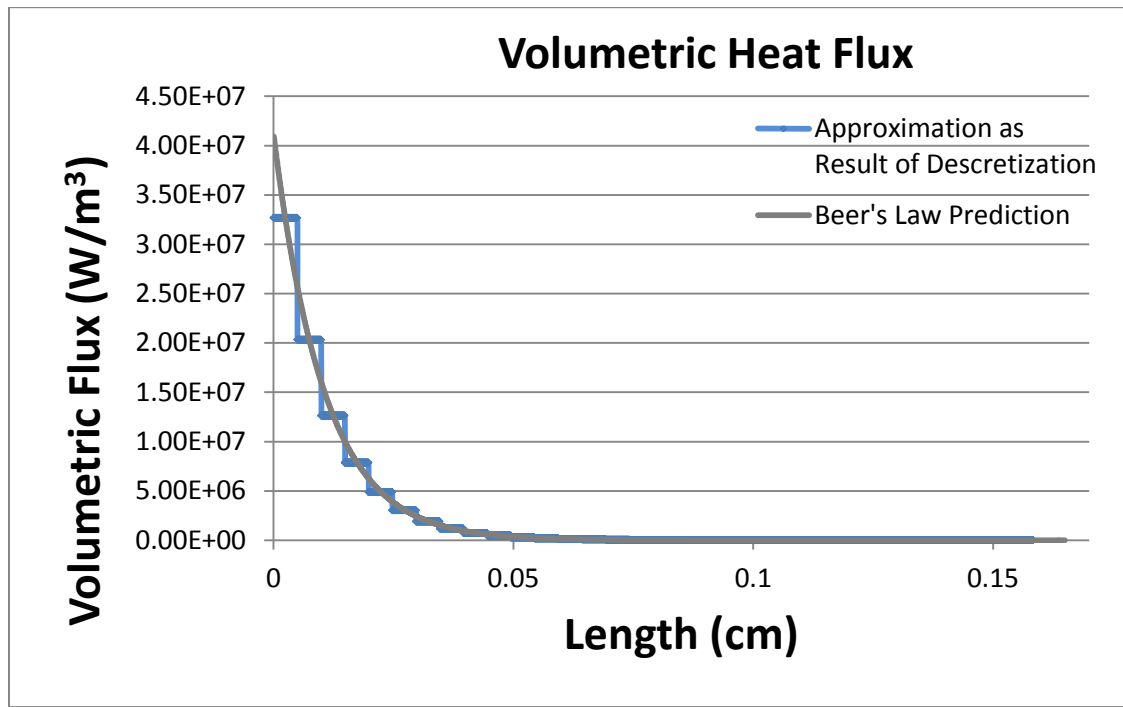


Figure 41: Discretized Heat Flux for FEA Model, t_{pulse} equal to $300\mu\text{s}$, α equal to 9.5cm^{-1} , η equal to 0.32, and P_{pump} equal to 720 W

The input parameters of this load routine could then be modified to match experimental conditions. Using this generation method single pulse flux values for a top pump configuration with a 540W Pump, 40% Thermal Efficiency, Absorption Coefficient of 9.5cm^{-1} , $300\mu\text{s}$ pulse duration.

Table 6: Body Flux Values Corresponding to a 540W Pump, 40% Thermal Efficiency, Absorption Coefficient of 9.5 cm^{-1}

Layer number	Volumetric Flux	
1	2.09E+10	W/m^3
2	1.38E+10	W/m^3
3	9.13E+09	W/m^3
4	6.04E+09	W/m^3
5	4.00E+09	W/m^3
6	2.65E+09	W/m^3
7	1.75E+09	W/m^3
8	1.16E+09	W/m^3
Total	5.94E+10	W/m^3
Avg. Power at 10 Hz	4.61E-01	W

These values best matched the loading parameters associated with a top pump configuration what was being used in Spectrum Lab experiments. These loads were then used as the input loads for FEA analysis at various operational frequencies. In addition to these loads (yellow squares) a constant temperature boundary condition was applied to the bottom of the Monoblock rail (yellow arrows), a symmetry condition (blue arrows) applied to the left side of the Monoblock and convection to all external faces with a coefficient of $2.5 \text{ Wm}^{-2}\text{K}^{-1}$ (Figure 42).

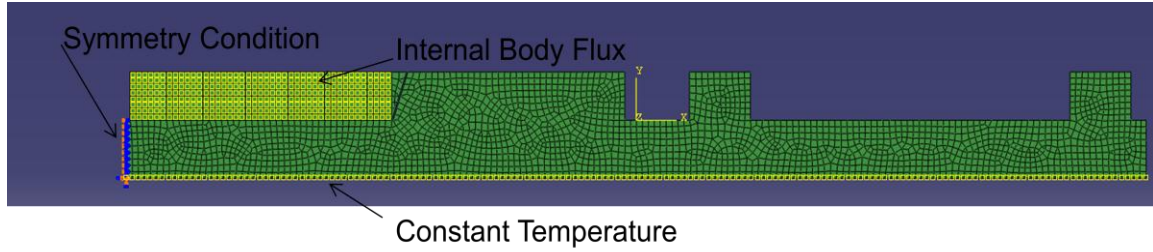


Figure 42: Boundary Condition Diagram for Monoblock FEA Models.

This model was then run in a cyclic manner for the equivalent of 50 pulses. Figure 43 shows the temperature at the Centroid as a function of time

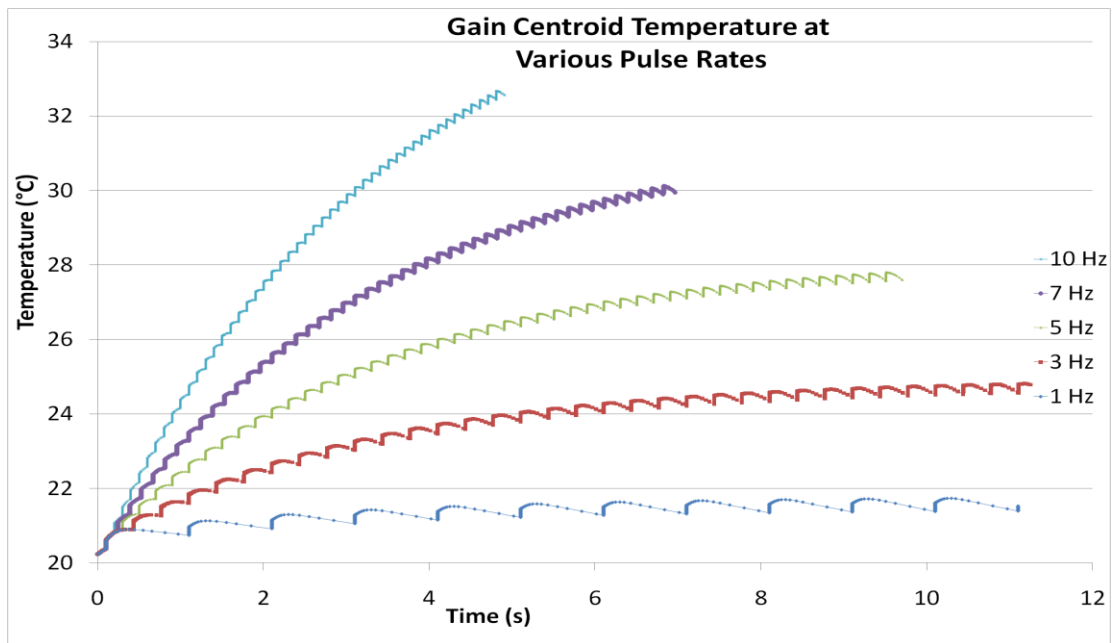


Figure 43: Predicted Gain Temperature at Various Pulse Rates

In addition to the temperature data the associated deflection studied. The angular deviation of the cavity from parallel was of primary interest (Figure 44).

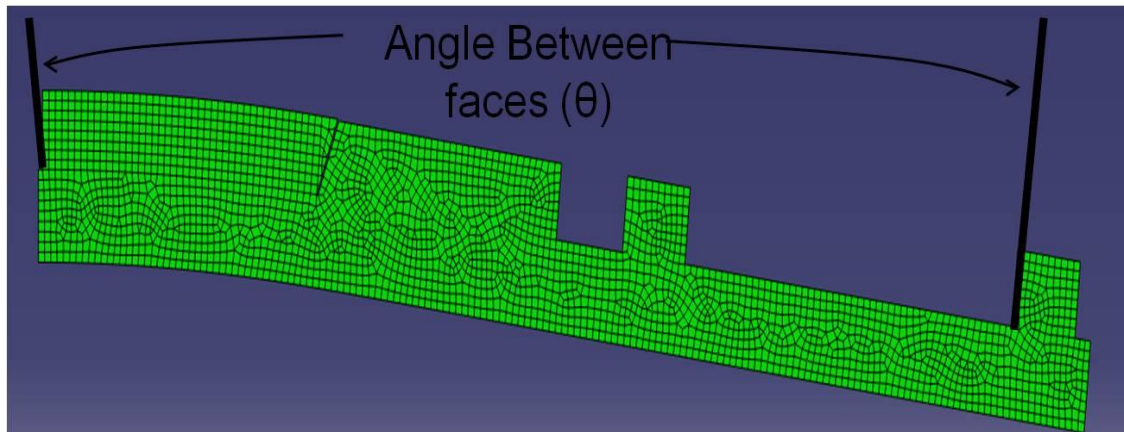


Figure 44: Diagram showing Angle between Faces of the Optical Cavity

Resulting angular displacements for repetition rates are shown in

Figure 45 along with the predicted limit for failure.

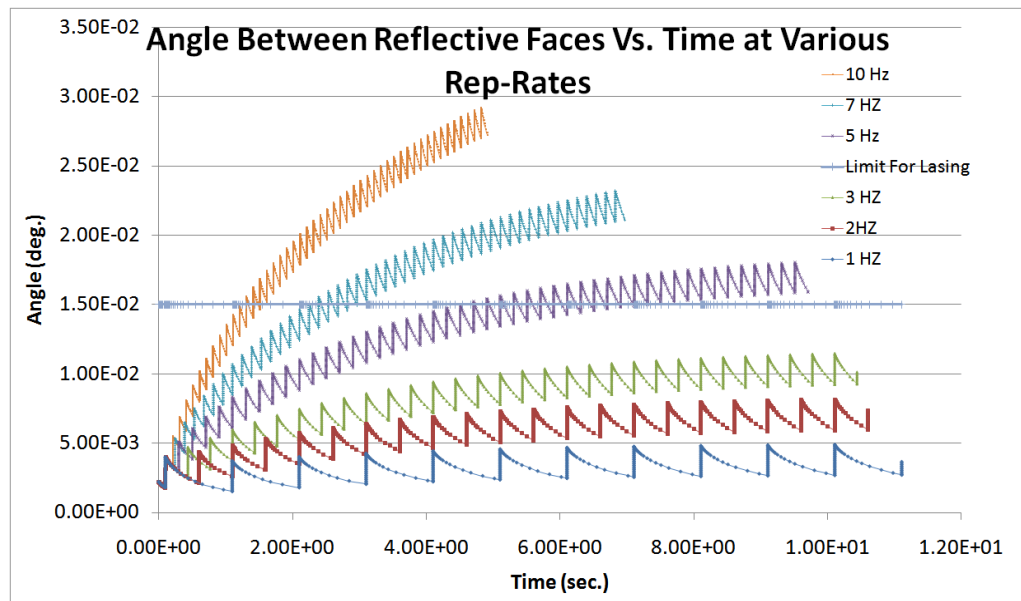


Figure 45: Predicted Angular Deformation at Various Pulse Rates

Note that FEA results predict that a 5 Hz pulse rate would result in deformation exceeding the predicted 0.015 degree limit for operation. A repeating pulse system is computationally expensive with each test taking in excess of 2 or 3 hours for calculation of 50 pulses. Experimental data was collected for more than 5 minutes per test or the equivalent of 3000 pulses. If the pulsed approach was used for comparison with experimental tests each FEA calculation could take in excess of 180 hours. In order to reduce the computational cost of the FEA model a time averaged flux was calculated by multiplying by the repetition rate (equation 20).

$$Flux_{avg}(n) = Flux(n) * RepRate \quad \text{equation 20}$$

This time average loading methods was compared to the pulsed loading (Figure 46) as expected the time average load predicted an intermediary value between the minimum and maximum predicted by the pulsed method. Additionally the use of a time averaged method significantly reduced computational cost, test computational time was reduced from 2-3 hours to 10-15 minutes.

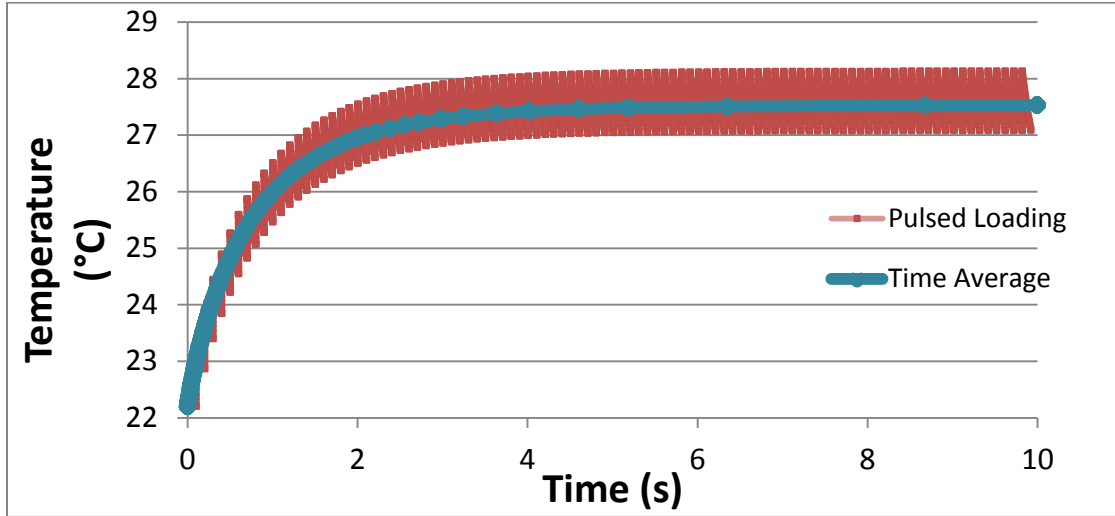


Figure 46: Time averaged Flux vs. Pulsed Flux

Using this time average method the angular deflection produced by back and top pumping were compared (Figure 47). Again, input parameters were used to best match a system in use at Spectrum Lab.

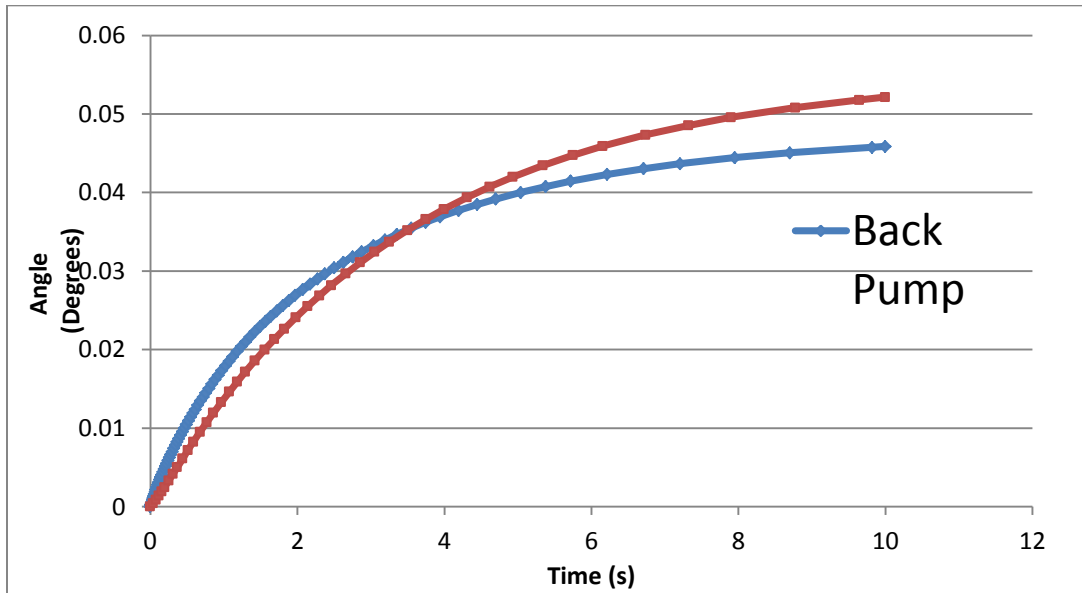


Figure 47: Angular Deformation of Back in Back and Top Pumping Configuration t_{pulse} equal to $300\mu\text{s}$, α equal to 9.5cm^{-1} , η equal to 0.38, and P_{pump} equal to 540 W.

FEA results showed a 12% decrease in angular deflection for a back pump configuration as compared to a top pump configuration. These tests established the utility of the modeling method and provided ample opportunity to learn the intricacies of the ABAQUS modeling environment prior to matching experimental data.

Final Model Creation

A final FEA model was created to compare to the 10Hz test sets. The 10Hz sets were used because the 10 Hz data had the best agreement across tests. The final FEA model of the Monoblock system was created to best match experimental data. Using the ABACUS CAE interface an accurate representation of the Monoblock geometry was created including the pedestals and the insulating layers described in the experimental method (Figure 48).

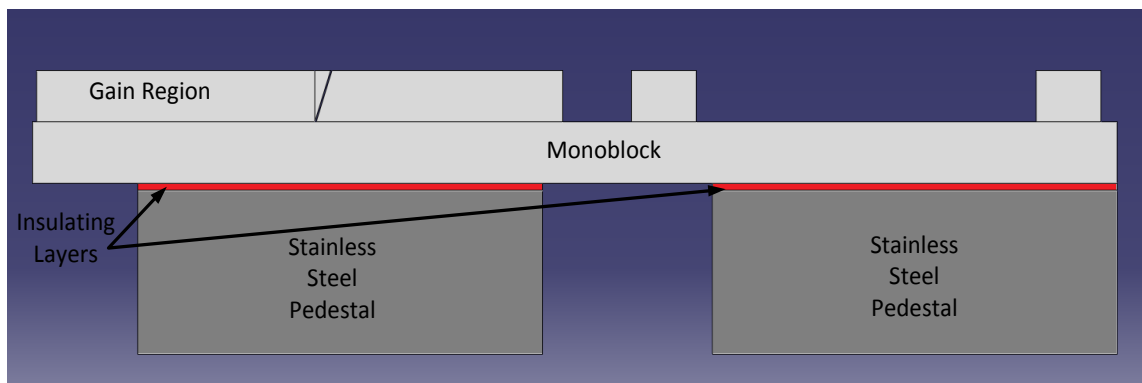


Figure 48: Two Dimensional Representation of Monoblock (Light Grey), Insulation Layers (Red) and Pedestal Mounts (Dark Grey)

Each line in Figure 48 represents a subdivided region of the model prior to meshing. By subdividing the model each sub region could be meshed independently and have separate material properties and thicknesses applied. YAG material properties were applied to all regions of the Monoblock, Double Sided tape is a PET film and PET properties were used for the insulation layers, and material properties for 304 stainless steel were used for the pedestal regions Table 7 lists the properties used for each material.

Table 7: Material Properties Used in FEA Model

	PET Film	Stainless Steel	YAG
Thermal Conductivity (W/m*K)	0.2	16.2	14 at 20.15°C 10.5 at 100°C
Density (kg/m3)	800	8000	4550
Young' Modulus (Pa)	7E+09	2E+11	2.82E+11
Poisson's Ratio	0.3	0.29	0.28
CTE (m/m*K)	5.50E-05	1.73E-05	8.20E-06
Specific Heat (J/kg*K)	1150	500	590
Plane Strain Thickness (m)	0.004	0.025	0.004

In addition to material specification each region was assigned a plane strain thickness to account for the thickness of the actual geometry in and out of plane thickness of the model.

FEA Mesh

To capture both the thermal and mechanical behavior of the system a coupled temperature-displacement continuum element type was used (CPE4T). The gain region was meshed with a sweep command creating uniformly sized elements that enabled each column to be treated as an independent absorption layer; the remainder of the model was meshed using the default meshing routine included in Abaqus. The high density at the interface between the pedestals and the Monoblock is a result of the thin layer of insulating material (Figure 49).

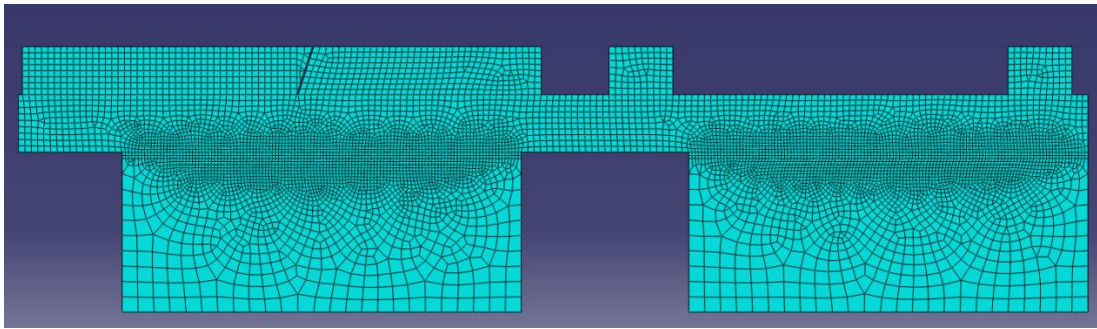


Figure 49: Meshed Geometry of Monoblock Model

Models were created that varied absorption coefficient (α), thermal efficiency (η), conductivity of the mounting pedestals, repetition rate. These models submitted to ABAQUS and then post processed using a combination of ABAQUS and Matlab.

Data Extraction

After model calculation data was extracted in order to produce plots providing a useful comparison to experimental data. The top region of the Monoblock (Figure 50)

will have the largest deformation and was compared with the same region in the experimental data.

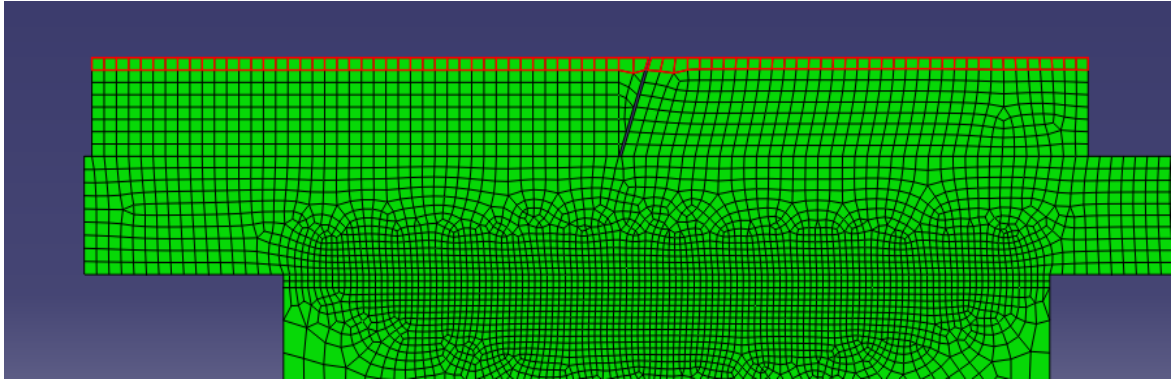


Figure 50: Diagram of OPL Element set (Red) Used for FEA Validation

Using ABAQUS the top element set of the gain region was selected and temperature points calculated for each sub element of that set. These temperatures were then averaged, Appendix E ABAQUS Scripts contains script commands used to automate this process. The time history of the average data was then exported into a text file and imported into Matlab. Using Matlab the temperature was converted into an equivalent optical path length using equation 12. This data could then be plotted and compared to the experimental data sets. In addition to plotting the predictions it is useful to be able to subtract FEA data from the experimental data. The experimental data was collected at a rate of 33.66 Hz but the FEA data is produced at non uniform time intervals as such to operate on the two sets together the FEA data has to be interpolated to produce data points at equivalent time intervals as the experimental data the scripting method to produce this data is listed in Appendix I: FEA and Test Difference Calculation Method.

Effect of Absorption Coefficient

Input files were created for absorption coefficient varying from 6 cm^{-1} to 12 cm^{-1} to study the effect of absorption coefficient on total OPL change in the top region of the Monoblock. All other parameters were held constant: thermal efficiency equal to 38.5%, Pump Power equal to 720W, Pulse Rate equal to 10Hz. The resulting FEA values are plotted along with the experimental test results in Figure 51 with red being the lowest value for alpha and blue the highest.

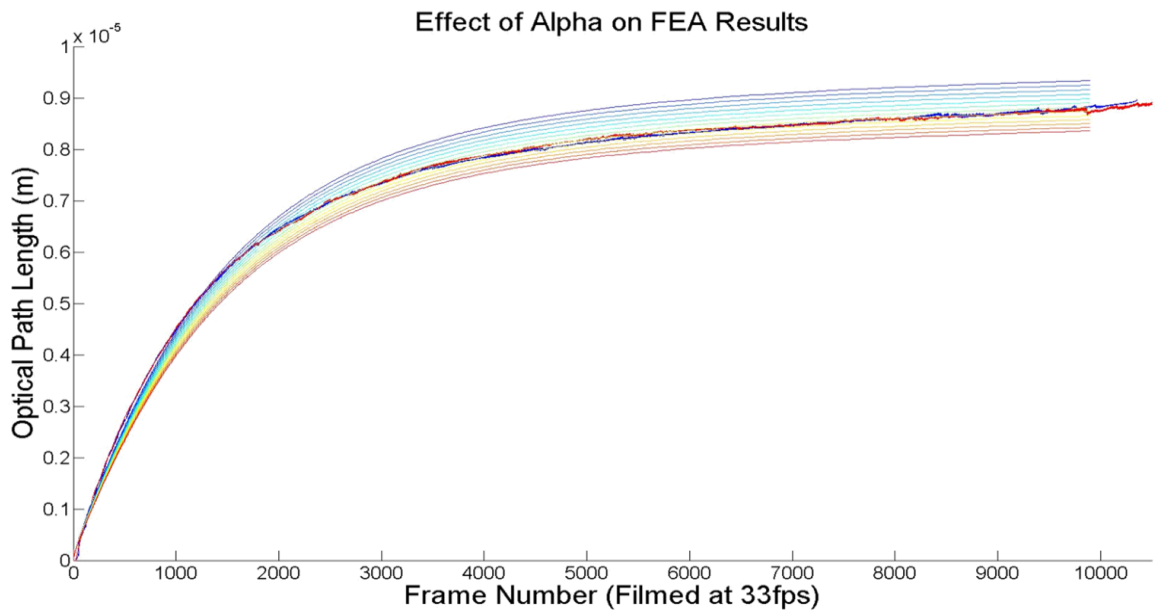


Figure 51: Effect of Varying Alpha on FEA Prediction of OPL, Alpha was varied from 6 cm^{-1} (red) to 12 cm^{-1} (blue) in 0.5 cm^{-1} increment and plotted with the experimental data, other parameters were held constant

Additionally the FEA results were subtracted from the experimental results for all data points. This resultant value was then divided by the 1064nm, the laser wavelength of Nd:YAG, to normalize the data to a number of waves of error (Figure 52).

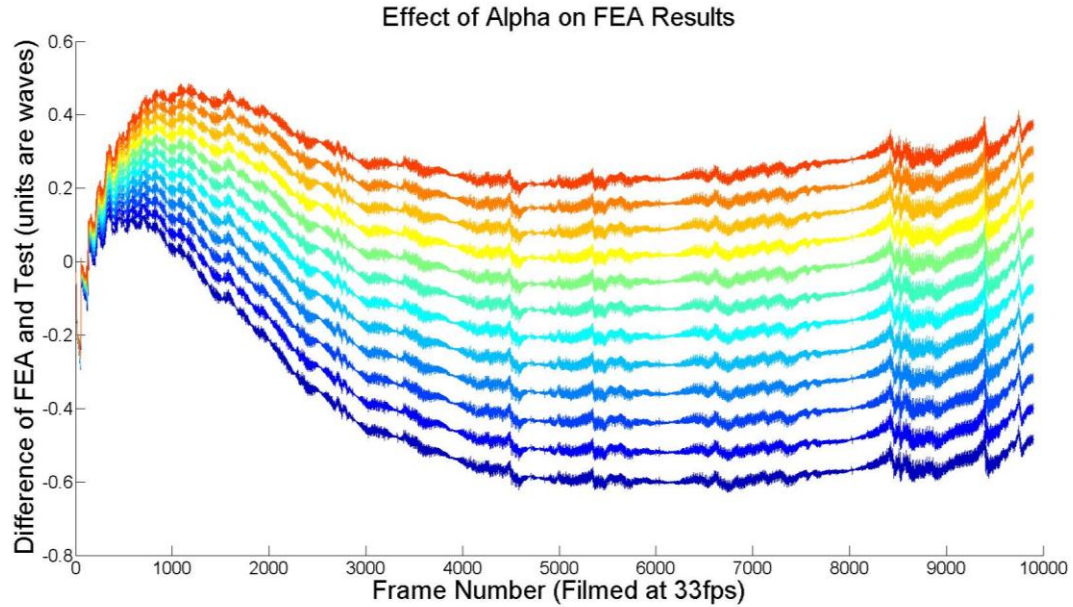


Figure 52: Difference of FEA and 10 Hz Test 1 Experimental data with Alpha varied from 6cm⁻¹ (red) to 12cm⁻¹ (blue) in 0.5cm⁻¹ increment and plotted with the experimental data, other parameters were held constant

To compare FEA predictions to the experimental results, the last 100 data points of the difference plot were averaged (3 sec of experimental data) for each data set and the absolute value of that average was plotted versus absorption coefficient (Figure 53).

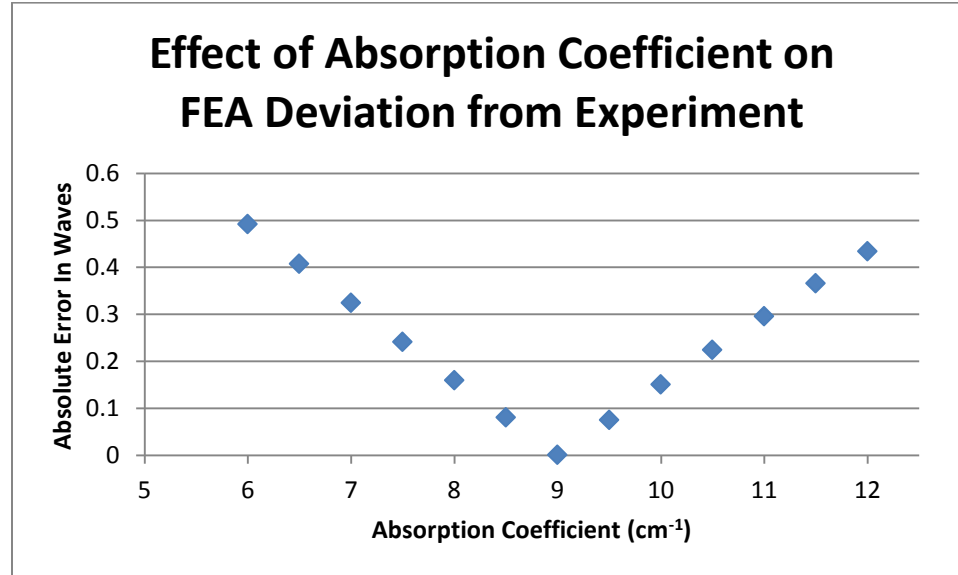


Figure 53: Effect of Absorption Coefficient on FEA Deviation from Experiment

From Figure 53 is apparent that an absorption coefficient of 9cm^{-1} best fits the experimental data.

Effect of Conversion Efficiency

Input files were created for varying thermal efficiency from 30% to 43% to study the effect of thermal efficiency on total OPL change in the top region of the Monoblock. All other parameters were held constant: absorption coefficient 9.0cm^{-1} , Pump Power equal to 720W, Pulse Rate equal to 10Hz. The resulting FEA values are plotted along with the experimental test results in Figure 54 with blue being the lowest value for alpha and red the highest.

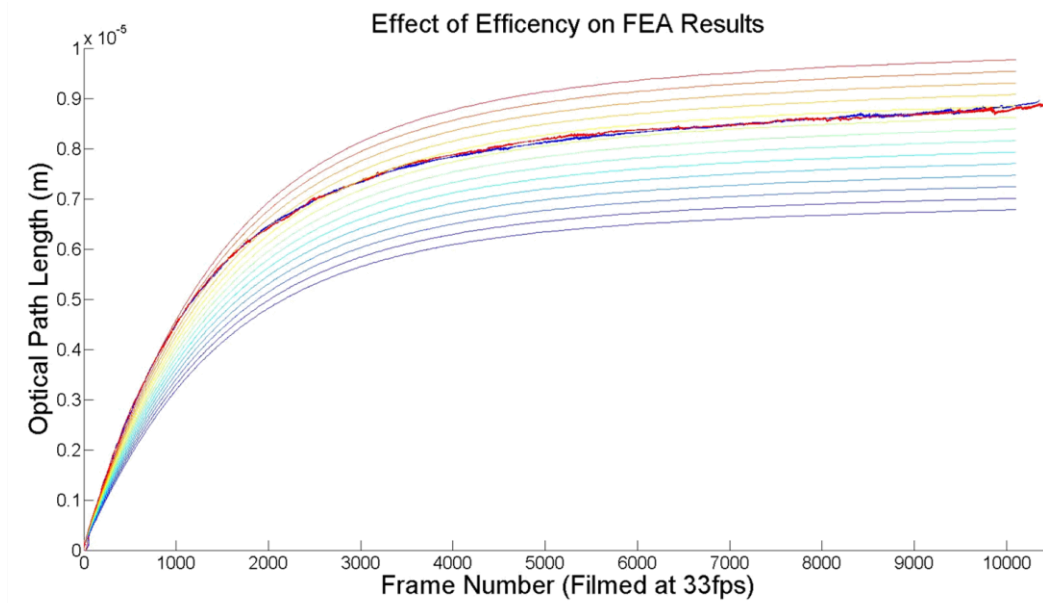


Figure 54: Effect of Varying Conversion Efficiency on FEA prediction of OPL, Efficiency was varied from 32% (blue) to 43% (red) in 1% increments and plotted with the experimental data, other parameters were held constant

Additionally the FEA results were subtracted from the experimental results for all data points. This resultant value was then divided by the 1064nm, the laser wavelength of Nd: YAG, to normalize the data to a number of waves of error (Figure 55).

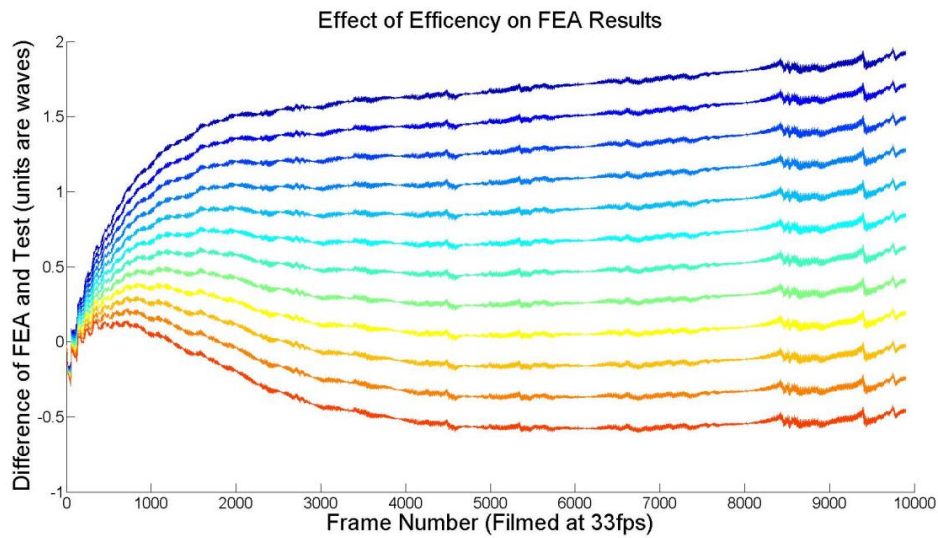


Figure 55: Difference of FEA and 10 Hz Test 1 Experimental data with Efficiency varied from 32% (blue) to 43% (red) in 1% increments and plotted with the experimental data, other parameters were held constant

To compare FEA predictions to the experimental results, the last 100 data points of the difference plot were averaged (3 sec of experimental data) for each data set and the absolute value of that average was plotted versus thermal efficiency (Figure 56).

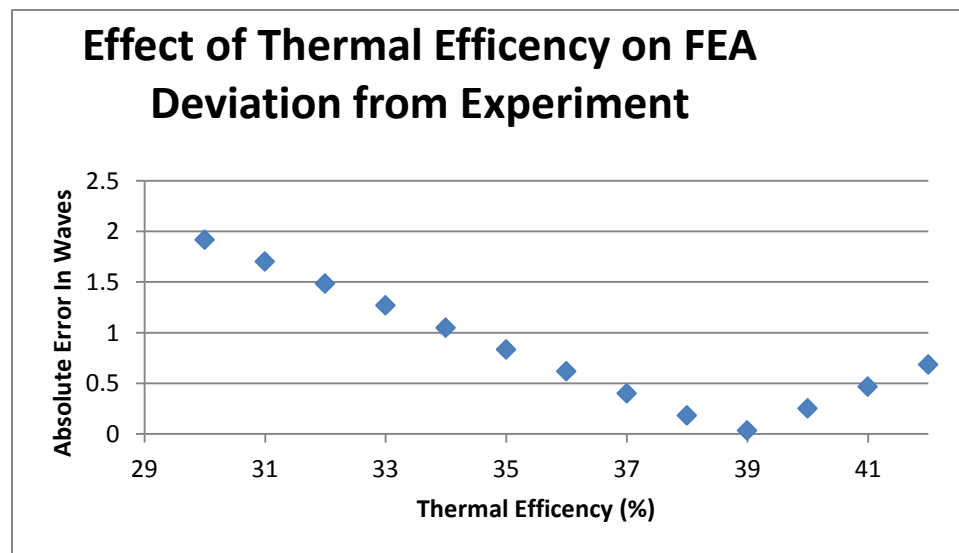


Figure 56: Effect of Absorption Coefficient on FEA Deviation from Experiment

From Figure 56 is apparent that 39% thermal efficiency best fits the data.

Final Parameters and Compared Results

Using the best fit parameters ($\alpha=9.0$ and $\eta=39\%$) models were created for each repetition rate and plotted with the experimental results (Figure 57).

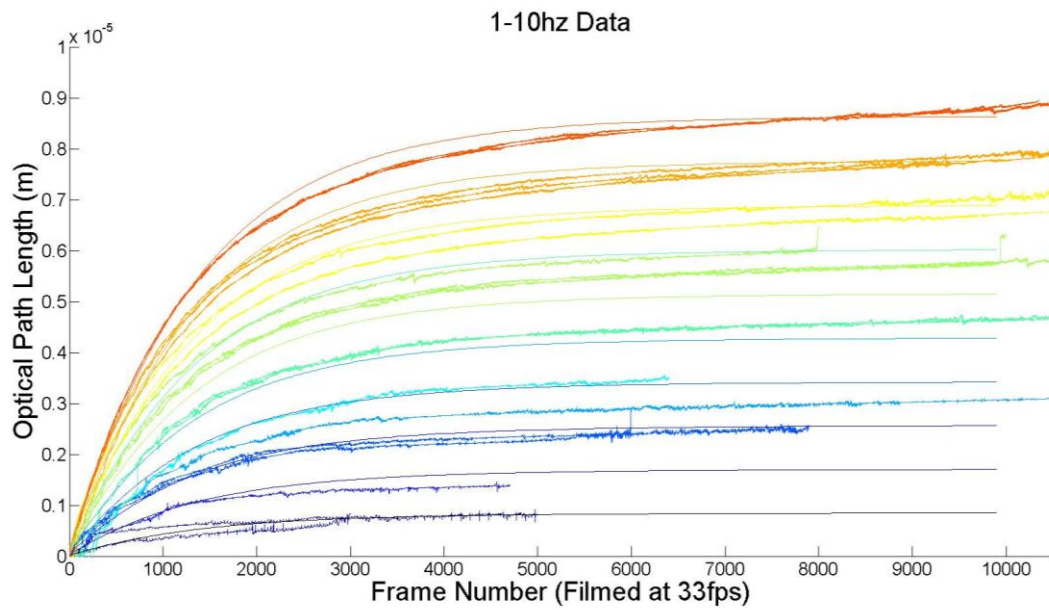


Figure 57: Comparison of FEA and Experimental Results

For each test the last 100 data points were again averaged and compared to the FEA predictions, the results of those calculations are shown in table 8.

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Table 8: Difference of Experimental Results and FEA Predictions for Steady State OPL
(units are meters)

Repetition Rate	Test 1	Test 2	Test 3	Minimum Error	Minimum Error in waves
1 Hz	9.60E-09	-7.51E-09	--	7.51E-09	0.0071
	1.29%	-0.93%	--	0.93%	
2 Hz	-2.57E-07	8.86E-07	8.33E-07	2.57E-07	0.2420
	-18.73%	33.60%	33.07%	18.73%	
3 Hz	--	-1.25E-07	-4.73E-08	4.73E-08	0.0445
	--	-5.25%	-1.89%	1.89%	
4 Hz	1.08E-06	-3.55E-07	1.98E-07	1.98E-07	0.1860
	24.18%	-11.39%	5.40%	5.40%	
5 Hz	-2.67E-07	-7.35E-07	2.90E-07	2.67E-07	0.2508
	-6.73%	-21.01%	6.40%	6.40%	
6 Hz	4.34E-07	-5.21E-07	-5.07E-07	4.34E-07	0.4082
	7.81%	-11.12%	-10.84%	7.81%	
7 Hz	4.34E-09	-2.52E-07	-2.79E-07	4.34E-09	0.0041
	0.07%	-4.32%	-4.86%	0.07%	
8 Hz	--	1.34E-07	-1.85E-07	1.34E-07	0.1258
	--	1.89%	-2.72%	1.89%	
9 Hz	8.01E-09	1.18E-07	3.70E-06	8.01E-09	0.0075
	0.10%	1.48%	47.72%	0.10%	
10 Hz	1.77E-07	1.21E-07	--	1.21E-07	0.1133
	1.98%	1.35%	--	1.35%	

The FEA results agreed well with the experimental data, with the best agreement exhibiting only 0.1% error. For the tests with high error (2Hz and 6 Hz) examination of the data shows significant occurrence of unwrap errors at those repetition rates leading to values that are not representative of the actual OPL of the test. Difference plots for all data sets can be found in Appendix J: Difference of FEA and Test Data.

Effect of Mount Thermal Resistance

In addition to the effect of the loading parameters the effect of changing boundary conditions was also studied. The parameters for the best fit 10 Hz (absorption coefficient 9.0cm^{-1} , Thermal Efficiency 39% Pump Power equal to 720W and Pulse Rate equal to 10Hz) were used to create loads and the conductivity of the support pedestals were varied from $2\text{Wm}^{-1}\text{K}^{-1}$ (red) to $22\text{Wm}^{-1}\text{K}^{-1}$ (Blue) in $2\text{Wm}^{-1}\text{K}^{-1}$ increments. The resulting FEA predictions are plotted in Figure 58, additionally a plot of the difference if FEA predictions and experimental test is shown in Figure 56.

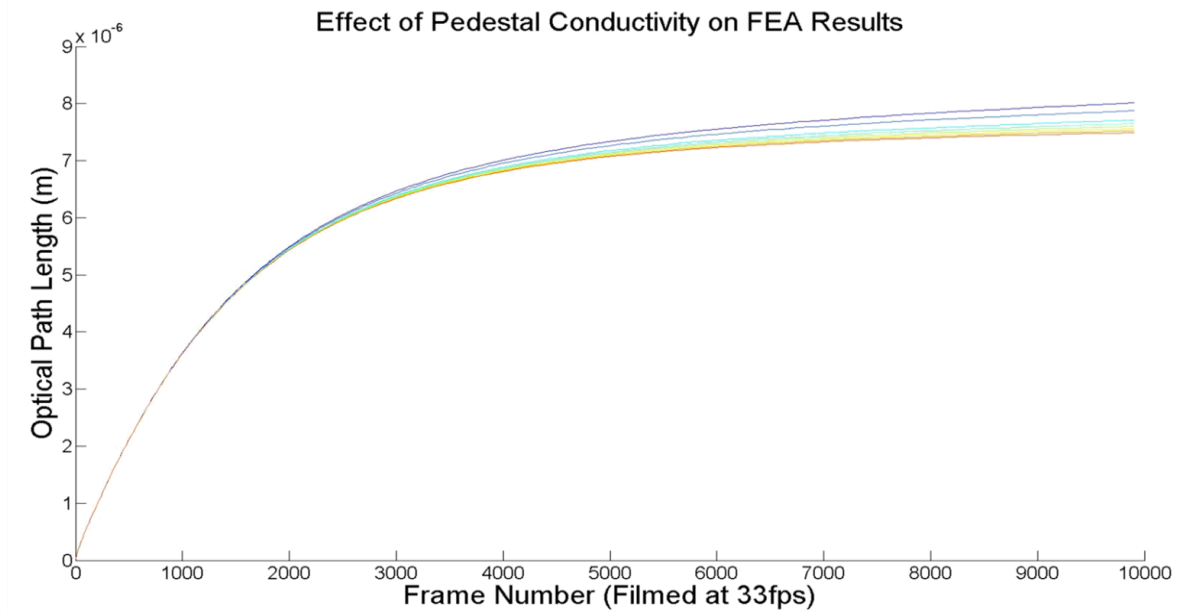


Figure 58: Effect of Varying Pedestal Conductivity on FEA prediction of OPL, Conductivity was varied from $2\text{Wm}^{-1}\text{K}^{-1}$ (blue) to $22\text{Wm}^{-1}\text{K}^{-1}$ (red) in $2\text{Wm}^{-1}\text{K}^{-1}$ increments and plotted with the experimental data, other parameters were held constant

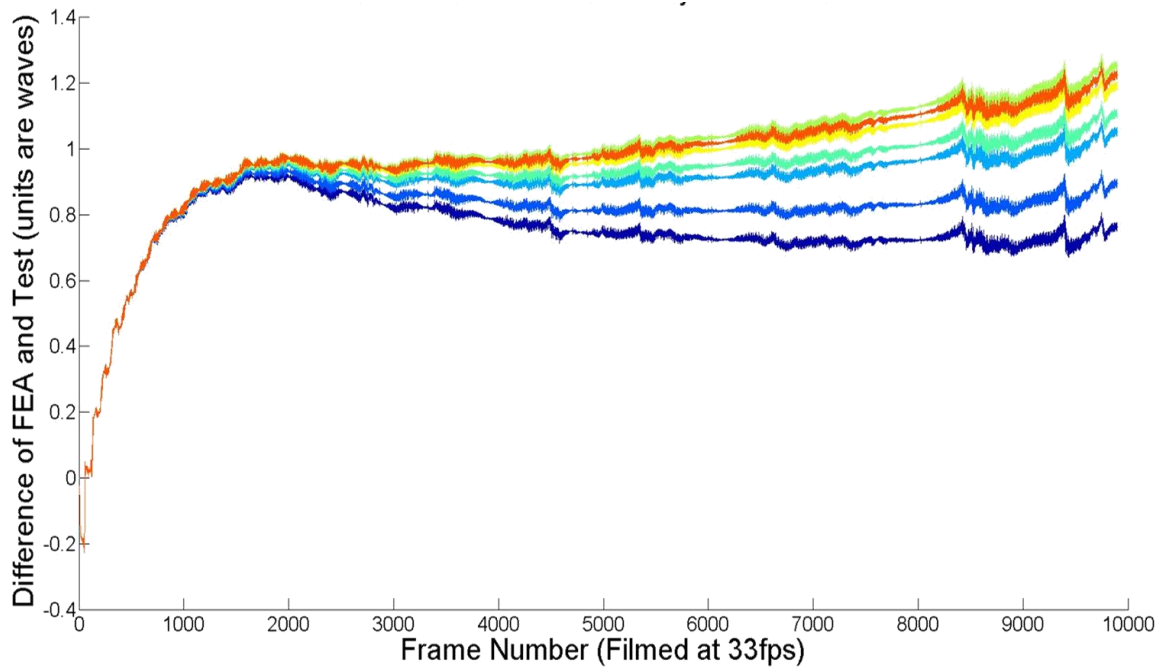


Figure 59: Difference of FEA and 10Hz Test 1 Experimental data with Conductivity varied from $2\text{Wm}^{-1}\text{K}^{-1}$ (blue) to $22\text{Wm}^{-1}\text{K}^{-1}$ (red) in $2\text{Wm}^{-1}\text{K}^{-1}$ increments and plotted with the experimental data, other parameters were held constant

Note that changing the conductivity of the system does not have any effect on the early start-up heating of the system but does have an effect of the long term heating to steady state. This accounts for the slight deviation in slope at steady state between the experimental data and the FEA predictions seen in Figure 57. The deviation in Figure 57 is a result of the current model over predicting the conductivity out of the system and ultimately coming to steady state sooner, the error is slight and is a misrepresentation of test conditions not a result of error in load prediction.

Addition of Pulsed Fluxes

After matching the long term steady state experimental measurements using the time averaged method of load creation loads using the original pulsed loading conditions were inserted. A plot for the 10Hz case is shown in Figure 60.

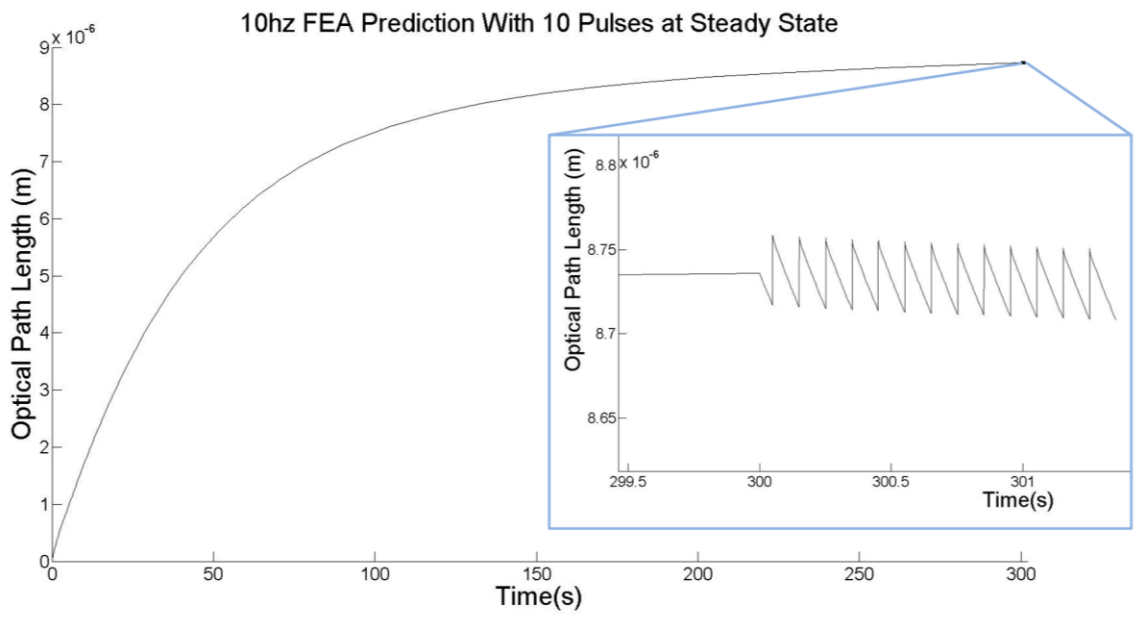


Figure 60: Final FEA model with the addition of Pulses at Steady State

To use in comparison a one second subset of both 10 Hz experimental results was taken at the 300 second mark. This subset was normalized to waves of OPL and centered about the mean of the span. The FEA data was also normalized and centered about the mean of the subset. A plot of all three data sets is shown in Figure 61.

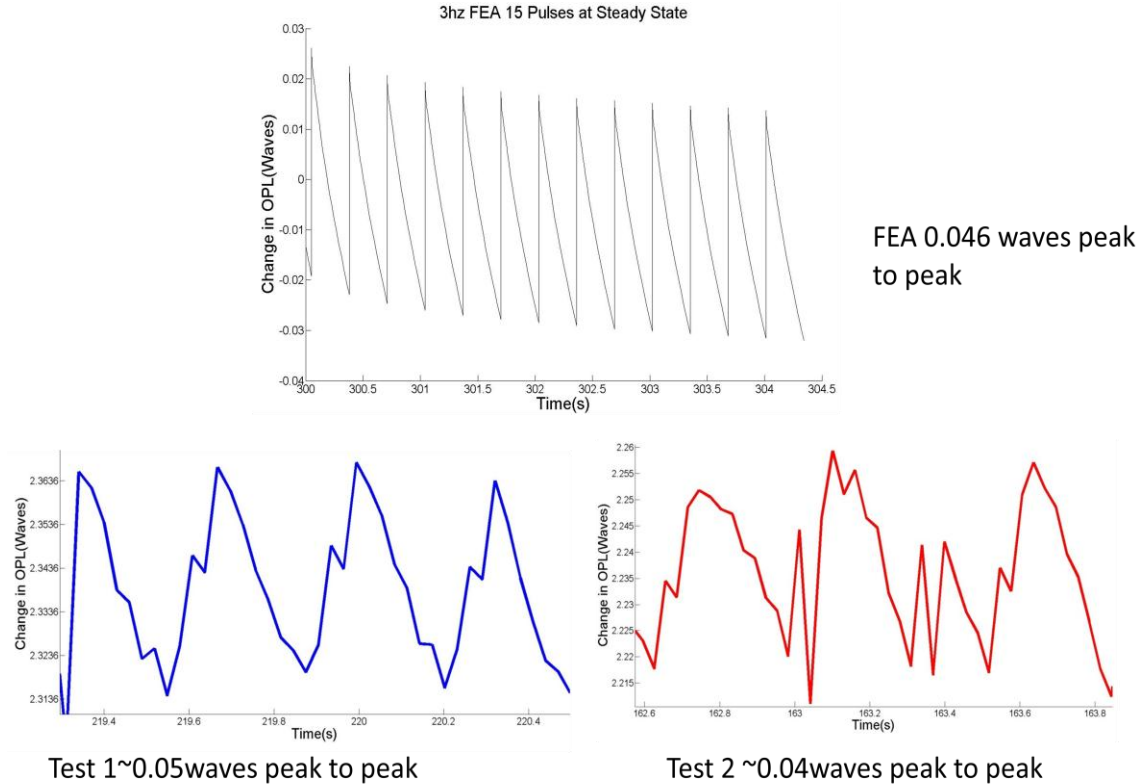


Figure 61: Impact of Diode Pulse on OPL at Steady State, 13 Hz Test 1 (red), 10 Hz Test 2 (blue), FEA Prediction (Black)

It is very difficult to synchronize the pulse peaks across the three data sets as such the pulse peaks are not aligned. Additionally the FEA data shows a slight decreasing trend where the experimental results show the increasing trend as discussed previously. Given those two errors the peak to peak correlation matches well especially between the test 1 results (red) and the FEA prediction (black) at the 300.4 second mark.

Model Omissions

Though this FEA model captures the physics heating associated with lasing it does omit some realities of the system. The FEA analogue is structured such that interfacial thermal resistances between components are omitted. This was done for the primary reason of simplicity and ease of repeated computational calculation. The layer of interfacial glue could now be added in and an additional calibration routine run in a similar method to the efficiency and absorption routines run in this work. The effect of this interfacial layer should be similar to the effect for varying conduction of the pedestals and result in a change of the intermediate to long term OPL shape but the initial transient heat up should remain unchanged. Additionally this model is a 2D system and as such neglects the in and out of plane effects of geometry. Some of these effects are captured by the application of a plane strain thickness to varying regions of the geometry but the effects induced by free edges and geometry boundaries are not represented in this system. Applying the modeling approach outlined in this thesis to a 3D system would allow a user to capture these interactions and increase the fidelity of the overall modeling method. Lastly, when calculating the OPL length from the FEA data an average temperature was used rather than a stain and temperature. If the thermal strain is compared to the total strain at individual nodes in top element set the difference ranges from 10-30% with higher percentage of error occurring at the central nodes in the set than at the edge nodes. This error in calculation means that the error in total OPL path length will range from 5-15% because thermal strain accounts for slightly less than half of the total OPL effect. This fluctuation is in the range of the absorption coefficient and

efficiency calibration curves used to calibrate the model and because this is a systemic error would result in selection of a different calibration curve rather than an invalidation of the method. If this model is to be used in the future refinement should use calculated strain from FEA results and temperature independently and recombine that result in the OPL calculation.

SUMMARY AND DISCUSSION

This work has successfully demonstrated an experimental method for measuring the change in optical path length associate with diode pumping of Nd: YAG. Using a Michelson interferometer OPL was measured for pulse rates ranging from 1 to 10 Hz. Those results were used as a validation tool for a FEA modeling approach. FEA results from the ABAQUS suite were able to match experimental measurements within 0.5 wavelengths at the Nd: YAG laser line of 1064nm. FEA models were created that minimize computational expense by utilizing time average loading to reach steady state and then applying a pulsed load at steady state to capture all transience of the system. These results demonstrated advantages in back pumping as opposed to top pumping, predicting a decrease in angular deformation of 12%. Modeling predictions also show that for changing thermal conductivity at the boundary of the Monoblock short term change in OPL at startup is unaffected but steady state length is dependent on boundary condition. Best fit parameters for heat generation are consistent with those published in work by Fan et al. [3] and Weber et al. [18]. Heat generation is causing thermal misalignment and laser failure in the Monoblock; FEA predictions for thermal deformation are consistent with experimental observations. End pumping will provide advantages for lower heat generation and deformation but for higher rate operation the Monoblock system should be redesigned to minimize thermal profile and deformation.

FUTURE WORK

Although significant progress has been made in understanding the failure mechanism of the Monoblock and FEA prediction methods further work should be pursued. Modeling parameters could be further refined by varying pump wavelength in experimental tests and further reducing error in modeling method. The FEA methodology developed in this thesis should be extended to three dimensions allowing complexity of edge geometry not captured in the two dimensional approach. Parametric studies could be performed on boundary conditions to better capture the experimental conditions. Using a three dimensional method the thermal lens of the system could be extracted. Of highest priority is to utilize this modeling method to redesign the Monoblock system for operation at higher repetition rates in a back pump configuration.

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APPENDICES

APPENDIX A

CUBIC SYMMETRY DERIVATION

Starting from generalized Hooke's law for an anisotropic material, the reduced stiffness matrix for a cubic material will be derived based on the derivation performed in Elastic and Inelastic Stress Analysis [23]. In index notation, the general form of linear elastic behavior is given in equation 21 where τ_{ij} is the second order symmetric stress tensor, C_{ijkl} is the fourth order elastic stiffness tensor, and ε_{kl} is the second order symmetric strain tensor.

$$\tau_{ij} = C_{ijkl}\varepsilon_{kl} \quad \text{equation 21}$$

For fully anisotropic materials, C_{ijkl} has 81 elements relating stress and strain. Because τ_{ij} is symmetric C_{ijkl} must also be symmetric in ij (equation 22). Symmetry can be proven by applying the equations of equilibrium and Newton's laws to the stress tensor for a differential volume and is developed fully in [23].

$$C_{ijlk} = C_{jikl} \quad \text{equation 22}$$

Similarly because ε_{kl} is symmetric C_{ijkl} must also be symmetric in kl (equation 23).

$$C_{ijlk} = C_{ijkl} \quad \text{equation 23}$$

Using the requirements of equation 22 and equation 23 it can be concluded that the indices $ijkl$ vary only as pairs of ij and kl . This limitation on pairing means that the 81 elements of the C tensor have now been reduced to 36 unique values. The C_{ij} matrix can be further reduced if additional symmetry is considered. In the case of YAG, the

stiffness matrix will be reduced for the symmetry associated with a cubic crystal. Cubic symmetry is a special case where the material possesses three orthogonal planes of elastic symmetry as well as symmetry in three orthogonal directions. Beginning with the associated planes of orthogonality the stiffness tensor C can be operated on by the direction cosine matrix and the resulting values set equal to the untransformed tensor, merely a change of the tensor reference frame. The stiffness tensor transforms as a fourth order tensor (equation 4). Where a is the direction cosine matrix transforming coordinate directions. This transformation of C results in four equalities given below in equations 24-28.

$$C_{m'n'o'p'} = a_{m'i}a_{n'j}a_{o'k}a_{p'l}C_{ijkl} \quad \text{Equation 24}$$

$$C_{1'1'1'2'} = -C_{1112} \quad \text{Equation 25}$$

$$C_{1'2'2'3'} = -C_{1223} \quad \text{Equation 26}$$

$$C_{1'1'1'2'} = C_{1112} \quad \text{Equation 27}$$

$$C_{1'2'2'3'} = C_{1223} \quad \text{Equation 28}$$

The equalities stipulated in equations 5-8 can only be satisfied if and only if C_{1112} and C_{1223} are exactly zero, this occurs because of the symmetry of the crystal structure. If this inversion is performed again for the two remaining orthotropic directions 12 elastic constants remain: C_{1122} , C_{2233} , C_{3311} , C_{2211} , C_{3322} , C_{1133} , C_{2323} , C_{3131} , C_{1212} , C_{1111} , C_{2222} , and C_{3333} . If the directionality symmetry is now imposed, permutations of the base coordinates must result in an invariant of the stiffness matrix. Permutations of the coordinate system that result in a left-handed coordinate system must be invariant

when viewed in any coordinate system; the resulting equalities are shown below in equations 9-11.

$$C_{1122} = C_{2233} = C_{3311} = C_{2211} = C_{3322} = C_{1133} \quad \text{Equation 29}$$

$$C_{2323} = C_{3131} = C_{1212} \quad \text{Equation 30}$$

$$C_{1111} = C_{2222} = C_{3333} \quad \text{Equation 31}$$

Using equations 9-11, it can be concluded that only three unique values are needed to fully define the stiffness matrix for a cubic material. It is now common to use Mandel-Voigt notation rules (Table 9) to transform the tensors to matrices.

Table 9: Mandel-Voigt Notation Rules

Tensor Subscript	Matrix Subscript
11	1
22	2
33	3
23 or 32	4
13 or 31	5
12 or 21	6

In the case of the stress and strain the transformation results in the second rank tensors being transformed into 6x1 matrices shown for the case of stress in equation 12.

$$\begin{bmatrix} \tau_{11} & \tau_{12} & \tau_{13} \\ \tau_{12} & \tau_{22} & \tau_{23} \\ \tau_{13} & \tau_{23} & \tau_{33} \end{bmatrix} \approx \langle \tau_1, \tau_2, \tau_3, \tau_4, \tau_5, \tau_6 \rangle \quad \text{Equation 32}$$

Similarly the C_{ij} tensor transforms into a 6x6 matrix. After transforming all three components, Hooke's law for anisotropic materials can be expressed in matrix notation as given in Equation 33, where τ is a 6x1 matrix of stress values, C is a 6x6 matrix of elastic constants, and ε is a 6x1 matrix of strain values.

$$\{\tau\} = [C]\{\varepsilon\} \quad \text{Equation 33}$$

For the case of cubic symmetry the resulting Hooke's law relation is explicitly given in Equation 34.

$$\begin{Bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{Bmatrix} \quad \text{Equation 34}$$

Sometimes it is also of use to calculate the degree of isotropy with respect to shear. The Isotropy factor is defined in equation 15 [34].

$$A = \frac{2C_{44}}{C_{11} - C_{12}} \quad \text{Equation 35}$$

As A approaches unity the material approaches Isotropic behavior with respect to shearing stress.

APPENDIX B

AVI IMPORT M-FILE FOR MATLAB

```

% Script converts a movie to regional intensity data and a
beep on
clear
disp('start')
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Type Path To Video Clip
Here%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
path='C:\Users\Aaron Anderson\Desktop\5-12-11 test data\10 Hz 2.avi';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Change directory path according to computer that is running the script
path
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Input Pixel locations of Edges of interferogram Square%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
LHbound=150;
RHbound=415;
topbound=84;
botbound=330;
currdir=pwd;
%Create references for midline and averaged regions%%
midline=round((RHbound-LHbound)/2+LHbound);
element=round((botbound-topbound)/8);
%Read avi video%
Clip=mmreader(path);
Info=aviinfo(path);
Frames=Info.NumFrames;
timeintensity=zeros(Frames,1,8);
tic
for n=1:Frames,
    Frame=read(Clip,n);
    avgintensity=0;
    intensity=0;
    imdoub=im2double(Frame);
    imgray=rgb2gray(imdoub);
    k=0;
    kk=0;
    ref1=0;
    for l=1:8
        k=0;
        intensity=0;
        for i=(midline-round(0.5*element)):(midline+round(0.5*element));
            %for i=LHbound:RHbound;
            for j=topbound+(l-1)*element:(topbound+l*element);
                %for j=topbound:botbound;
                intensity=intensity+imgray(j,i);
                k=k+1;
            end
        end
    end
end

```

```

avgintensity=intensity/k;
timeintensity(n,1,l)=avgintensity;
end
for ii=1:20;
    for jj=1:20;
        ref1=ref1+imgray(jj,ii);
        kk=kk+1;
    end
end
ref(n,1)=ref1/kk;
time1(n,1)=timeintensity(n,1,1);
time2(n,1)=timeintensity(n,1,2);
time3(n,1)=timeintensity(n,1,3);
time4(n,1)=timeintensity(n,1,4);
time5(n,1)=timeintensity(n,1,5);
time6(n,1)=timeintensity(n,1,6);
time7(n,1)=timeintensity(n,1,7);
time8(n,1)=timeintensity(n,1,8);
end
toc
cd(currdir);
disp('done')

```

APPENDIX C

RMS PROCESS MFILE FOR MATLAB

```

%%define moving average span%%
N=10;
%%name of import Data set%%
Data=h11;
%%Scaling factor for outlier search
B=1.25;
Data_Use=Data;
SData=smooth(Data,N,'moving');
RMS_Raw=norm(Data-SData)/sqrt(length(Data));
I_bad=find(abs(Data-SData)>B*(RMS_Raw));
Data_Use(I_bad)=(Data(I_bad-1)+Data(I_bad+1))/2;
figure(21);clf
hold off
plot(Data,'b*')
hold on;
plot(Data_Use,'r*')
plot(Data,'b')

```

APPENDIX D

DATA PROCESS AND PLOT M-FILE

```

Clear
close all
%%Desktop Path%%
load('C:\Users\Aaron\Documents\My Dropbox\Thesis\raw data.mat')
%%Laptop Path%%
%load('C:\Users\Aaron Anderson\Dropbox\Thesis\raw data.mat')
nyag=1.8283;
yagwavelength=1060e-9;
lengthgain=0.033;
dndt=7.8e-6;
CTE=8.2e-6;
startingtemp=23;

FEA1=[reprate(:,1),(reprate(:,2)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA2=[reprate(:,1),(reprate(:,3)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA3=[reprate(:,1),(reprate(:,4)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA4=[reprate(:,1),(reprate(:,5)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA5=[reprate(:,1),(reprate(:,6)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA6=[reprate(:,1),(reprate(:,7)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA7=[reprate(:,1),(reprate(:,8)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA8=[reprate(:,1),(reprate(:,9)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA9=[reprate(:,1),(reprate(:,10)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];
FEA10=[reprate(:,1),(reprate(:,11)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag)];

%Frame number where diode turns on in each test
shz11=250;
shz12=177;
shz21=200;
shz22=208;
shz23=180;
shz32=230;
shz33=283;
shz41=239;
shz42=181;

```

```

shz43=161;
shz51=221;
shz52=301;
shz53=245;
shz61=280;
shz62=143;
shz63=422;
shz71=189;
shz72=240;
shz73=155;
shz82=207;
shz83=265;
shz91=531;
shz92=256;
shz93=373;
shz101=645;
shz102=385;
%Convert processed data into unwrapped plots
hz11uw=-3.3880+unwrap(angle(hilbert(hz11rms(shz11:11000)-
mean(hz11rms(shz11:11000)))));
hz12uw=.9843+unwrap(angle(hilbert(hz12rms(shz12:11000)-
mean(hz12rms(shz12:11000)))));
hz21uw=1.0814+unwrap(angle(hilbert(hz21rms(shz21:11000)-
mean(hz21rms(shz21:11000)))));
hz22uw=1.6501+unwrap(angle(hilbert(hz22rms(shz22:11000)-
mean(hz22rms(shz22:11000)))));
hz23uw=1.5784+unwrap(angle(hilbert(hz23rms(shz23:11000)-
mean(hz23rms(shz23:11000)))));
hz32uw=1.1114+unwrap(angle(hilbert(hz32rms(shz32:11000)-
mean(hz32rms(shz32:11000)))));
hz33uw=-3.2966+unwrap(angle(hilbert(hz33rms(shz33:11000)-
mean(hz33rms(shz33:11000)))));
hz41uw=-1.9315+unwrap(angle(hilbert(hz41rms(shz41:11000)-
mean(hz41rms(shz41:11000)))));
hz42uw=-1.8011+unwrap(angle(hilbert(hz42rms(shz42:11000)-
mean(hz42rms(shz42:11000)))));
hz43uw=-1.7102+unwrap(angle(hilbert(hz43rms(shz43:11000)-
mean(hz43rms(shz43:11000)))));
hz51uw=2.1900+unwrap(angle(hilbert(hz51rms(shz51:11000)-
mean(hz51rms(shz51:11000)))));
hz52uw=1.9291+unwrap(angle(hilbert(hz52rms(shz52:11000)-
mean(hz52rms(shz52:11000)))));
hz53uw=1.8278+unwrap(angle(hilbert(hz53rms(shz53:11000)-
mean(hz53rms(shz53:11000)))));

```

```

hz61uw=-1.1695+unwrap(angle(hilbert(hz61rms(shz61:11000)-
mean(hz61rms(shz61:11000)))));
hz62uw=-2.1103+unwrap(angle(hilbert(hz62rms(shz62:11000)-
mean(hz62rms(shz62:11000)))));
hz63uw=-2.1991+unwrap(angle(hilbert(hz63rms(shz63:11000)-
mean(hz63rms(shz63:11000)))));
hz71uw=-2.1142+unwrap(angle(hilbert(hz71rms(shz71:11000)-
mean(hz71rms(shz71:11000)))));
hz72uw=-1.5210+unwrap(angle(hilbert(hz72rms(shz72:11000)-
mean(hz72rms(shz72:11000)))));
hz73uw=-2.1622+unwrap(angle(hilbert(hz73rms(shz73:11000)-
mean(hz73rms(shz73:11000)))));
hz82uw=-3.3239+unwrap(angle(hilbert(hz82rms(shz82:11000)-
mean(hz82rms(shz82:11000)))));
hz83uw=-1.8661+unwrap(angle(hilbert(hz83rms(shz83:11000)-
mean(hz83rms(shz83:11000)))));
hz91uw=1.2841+unwrap(angle(hilbert(hz91rms(shz91:11000)-
mean(hz91rms(shz91:11000)))));
hz92uw=-2.2711+unwrap(angle(hilbert(hz92rms(shz92:11000)-
mean(hz92rms(shz92:11000)))));
hz93uw=-0.8733+unwrap(angle(hilbert(hz93rms(shz93:11000)-
mean(hz93rms(shz93:11000)))));
hz101uw=-1.7733+unwrap(angle(hilbert(hz101rms(shz101:11000)-
mean(hz101rms(shz101:11000)))));
hz102uw=-.9742+unwrap(angle(hilbert(hz102rms(shz102:11000)-
mean(hz102rms(shz102:11000)))));

diff101=zeros(length(9000),1);
er101=zeros(length(9000),1);
interp101=zeros(length(9000),1);
for n=1:length(hz101uw),
    diff101(n,1)=(hz101uw(n,1)/(2*pi)*yagwavelength/2)-
interp1(FEA10(:,1),FEA10(:,2),(1/33)*n,'linear');
    er101(n,1)=diff101(n,1)/interp1(FEA10(:,1),FEA10(:,2),(1/33)*n,'linear');
    interp101(n,1)=interp1(FEA10(:,1),FEA10(:,2),(1/33)*n,'linear');
end

%Use to zero stating data
%
% mean(hz12uw(1:10))
% mean(hz21uw(1:10))
% mean(hz22uw(1:10))

```

```

% mean(hz23uw(1:10))
% mean(hz32uw(1:10))
% mean(hz33uw(1:10))
% mean(hz41uw(1:10))
% mean(hz42uw(1:10))
% mean(hz43uw(1:10))
% mean(hz51uw(1:10))
% mean(hz52uw(1:10))
% mean(hz53uw(1:10))
% mean(hz61uw(1:10))
% mean(hz62uw(1:10))
% mean(hz63uw(1:10))
% mean(hz71uw(1:10))
% mean(hz72uw(1:10))
% mean(hz73uw(1:10))
% mean(hz82uw(1:10))
% mean(hz83uw(1:10))
% mean(hz91uw(1:10))
% mean(hz92uw(1:10))
% mean(hz93uw(1:10))
% mean(hz101uw(1:10))
% mean(hz102uw(1:10))

```

```

avg1hz=((hz11uw(1:3000)+hz12uw(1:3000))/2);
avg2hz=hz21uw(1:4700);
avg3hz=((hz32uw(1:6000)+hz33uw(1:6000))/2);
avg4hz=hz42uw;
avg5hz=hz52uw(1:6400);
avg6hz=((hz62uw(1:10579)+hz63uw(1:10579))/2);
avg7hz=((hz71uw(1:8000)+hz72uw(1:8000)+hz73uw(1:8000))/3);
avg8hz=((hz82uw(1:10500)+hz83uw(1:10500))/2);
avg9hz=((hz91uw(1:9400)+hz92uw(1:9400)+hz93uw(1:9400))/3);
avg10hz=((hz101uw(1:10356)+hz102uw(1:10356))/2);

```

```

figure(1)
title('1hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz11uw/(2*pi)*yagwavelength/2,'b')
plot(hz12uw/(2*pi)*yagwavelength/2,'r')

```

```
plot(33*reprate(:,1),(reprate(:,2)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(2)
title('2hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16,'FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16,'FontSize',16)
hold on
plot(hz21uw/(2*pi)*yagwavelength/2,'b')
plot(hz22uw/(2*pi)*yagwavelength/2,'r')
plot(hz23uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,3)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(3)
title('3hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz32uw/(2*pi)*yagwavelength/2,'r')
plot(hz33uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,4)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(4)
title('4hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz41uw/(2*pi)*yagwavelength/2,'b')
plot(hz42uw/(2*pi)*yagwavelength/2,'r')
plot(hz43uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,5)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(5)
title('5hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz51uw/(2*pi)*yagwavelength/2,'b')
plot(hz52uw/(2*pi)*yagwavelength/2,'r')
plot(hz53uw/(2*pi)*yagwavelength/2,'m')
```

```
plot(33*reprate(:,1),(reprate(:,6)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(6)
title('6hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz61uw/(2*pi)*yagwavelength/2,'b')
plot(hz62uw/(2*pi)*yagwavelength/2,'r')
plot(hz63uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,7)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(7)
title('7hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz71uw/(2*pi)*yagwavelength/2,'b')
plot(hz72uw/(2*pi)*yagwavelength/2,'r')
plot(hz73uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,8)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(8)
title('8hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz82uw/(2*pi)*yagwavelength/2,'r')
plot(hz83uw/(2*pi)*yagwavelength/2,'m')
plot(33*reprate(:,1),(reprate(:,9)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(9)
title('9hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz91uw/(2*pi)*yagwavelength/2,'b')
plot(hz92uw/(2*pi)*yagwavelength/2,'r')
plot(hz93uw/(2*pi)*yagwavelength/2,'m')
```

```
plot(33*reprate(:,1),(reprate(:,10)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
```

```
figure(10)
title('10hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz101uw/(2*pi)*yagwavelength/2,'b')
plot(hz102uw/(2*pi)*yagwavelength/2,'r')
plot(33*reprate(:,1),(reprate(:,11)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
plot(33*data(:,1),(data(:,2)-startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
plot(33*data(:,1),(data(:,3)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.666 1])
plot(33*data(:,1),(data(:,4)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 1 1])
plot(33*data(:,1),(data(:,5)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[.333 1 .666])
plot(33*data(:,1),(data(:,6)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[.666 1 .333])
plot(33*data(:,1),(data(:,7)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1 1 0])
plot(33*data(:,1),(data(:,8)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1 .666 0])
```

```
figure(99)
title('10hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz101uw/(2*pi)*yagwavelength/2,'b')
plot(hz102uw/(2*pi)*yagwavelength/2,'r')
plot(33*efficiency(:,1),(efficiency(:,2)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
plot(33*efficiency(:,1),(efficiency(:,3)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 0.6667])
plot(33*efficiency(:,1),(efficiency(:,4)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 1.0000])
plot(33*efficiency(:,1),(efficiency(:,5)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.3333 1.0000])
plot(33*efficiency(:,1),(efficiency(:,6)-
startintemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.6667 1.0000])
```

```

plot(33*efficiency(:,1),(efficiency(:,7)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 1.0000 1.0000])
plot(33*efficiency(:,1),(efficiency(:,8)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.3333 1.0000
0.6667])
plot(33*efficiency(:,1),(efficiency(:,7)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.6667 1.0000
0.3333])
plot(33*efficiency(:,1),(efficiency(:,9)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 1.0000 0])
plot(33*efficiency(:,1),(efficiency(:,10)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.6667 0])
plot(33*efficiency(:,1),(efficiency(:,11)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.3333 0])
plot(33*efficiency(:,1),(efficiency(:,12)-
starttemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0 0])

```

```

figure(11)
title('1-10hz Data','FontSize',16)
xlabel('Frame Number (Filmed at 33fps)','FontSize',16)
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot(hz11uw(1:3000)/(2*pi)*yagwavelength/2,'color',[0 0 .667])
plot(hz12uw(1:5000)/(2*pi)*yagwavelength/2,'color',[0 0 .667])
plot(hz21uw(1:4700)/(2*pi)*yagwavelength/2,'color',[0 0 1])
% plot(hz22uw,'color',[0 0 1])
% plot(hz23uw(1:7100),'color',[0 0 1])
plot(hz32uw(1:6000)/(2*pi)*yagwavelength/2,'color',[0 0.333 1])
plot(hz33uw(1:7900)/(2*pi)*yagwavelength/2,'color',[0 0.333 1])
% plot(hz41uw(1:6400),'color',[0 0.666 1])
plot(hz42uw/(2*pi)*yagwavelength/2,'color',[0 0.666 1])
% plot(hz43uw,'color',[0 0.666 1])
% plot(hz51uw(1:6400),'color',[0 1 1])
plot(hz52uw(1:6400)/(2*pi)*yagwavelength/2,'color',[0 1 1])
% plot(hz53uw(1:6400),'color',[0 1 1])
% plot(hz61uw(1:8200),'color',[.333 1 .666])
plot(hz62uw/(2*pi)*yagwavelength/2,'color',[.333 1 .666])
plot(hz63uw/(2*pi)*yagwavelength/2,'color',[.333 1 .666])
plot(hz71uw(1:8000)/(2*pi)*yagwavelength/2,'color',[.666 1 .333])
plot(hz72uw/(2*pi)*yagwavelength/2,'color',[.666 1 .333])
plot(hz73uw(1:10000)/(2*pi)*yagwavelength/2,'color',[.666 1 .333])
plot(hz82uw(1:10500)/(2*pi)*yagwavelength/2,'color',[1 1 0])
plot(hz83uw/(2*pi)*yagwavelength/2,'color',[1 1 0])

```

```

plot(hz91uw/(2*pi)*yagwavelength/2,'color',[1 .666 0])
plot(hz92uw/(2*pi)*yagwavelength/2,'color',[1 .666 0])
plot(hz93uw/(2*pi)*yagwavelength/2,'color',[1 .666 0])
plot(hz101uw/(2*pi)*yagwavelength/2,'color',[1 .333 0])
plot(hz102uw/(2*pi)*yagwavelength/2,'color',[1 .333 0])
plot(33*replate(:,1),(replate(:,2)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
plot(33*replate(:,1),(replate(:,3)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 0.6667])
plot(33*replate(:,1),(replate(:,4)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 1.0000])
plot(33*replate(:,1),(replate(:,5)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.3333 1.0000])
plot(33*replate(:,1),(replate(:,6)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.6667 1.0000])
plot(33*replate(:,1),(replate(:,7)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 1.0000 1.0000])
plot(33*replate(:,1),(replate(:,8)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.3333 1.0000
0.6667])
plot(33*replate(:,1),(replate(:,7)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.6667 1.0000
0.3333])
plot(33*replate(:,1),(replate(:,9)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 1.0000 0])
plot(33*replate(:,1),(replate(:,10)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.6667 0])
plot(33*replate(:,1),(replate(:,11)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.3333 0])

```

```

figure(12)
title('1-10hz Averaged Data','FontSize',16)
xlabel('Time (s)')
ylabel('Optical Path Length (m)','FontSize',16)
hold on
plot((1/33)*(1:length(avg1hz)),avg1hz/(2*pi)*yagwavelength/2,'color',[0 0 .667])
plot((1/33)*(1:length(avg2hz)),avg2hz/(2*pi)*yagwavelength/2,'color',[0 0 1])
plot((1/33)*(1:length(avg3hz)),avg3hz/(2*pi)*yagwavelength/2,'color',[0 0.333 1])
plot((1/33)*(1:length(avg4hz)),avg4hz/(2*pi)*yagwavelength/2,'color',[0 0.666 1])
plot((1/33)*(1:length(avg5hz)),avg5hz/(2*pi)*yagwavelength/2,'color',[0 1 1])
plot((1/33)*(1:length(avg6hz)),avg6hz/(2*pi)*yagwavelength/2,'color',[.333 1 .666])
plot((1/33)*(1:length(avg7hz)),avg7hz/(2*pi)*yagwavelength/2,'color',[.666 1 .333])

```

```

plot((1/33)*(1:length(avg8hz)),avg8hz/(2*pi)*yagwavelength/2,'color',[1 1 0])
plot((1/33)*(1:length(avg9hz)),avg9hz/(2*pi)*yagwavelength/2,'color',[1 .666 0])
plot((1/33)*(1:length(avg10hz)),avg10hz/(2*pi)*yagwavelength/2,'color',[1 .333 0])
plot(reprate(:,1),(reprate(:,2)-startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'k')
plot(reprate(:,1),(reprate(:,3)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 0.6667])
plot(reprate(:,1),(reprate(:,4)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0 1.0000])
plot(reprate(:,1),(reprate(:,5)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.3333 1.0000])
plot(reprate(:,1),(reprate(:,6)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 0.6667 1.0000])
plot(reprate(:,1),(reprate(:,7)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0 1.0000 1.0000])
plot(reprate(:,1),(reprate(:,8)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.3333 1.0000
0.6667])
plot(reprate(:,1),(reprate(:,7)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[0.6667 1.0000
0.3333])
plot(reprate(:,1),(reprate(:,9)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 1.0000 0])
plot(reprate(:,1),(reprate(:,10)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.6667 0])
plot(reprate(:,1),(reprate(:,11)-
startingtemp)*(CTE*lengthgain+dndt*lengthgain*nyag),'color',[1.0000 0.3333 0])

```

APPENDIX E

PLOTS OF UNWRAPPED EXPERIMENTAL DATA

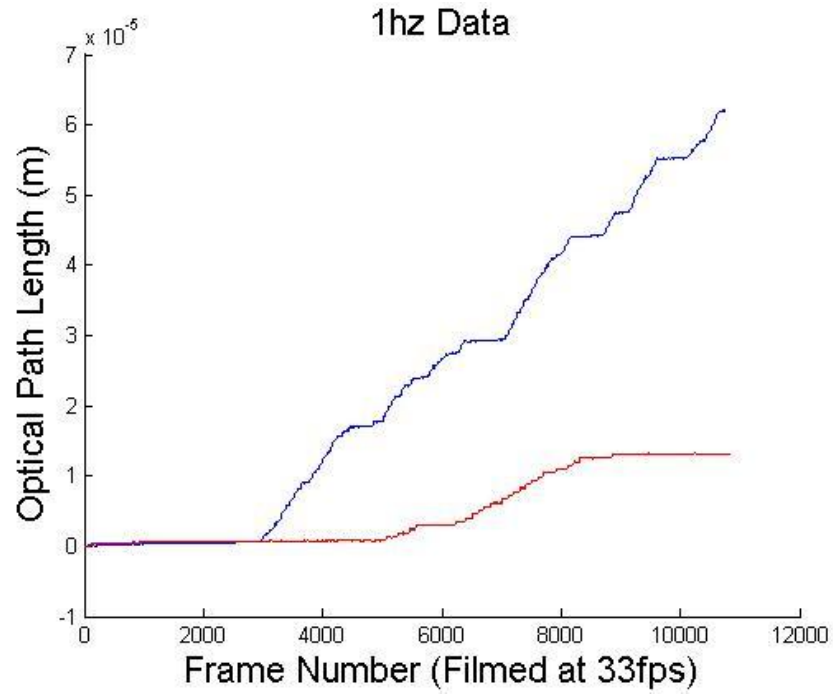


Figure 62: Experimental Data for 1 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red)

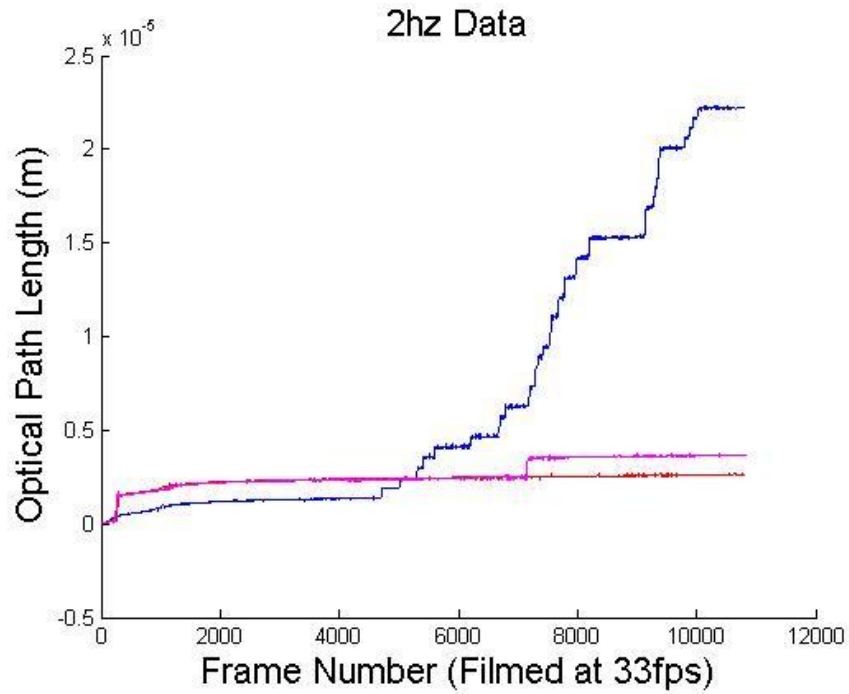


Figure 63: Experimental Data for 2 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

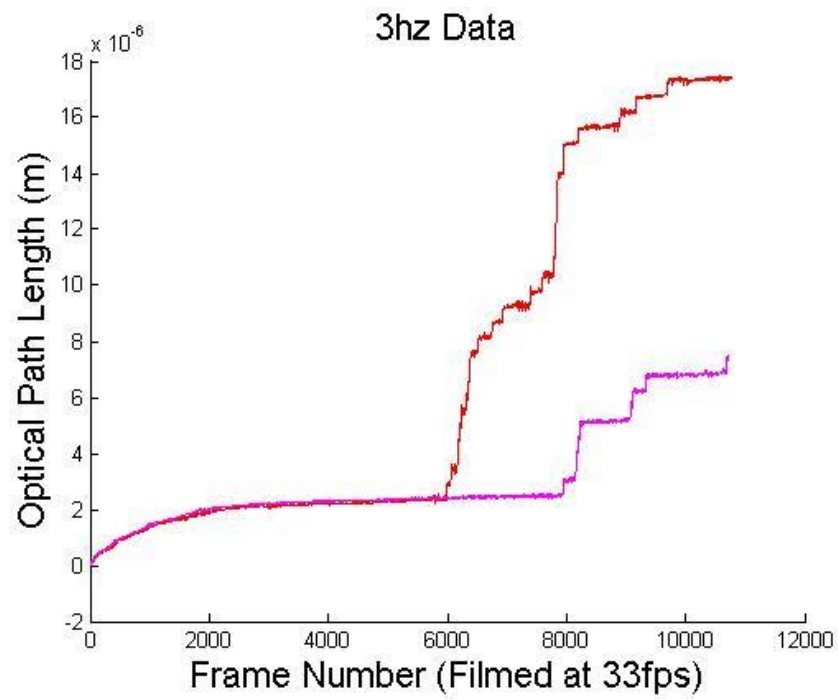


Figure 64: Experimental Data for 3 Hz Tests, Test Run 2 (Red), Test Run 3 (Magenta)

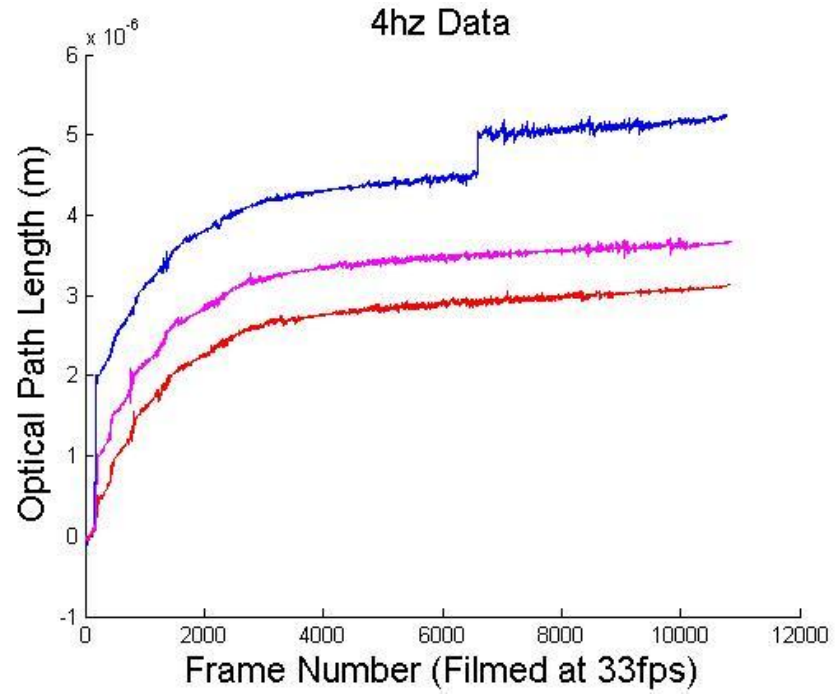


Figure 65: Experimental Data for 4 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

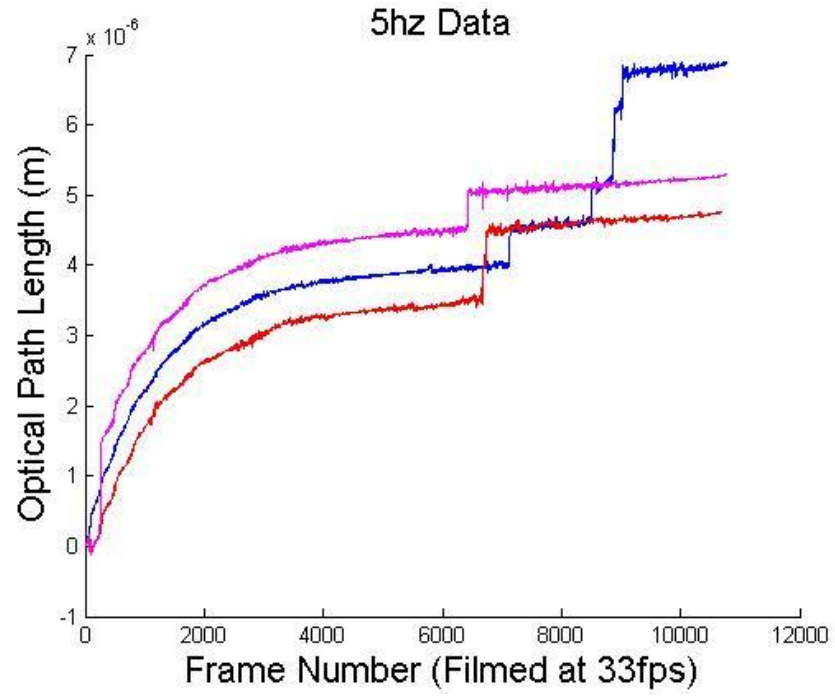


Figure 66: Experimental Data for 5 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

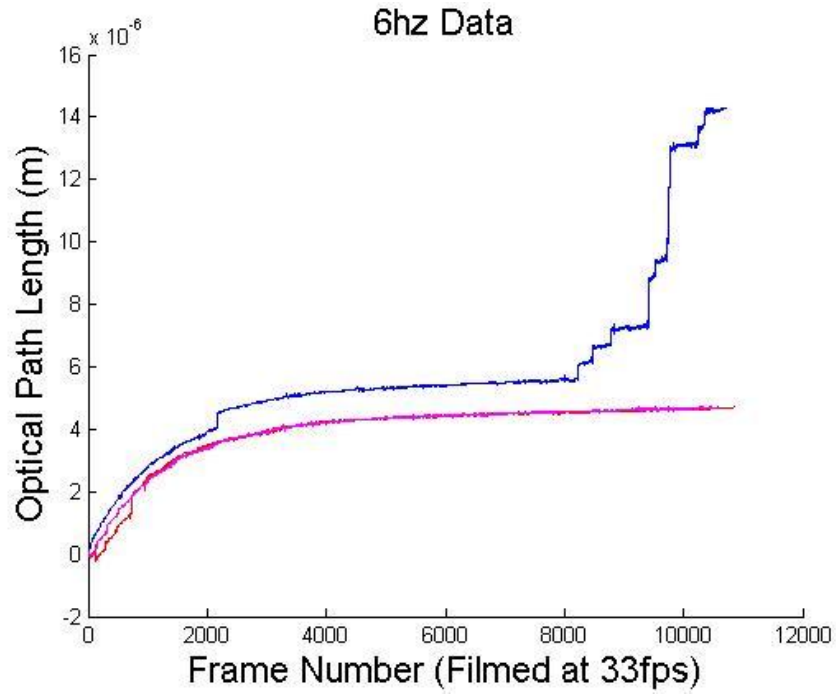


Figure 67: Experimental Data for 6 Hz Tests, Test Run 1 (Blue), Test Run 3 (Magenta)

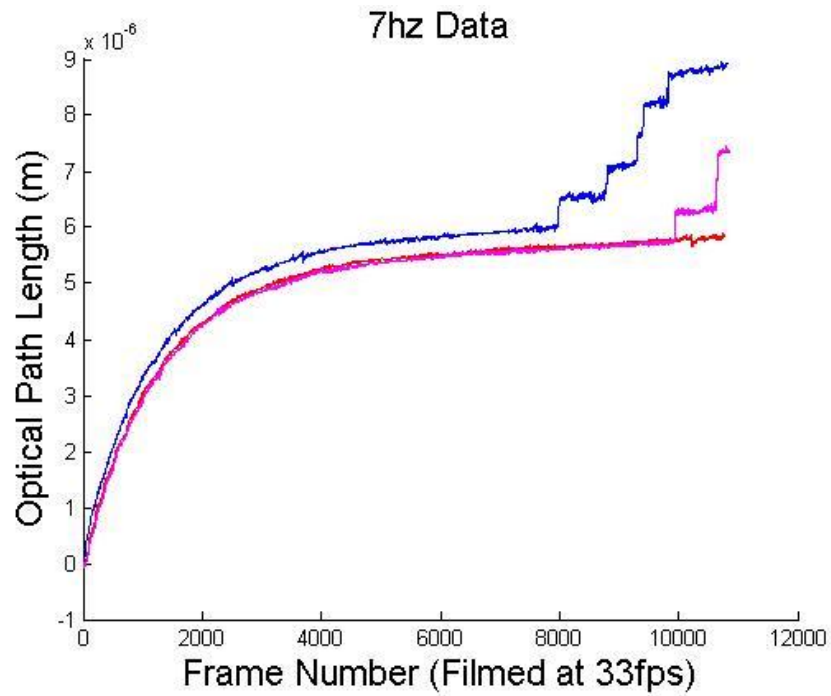


Figure 68: Experimental Data for 7 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

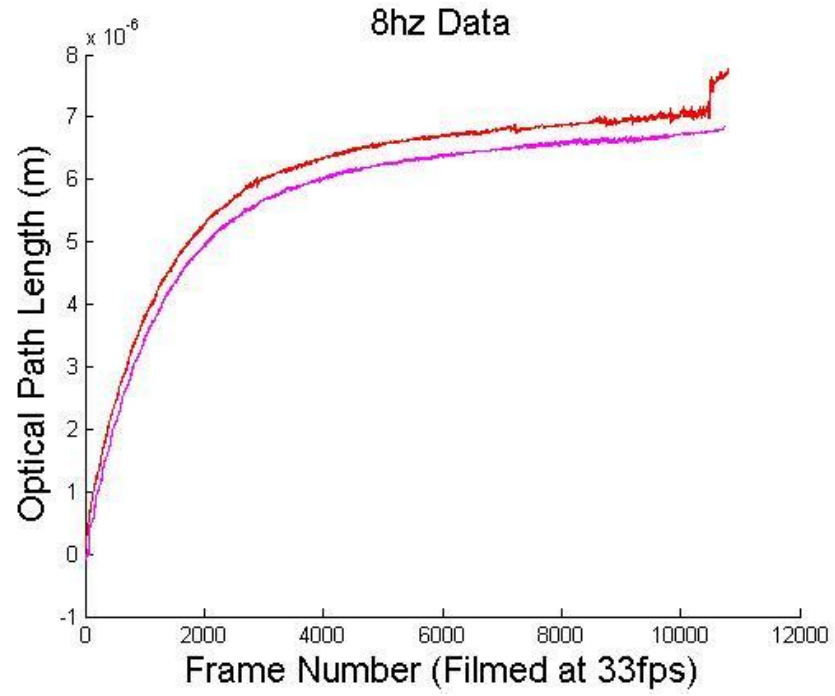


Figure 69: Experimental Data for 8 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

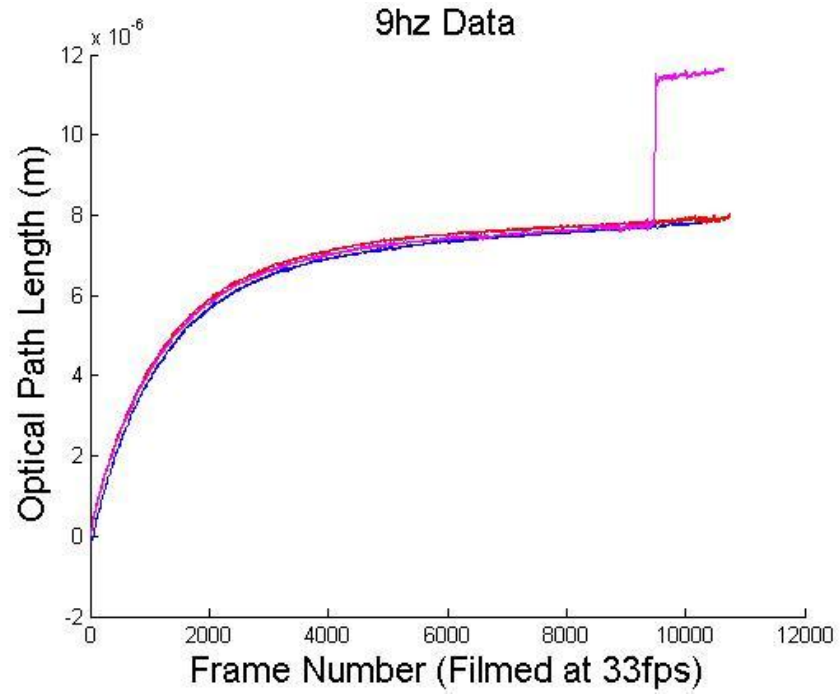


Figure 70: Experimental Data for 9 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

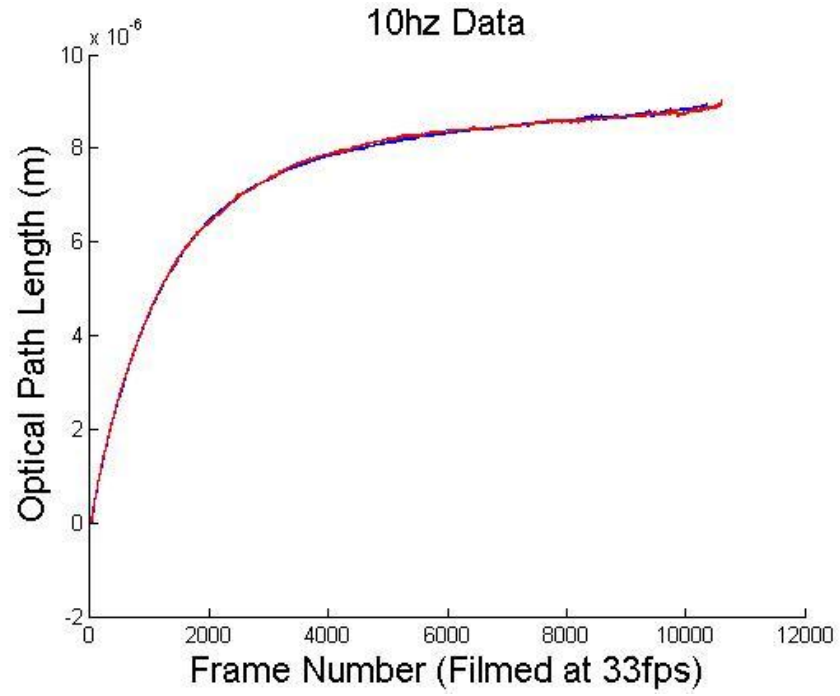


Figure 71: Experimental Data for 10 Hz Tests, Test Run 1 (Blue), Test Run 2 (Red), Test Run 3 (Magenta)

APPENDIX F

ABAQUS SCRIPTS

```

def runstuff():
    # Script will import all input files in current working
    # directory and create jobfiles for each input file uncommenting
    # final 2 lines will also begin running each file as it is imported
    # and wait to begin the next file until the previous has completed
    import os, glob
    import section
    import regionToolset
    import displayGroupMdbToolset as dgm
    import part
    import material
    import assembly
    import step
    import interaction
    import load
    import mesh
    import job
    import sketch
    import visualization
    import xyPlot
    import displayGroupOdbToolset as dgo
    import connectorBehavior
    NewInputFiles=glob.glob('*.inp') # this will list all the input files in the folder
    for file in NewInputFiles:
        text=str(file)
        jobname=text.rstrip(".inp")
        print jobname
        mdb.JobFromInputFile(name=jobname,

        inputFileName='C:\\ABAQUS_FILES\\alpha4\\'+str(jobname)+'.inp',
type=ANALYSIS,
        atTime=None, waitMinutes=0, waitHours=0, queue=None,
memory=90,
        memoryUnits=PERCENTAGE, getMemoryFromAnalysis=True,
        explicitPrecision=SINGLE, nodalOutputPrecision=SINGLE,
        userSubroutine="", scratch="",
parallelizationMethodExplicit=DOMAIN,
        multiprocessingMode=THREADS, numDomains=8, numCpus=8)
        # mdb.jobs[jobname].submit(consistencyChecking=OFF)
        # mdb.jobs[jobname].waitForCompletion()
def plotstuff():
    # Script will open all output databases in current working
    # directory and calculate mean temperature for elements specified
    NewInputFiles=glob.glob('*.odb') # this will list all the input files in the folder

```

```

for file in NewInputFiles:
    text=str(file)
    jobname=text.rstrip(".odb")
    print jobname
    o1 =
session.openOdb(name='C:/ABAQUS_FILES/alpha3/'+str(jobname)+'.odb')
session.viewports['Viewport: 1'].setValues(displayedObject=o1)
odb = session.odbs['C:/ABAQUS_FILES/alpha3/'+str(jobname)+'.odb']
session.xyDataListFromField(odb=odb,
outputPosition=INTEGRATION_POINT,
    variable= (('TEMP', INTEGRATION_POINT), ), elementSets=(
    'MONOBLOCK-1.TOP OF MONOBLOCK', ))
xy322.setValues(
    sourceDescription='avg ( (dataset ) )')
tmpName = xy322.name
session.xyDataObjects.changeKey(tmpName, str(jobname))

```

APPENDIX G

SCRIPT FOR BODY FLUX GENERATION

```

import os
import math
os.chdir('C:\Users\Aaron\Desktop\Python test')
ayag=11.5
ayag=ayag*100
nheat=.385
tpulse=300e-6
ppump=720
lside=0.004
nelement=8
lgain=0.017
reprate=10
hz=reprate
sec=1/hz
hz2=sec/100000
aback=lside*lside
esize=lside/nelement
vlayer=aback*esize
iheat=ppump*nheat
filename='loads.txt'
fout=open(filename,"w")
clear=' '
fout.write(clear)
fout.close()
# filename2='sets.txt'
# fout2=open(filename2,"w")
# clear=' '
# fout2.write(clear)
# fout2.close()
def pcentabs(n):
    zz=(ppump-ppump*math.exp(-ayag*n*esize))/ppump
    return zz
def layerabs(n):
    zz=pcentabs(n)-pcentabs(n-1)
    return zz
def pwrlayer(n):
    zz=iheat*layerabs(n)
    return zz
def fluxlayer(n):
    zz=pwrlayer(n)/vlayer
    return zz
def timeavgflux(n):
    zz=fluxlayer(n)*tpulse*reprate
    return zz

```

```

for i in range(1,33):
    fout=open(filename,"a")
    mytext="\n** Name: BODYFLUX-'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nMONOBLOCK-1.LAYER-'+str(i)+' BF, '+str(timeavgflux(i))

    fout.write(mytext)
    fout.close()
# for i in range(1,33):
    # fout2=open(filename2,"a")
    # mytext2="\n*Elset, elset="LAYER-'+str(i)+'", generate\
# \n '+str(3896+i*8)+' '+str(3903+i*8)+' 1'

    # fout2.write(mytext2)
    # fout2.close()

else:
    print 'for loop over'

```

APPENDIX H

SCRIPT FOR LOAD REPETITION

```

import os
os.chdir('C:\Users\Aaron\Desktop\Python test')
filename='backpumppulse.txt'
fout=open(filename,"w")
clear=' '
fout.write(clear)
fout.close()
hz=10.00000
print 'Pulse rate '+str(hz)+' Hz'
sec=1/hz
print 'relaxation period '+str(sec)+" s"
hz2=sec/100000
##print hz2
for i in range(2,100):
    fout=open(filename,"a")
    mytext="\n** \
\n** STEP: pulse '+str(i)+'\
\n** \
\n*Step, name=pulse '+str(i)+'\
\n*Coupled Temperature-Displacement, deltmx=0.1\
\n230e-6., 230e-6., 2.3e-09, 230e-6.\
\n** \
\n** BOUNDARY CONDITIONS\
\n** \
\n** Name: Temp-BC-1 Type: Temperature\
\n*Boundary\
\n_PICKEDSET12, 11, 11, 22.2\
\n** \
\n** LOADS\
\n** \
\n** Name: BODYFLUX-1'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-1, BF, 1.219e10\
\n** Name: BODYFLUX-2'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-2, BF, 7.031e9\
\n** Name: BODYFLUX-3'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-3, BF, 4.054e9\
\n** Name: BODYFLUX-4'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-4, BF, 2.338e9\
\n** Name: BODYFLUX-5'+str(i)+' Type: Body heat flux\
\n*Dflux\

```

```

\nPART-1-1.SET-5, BF, 1.348e9\
\n** Name: BODYFLUX-6'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-6, BF, 7.776e8\
\n** Name: BODYFLUX-7'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-7, BF, 4.484e8\
\n** Name: BODYFLUX-8'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-8, BF, 2.586e8\
\n** Name: BODYFLUX-9'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-9, BF, 1.491e8\
\n** Name: BODYFLUX-10'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-10, BF, 8.601e7\
\n** Name: BODYFLUX-11'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-11, BF, 4.96e7\
\n** Name: BODYFLUX-12'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-12, BF, 2.86e7\
\n** Name: BODYFLUX-13'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-13, BF, 1.65e7\
\n** Name: BODYFLUX-14'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-14, BF, 9.513e6\
\n** Name: BODYFLUX-15'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-15, BF, 5.486e6\
\n** Name: BODYFLUX-16'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-16, BF, 3.164e6\
\n** Name: BODYFLUX-17'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-17, BF, 1.824e6\
\n** Name: BODYFLUX-18'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-18, BF, 1.052e6\
\n** Name: BODYFLUX-19'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-19, BF, 6.068e5\
\n** Name: BODYFLUX-20'+str(i)+' Type: Body heat flux\

```

```

\n*Dflux\
\nPART-1-1.SET-20, BF, 3.499e5\
\n** Name: BODYFLUX-21'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-21, BF, 2.018e5\
\n** Name: BODYFLUX-22'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-22, BF, 1.164e5\
\n** Name: BODYFLUX-23'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-23, BF, 6.711e4\
\n** Name: BODYFLUX-24'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-24, BF, 3.87e4\
\n** Name: BODYFLUX-25'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-25, BF, 2.232e4\
\n** Name: BODYFLUX-26'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-26, BF, 1.287e4\
\n** Name: BODYFLUX-27'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-27, BF, 7.423e3\
\n** Name: BODYFLUX-28'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-28, BF, 4.281e3\
\n** Name: BODYFLUX-29'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-29, BF, 2.469e3\
\n** Name: BODYFLUX-30'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-30, BF, 1.424e3\
\n** Name: BODYFLUX-31'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-31, BF, 820.973\
\n** Name: BODYFLUX-32'+str(i)+' Type: Body heat flux\
\n*Dflux\
\nPART-1-1.SET-32, BF, 0.628\
\n\
\n*End Step\
\n** -----\
\n** \
\n** STEP: relax'+str(i)+' \
\n** \

```

```

\n*Step, name=relax'+str(i)+' \
\n*Coupled Temperature-Displacement, creep=none, deltmx=0.1\
\n0.1, 0.1, 1e-06, 0.1\
\n** \
\n** LOADS\
\n** \
\n** Name: BODYFLUX-1'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-2'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-3'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-4'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-5'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-6'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-7'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-8'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-9'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-10'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-11'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-12'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-13'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-14'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-15'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-16'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-17'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-18'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-19'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\

```

```

\n** Name: BODYFLUX-20'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-21'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-22'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-23'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-24'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-25'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-26'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-27'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-28'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-29'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-30'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-31'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n** Name: BODYFLUX-32'+str(i)+' Type: Body heat flux\
\n*Dflux, op=NEW\
\n*End Step'
        fout.write(mytext)
        fout.close()
else:

```

APPENDIX I

SIMPLIFIED ABAQUS INPUT FILE

```

*Heading
** Job name: Job-1 Model name: a12n385hz10
** Generated by: Abaqus/CAE 6.9-2
**Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name=MONOBLOCK
*Node

      NODE DEFINITIONS GO HERE
*Element, type=CPE3T
      ELEMENT DEFINITIONS GO HERE
*Elset, elset="TOP OF MONOBLOCK"
3643, 3650, 3904, 3912, 3920, 3928, 3936, 3944, 3952, 3960, 3968, 3976, 3984, 3992,
4000, 4008
4016, 4024, 4032, 4040, 4048, 4056, 4064, 4072, 4080, 4088, 4096, 4104, 4112, 4120,
4128, 4136
4144, 4152, 4160, 4168, 4176, 4184, 4192, 4200, 4208, 4216, 4224, 4232, 4240, 4282,
4287, 4289
4294, 4298, 4299, 4300, 4301, 4302, 4303, 4304, 4305, 4306, 4307, 4308, 4309, 4310,
4311, 4312
4313, 4314, 4315, 4316, 4317, 4318, 4319, 4320, 4321, 4322, 4323, 4324, 4326, 4327,
4334, 4337
4407,
*Elset, elset=LAYER-1, generate
3904, 3911, 1
      DEFINE LAYERS 2-32
4144, 4151, 1
*Elset, elset=LAYER-32, generate
4152, 4159, 1
** Section: Section-1-_PICKEDSET48
*Solid Section, elset=_PICKEDSET48, material=STAINLESS
0.025,
** Section: Section-2-_PICKEDSET46
*Solid Section, elset=_PICKEDSET46, material=YAG
0.003,
** Section: Section-3-_PICKEDSET47
*Solid Section, elset=_PICKEDSET47, material="PET FILM"
0.004,
*End Part
**
**
** ASSEMBLY
**

```

```

*Assembly, name=Assembly
**
*Instance, name=MONOBLOCK-1, part=MONOBLOCK
*End Instance

*End Assembly
**
** MATERIALS
**
*Material, name="PET FILM"
*Conductivity
0.2,
*Density
800.,
*Elastic
7e+09, 0.3
*Specific Heat
1150.,
*Material, name=STAINLESS
*Conductivity
16.2,
*Density
8000.,
*Elastic
2e+11, 0.29
*Expansion
1.73e-05,
*Specific Heat
500.,
*Material, name=YAG
*Conductivity
14., 20.15
10.5, 100.
*Density
4550.,
*Elastic
2.82e+11, 0.28
*Expansion, zero=20.
8.2e-06,
*Specific Heat
590.,
**
** BOUNDARY CONDITIONS
**

```

```

** Name: Disp-BC-1 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PICKEDSET73, ENCASTRE
** Name: Disp-BC-2 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PICKEDSET74, YSYMM
** Name: Disp-BC-3 Type: Symmetry/Antisymmetry/Encastre
*Boundary
_PICKEDSET75, YSYMM
**
** PREDEFINED FIELDS
**
** Name: Field-1 Type: Temperature
*Initial Conditions, type=TEMPERATURE
_PICKEDSET78, 23.
** -----
**
** STEP: Pulse 1
**
*Step, name="Pulse 1", inc=100000
*Coupled Temperature-Displacement, deltmx=0.25
11., 300., 0.0003, 300.
**
** BOUNDARY CONDITIONS
**
** Name: Temp-BC-1 Type: Temperature
*Boundary
_PICKEDSET82, 11, 11, 23.
**
** LOADS
**

** Name: BODYFLUX-1 Type: Body heat flux
*Dflux
MONOBLOCK-1.LAYER-1, BF, 45456828.8875
DEFINE LOADS 2-32
** Name: BODYFLUX-32 Type: Body heat flux
*Dflux
MONOBLOCK-1.LAYER-32, BF, 0.824707598812
**
** INTERACTIONS
**
** Interaction: SURFFILM-1
*Sfilm

```

```

_PICKEDSURF79, F, 23., 2.5
**
** OUTPUT REQUESTS
**
*Restart, write, frequency=0
**
** FIELD OUTPUT: F-Output-1
**
*Output, field
*Node Output
CF, NT, RF, RFL, RFLE, RT, U, UT
**
** FIELD OUTPUT: F-Output-2
**
*Element Output, directions=YES
E, HFL, MISESMAX, PE, PEEQ, S, TEMP, THE
**
** FIELD OUTPUT: F-Output-3
**
*Radiation Output
FTEMP,
**
** FIELD OUTPUT: F-Output-4
**
*Contact Output
HFLA, HTL, HTLA
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history
*Radiation Output
FTEMP,
**
** HISTORY OUTPUT: H-Output-2
**
*Contact Output
HFLA,
*End Step

```

APPENDIX J

FEA AND TEST DIFFERENCE CALCULATION METHOD

```

diff11=zeros(length(9000),1);
er11=zeros(length(9000),1);
interp11=zeros(length(9000),1);
for n=1:length(hz11uw),
    diff11(n,1)=(hz11uw(n,1)/(2*pi)*yagwavelength/2)-
interp1(FEA1(:,1),FEA1(:,2),(1/33)*n,'linear');
    er11(n,1)=diff11(n,1)/interp1(FEA10(:,1),FEA1(:,2),(1/33)*n,'linear');
    interp11(n,1)=interp1(FEA1(:,1),FEA1(:,2),(1/33)*n,'linear');
end
diff12=zeros(length(9000),1);
er12=zeros(length(9000),1);
interp12=zeros(length(9000),1);
for n=1:length(hz12uw),
    diff12(n,1)=(hz12uw(n,1)/(2*pi)*yagwavelength/2)-
interp1(FEA1(:,1),FEA1(:,2),(1/33)*n,'linear');
    er12(n,1)=diff12(n,1)/interp1(FEA10(:,1),FEA1(:,2),(1/33)*n,'linear');
    interp12(n,1)=interp1(FEA1(:,1),FEA1(:,2),(1/33)*n,'linear');
end

```

CONTINUE FOR EACH DATA SET

APPENDIX K

DIFFERENCE OF FEA AND TEST DATA

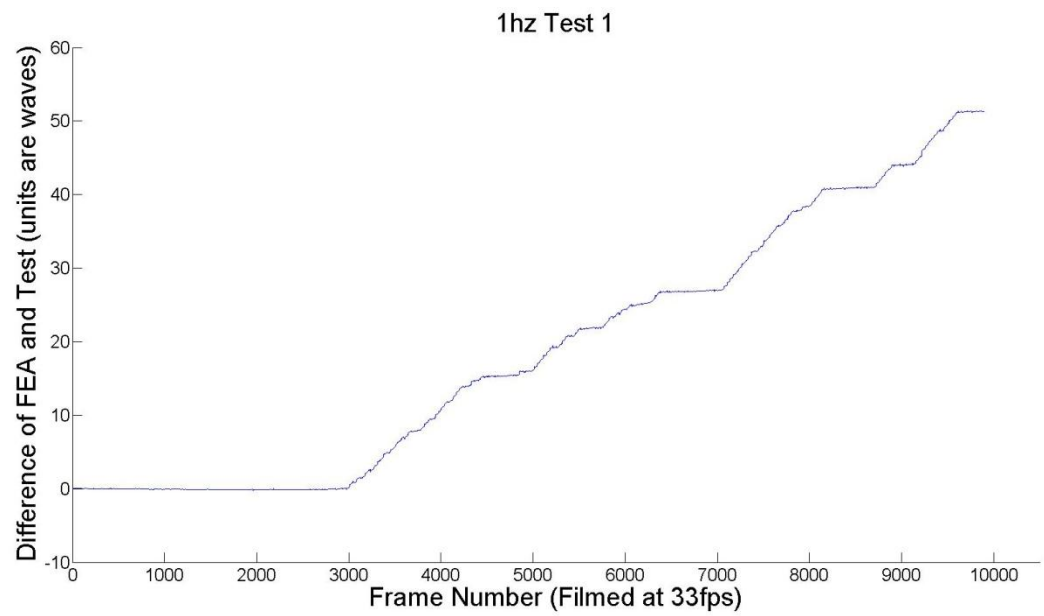


Figure 72: Difference of FEA and Test Data 1 Hz Pulse Rate Test 1

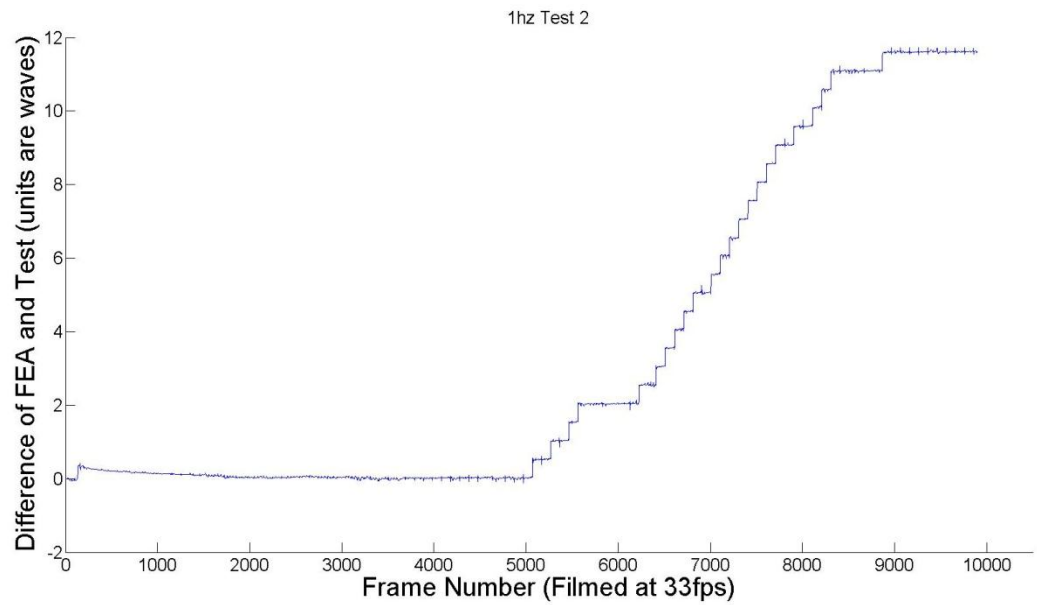


Figure 73: Difference of FEA and Test Data 1 Hz Pulse Rate Test 2

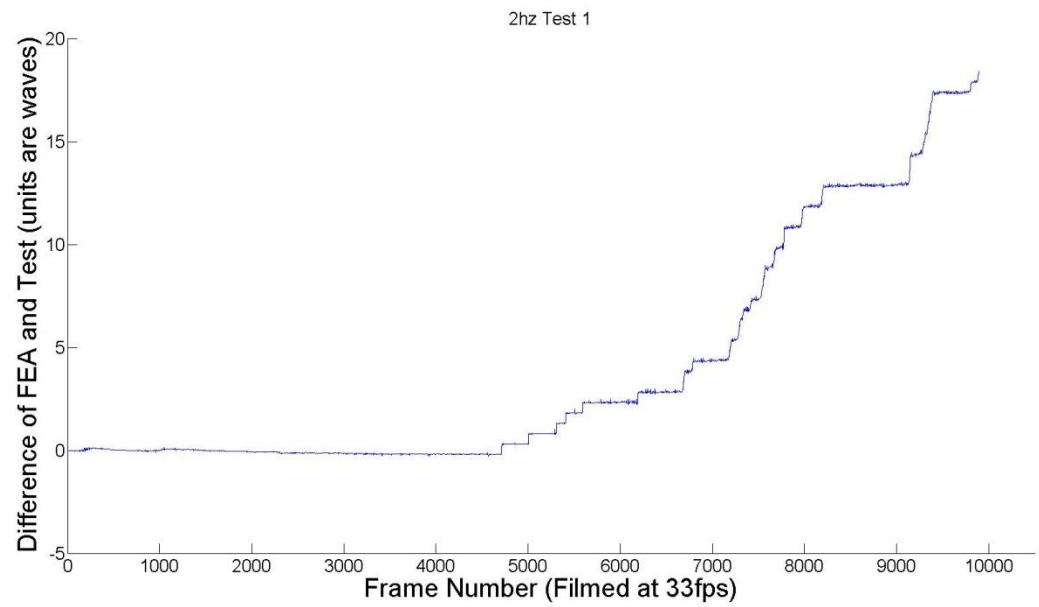


Figure 74: Difference of FEA and Test Data 2 Hz Pulse Rate Test 1

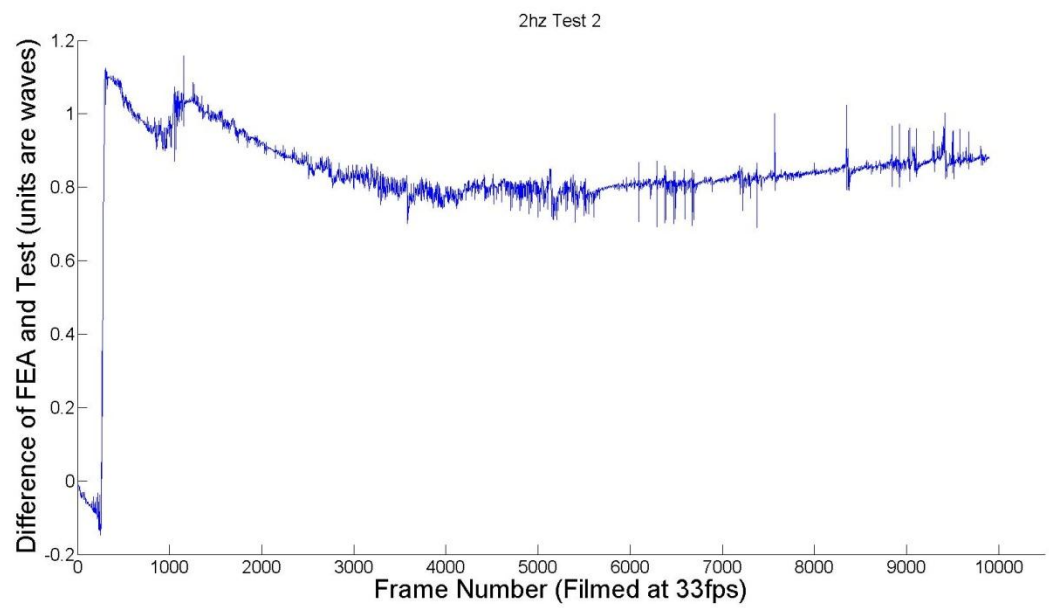


Figure 75: Difference of FEA and Test Data 2 Hz Pulse Rate Test 2

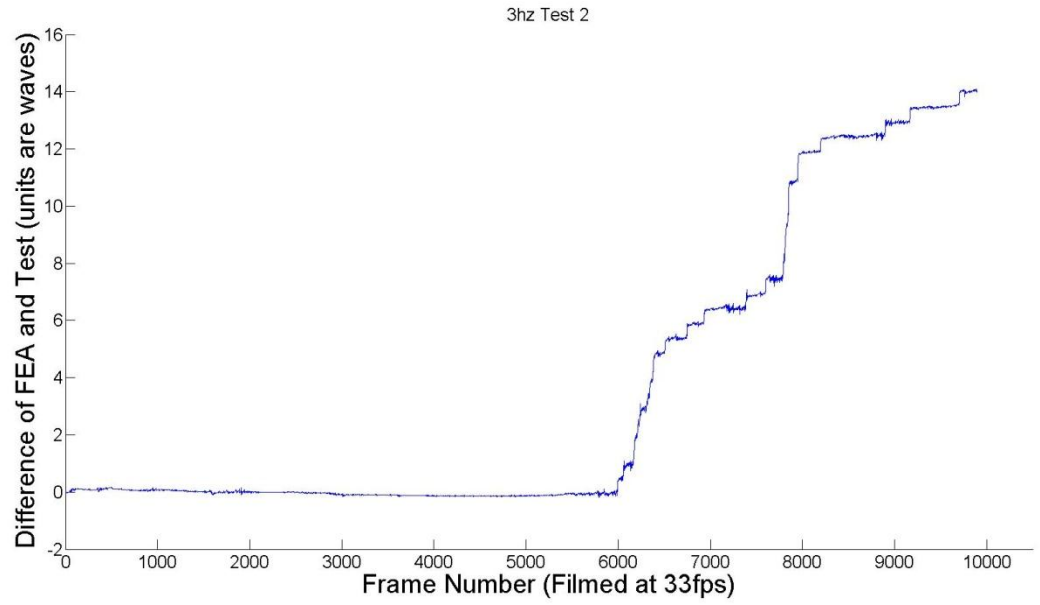


Figure 76: Difference of FEA and Test Data 3 Hz Pulse Rate Test 2

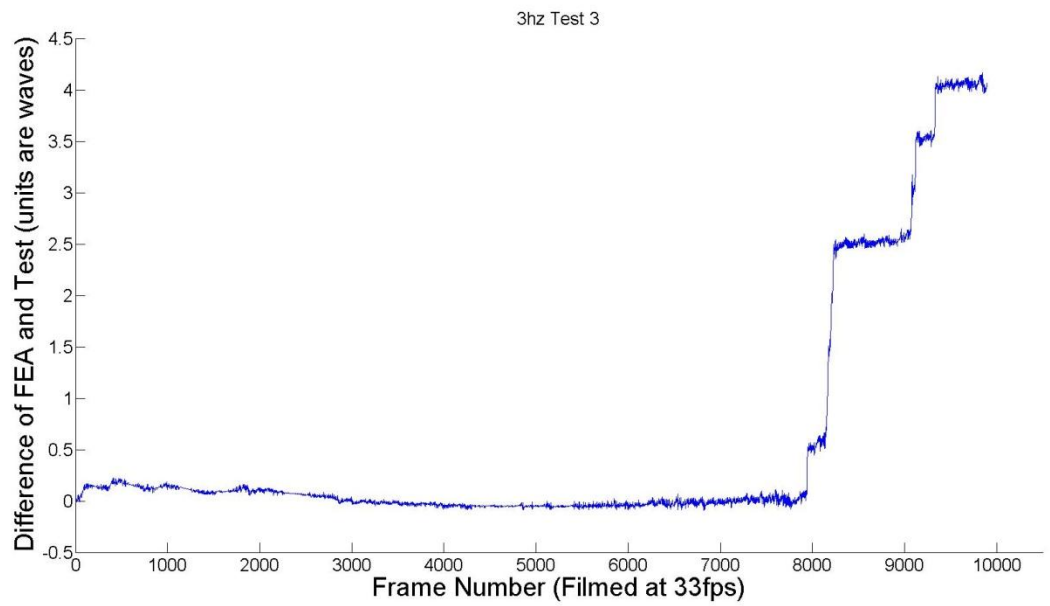


Figure 77: Difference of FEA and Test Data 3 Hz Pulse Rate Test 3

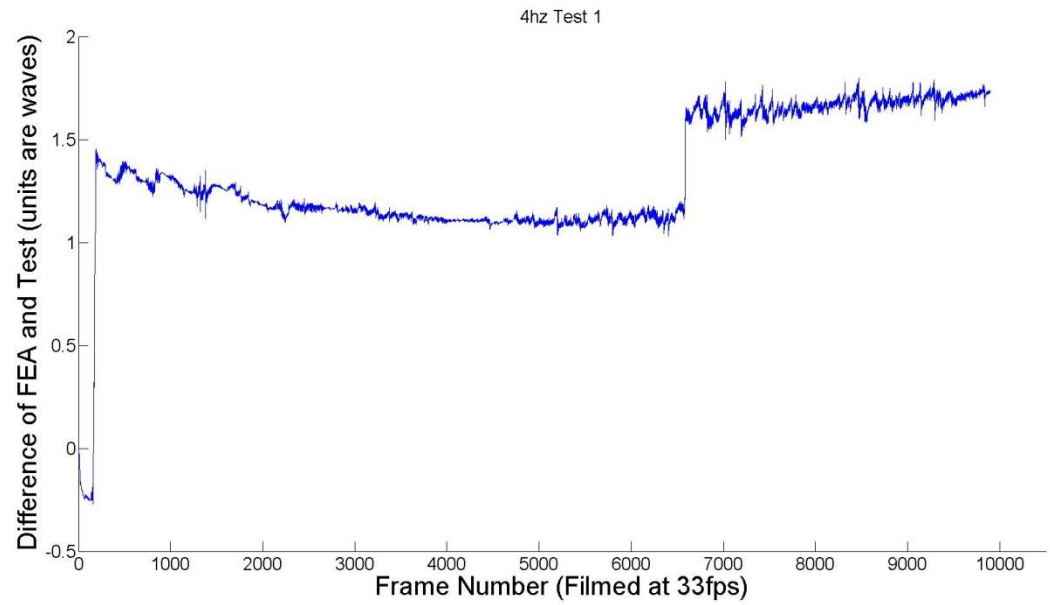


Figure 78: Difference of FEA and Test Data 4 Hz Pulse Rate Test 1

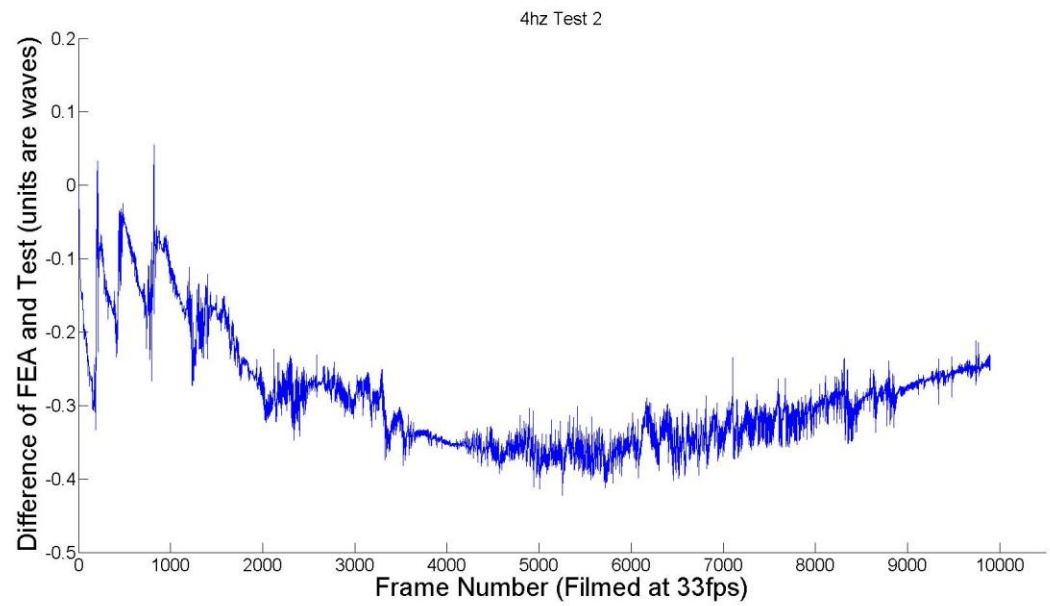


Figure 79: Difference of FEA and Test Data 4 Hz Pulse Rate Test 2

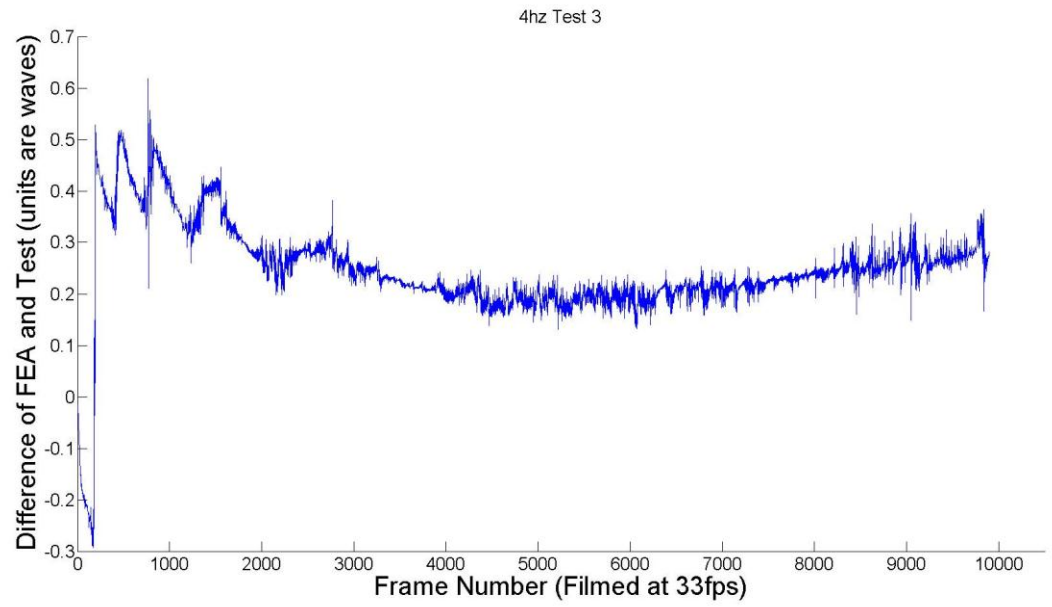


Figure 80: Difference of FEA and Test Data 4 Hz Pulse Rate Test 3

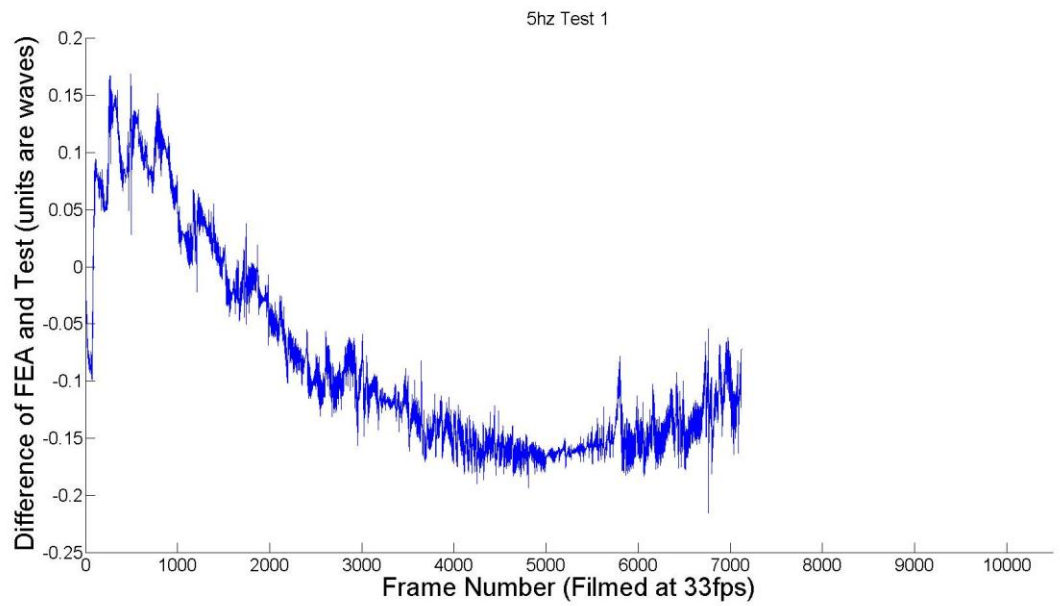


Figure 81: Difference of FEA and Test Data 5 Hz Pulse Rate Test 1

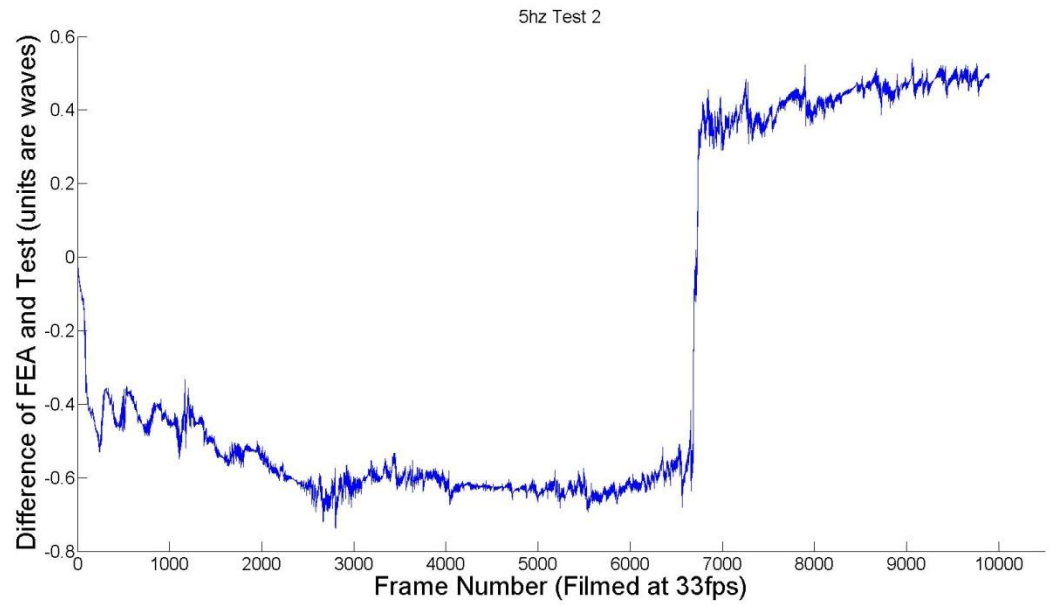


Figure 82: Difference of FEA and Test Data 5 Hz Pulse Rate Test 2

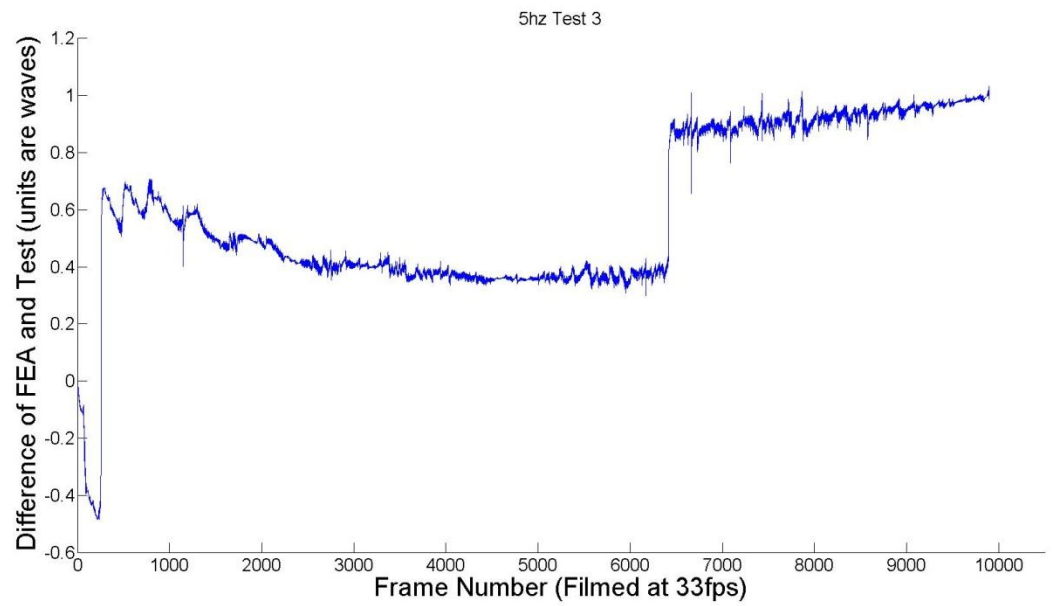


Figure 83: Difference of FEA and Test Data 5 Hz Pulse Rate Test 3

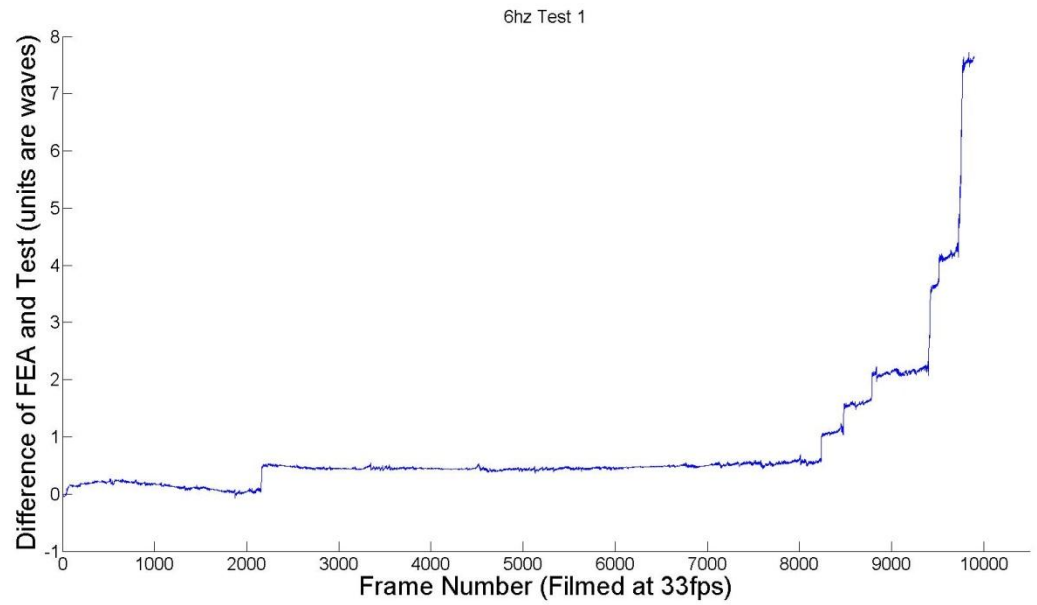


Figure 84: Difference of FEA and Test Data 6 Hz Pulse Rate Test 1

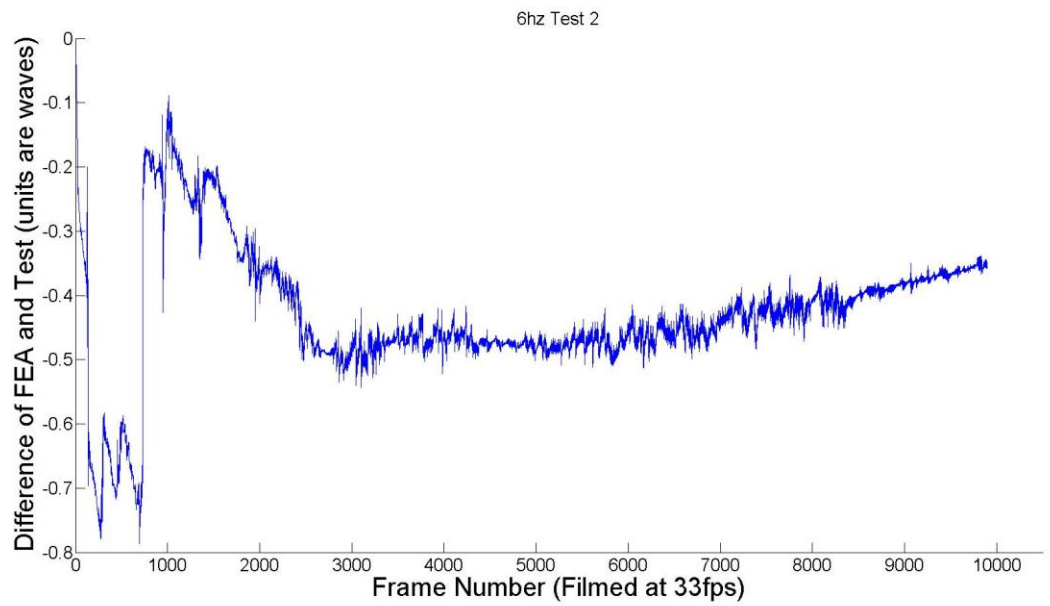


Figure 85: Difference of FEA and Test Data 6 Hz Pulse Rate Test 2

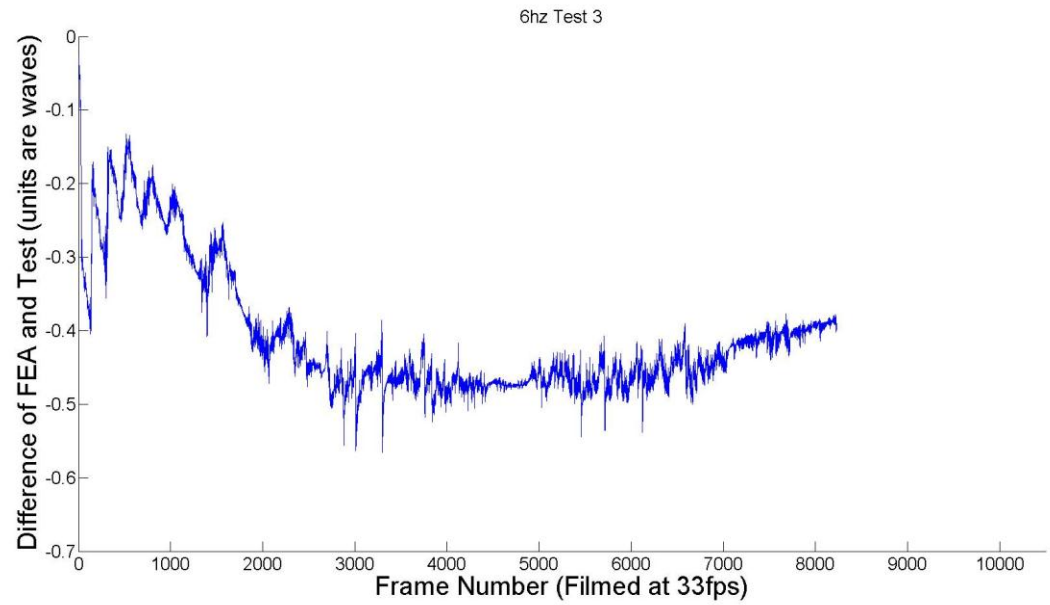


Figure 86: Difference of FEA and Test Data 6 Hz Pulse Rate Test 3

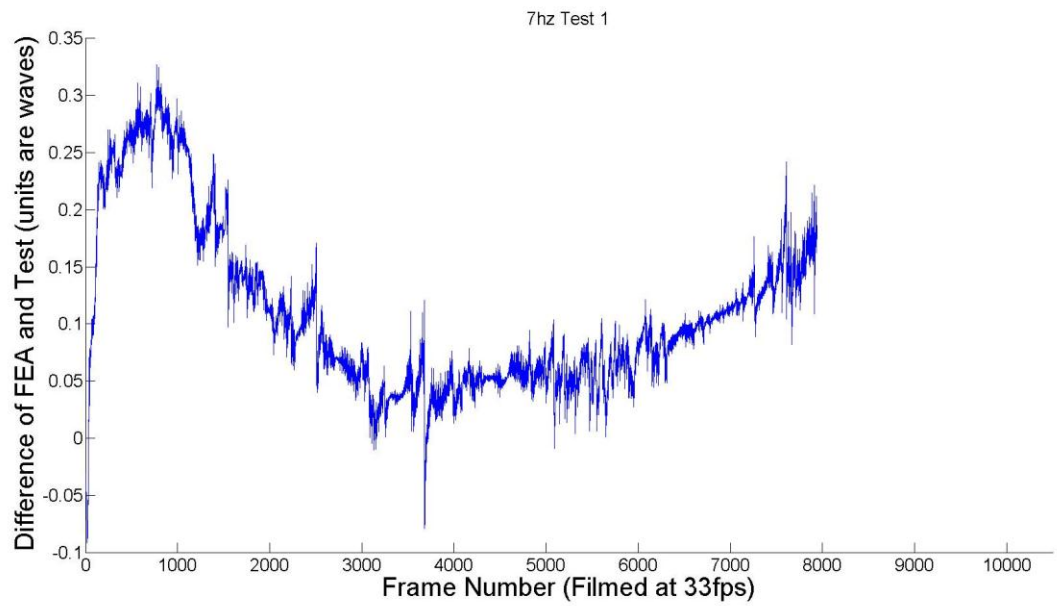


Figure 87: Difference of FEA and Test Data 7 Hz Pulse Rate Test 1

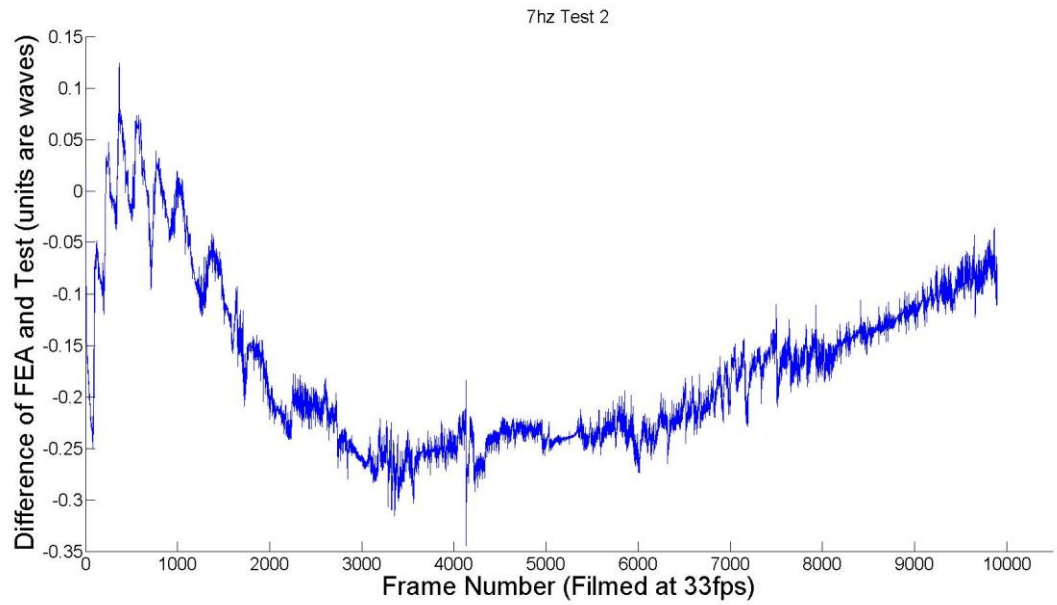


Figure 88: Difference of FEA and Test Data 7 Hz Pulse Rate Test 2

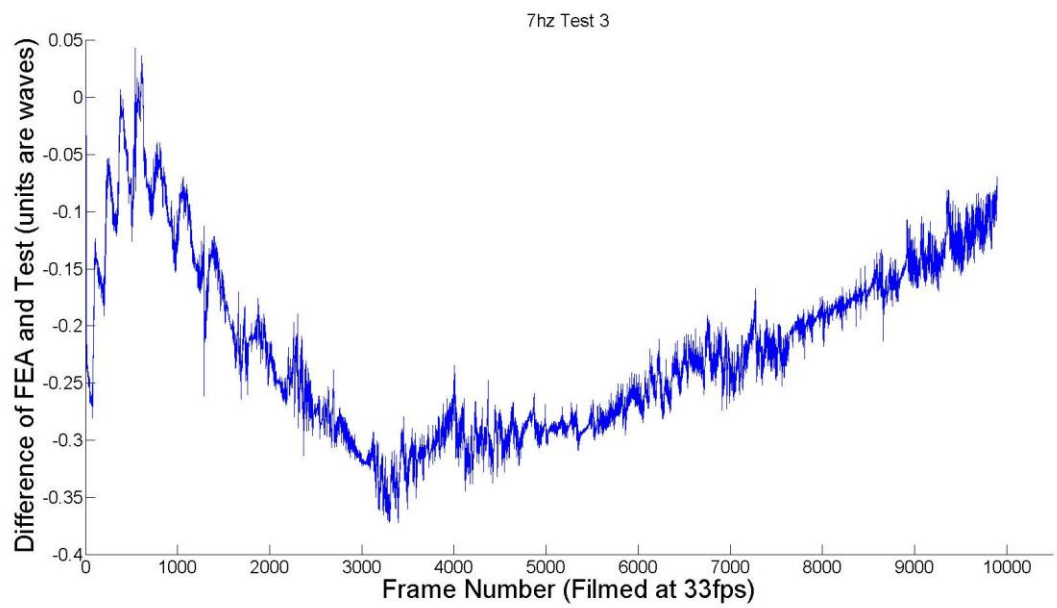


Figure 89: Difference of FEA and Test Data 7 Hz Pulse Rate Test 3

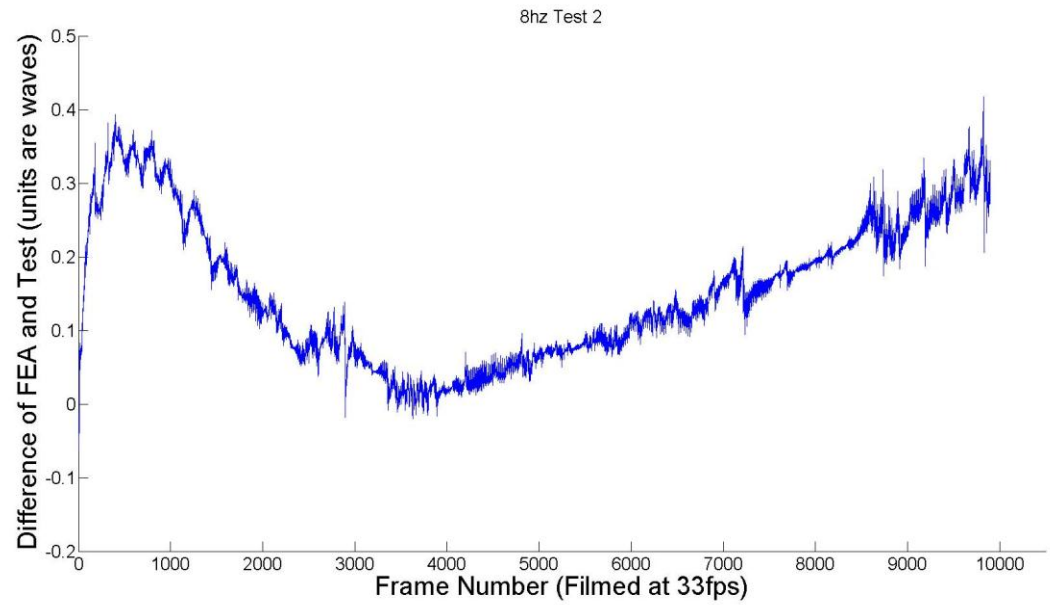


Figure 90: Difference of FEA and Test Data 8 Hz Pulse Rate Test 2

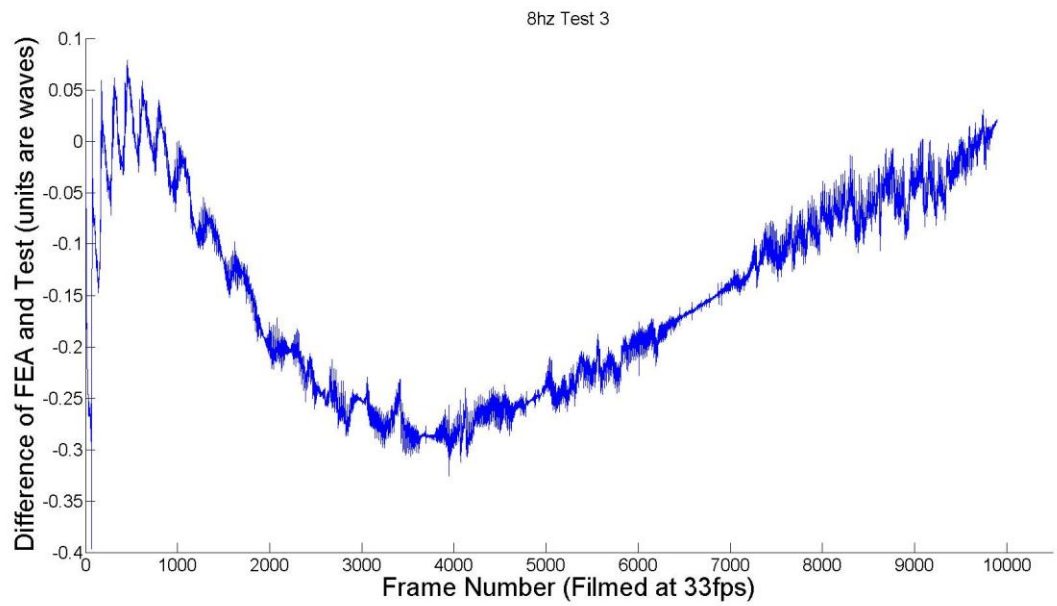


Figure 91: Difference of FEA and Test Data 8 Hz Pulse Rate Test 3

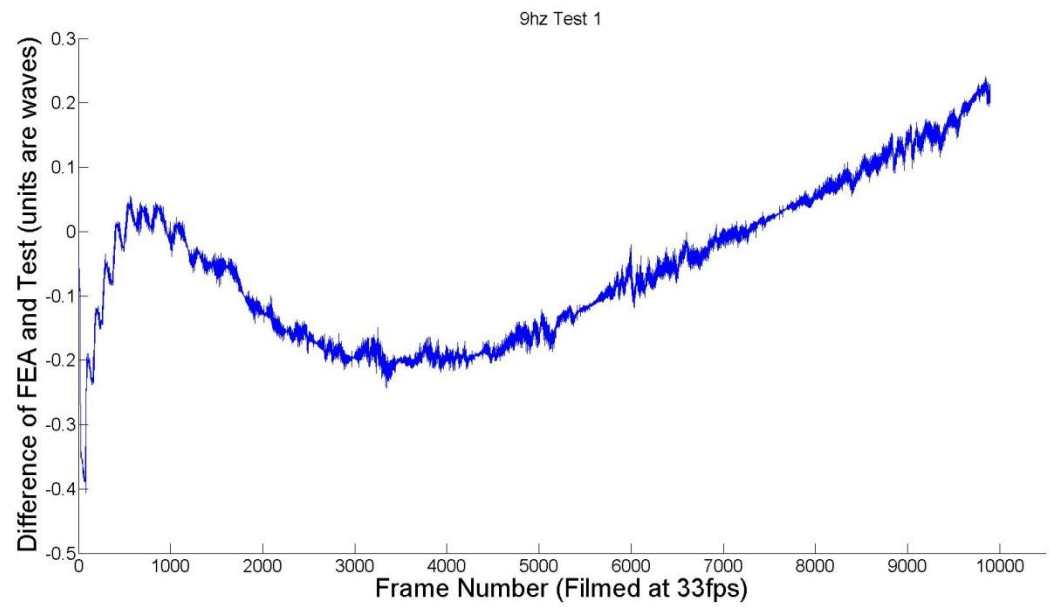


Figure 92: Difference of FEA and Test Data 9 Hz Pulse Rate Test 1

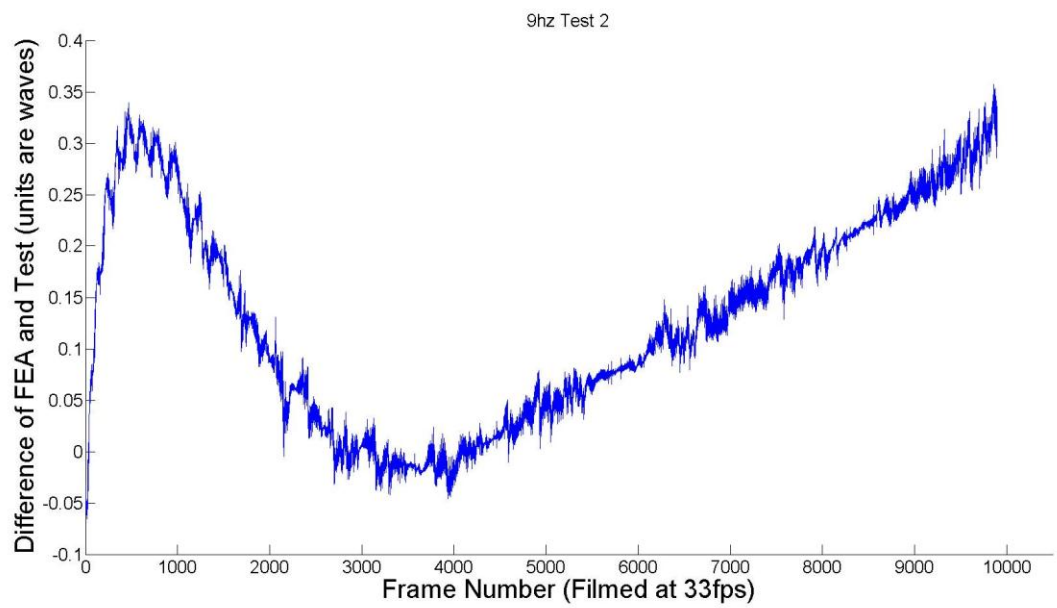


Figure 93: Difference of FEA and Test Data 9 Hz Pulse Rate Test 2

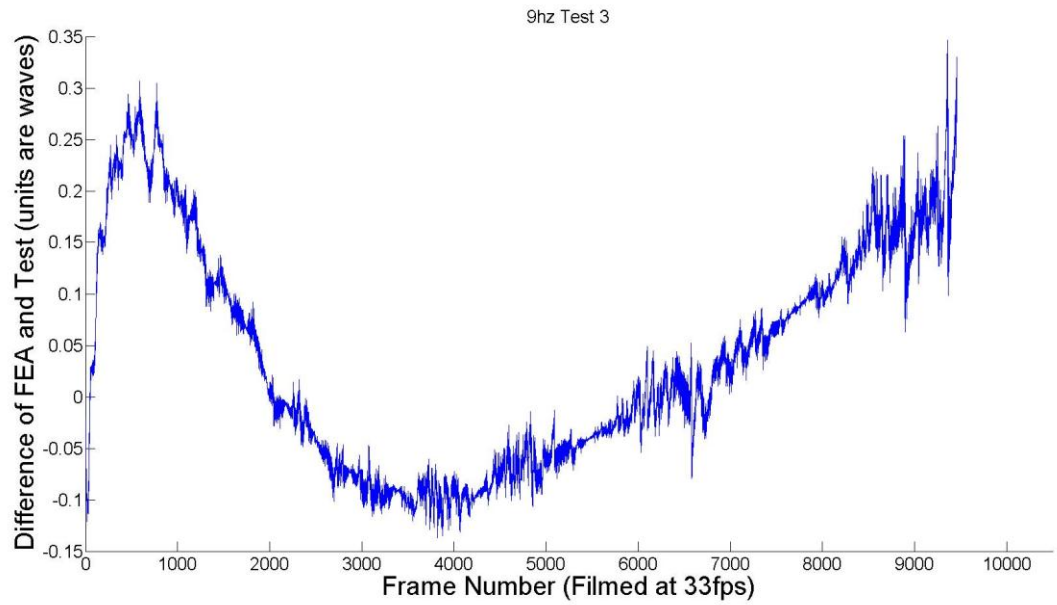


Figure 94: Difference of FEA and Test Data 9 Hz Pulse Rate Test 3

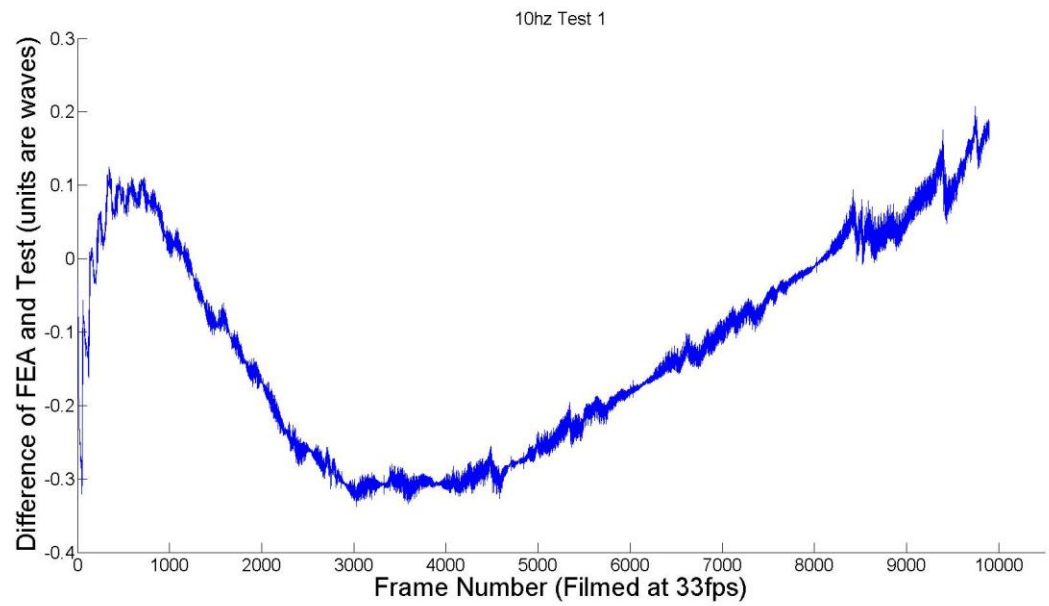


Figure 95: Difference of FEA and Test Data 10 Hz Pulse Rate Test 1

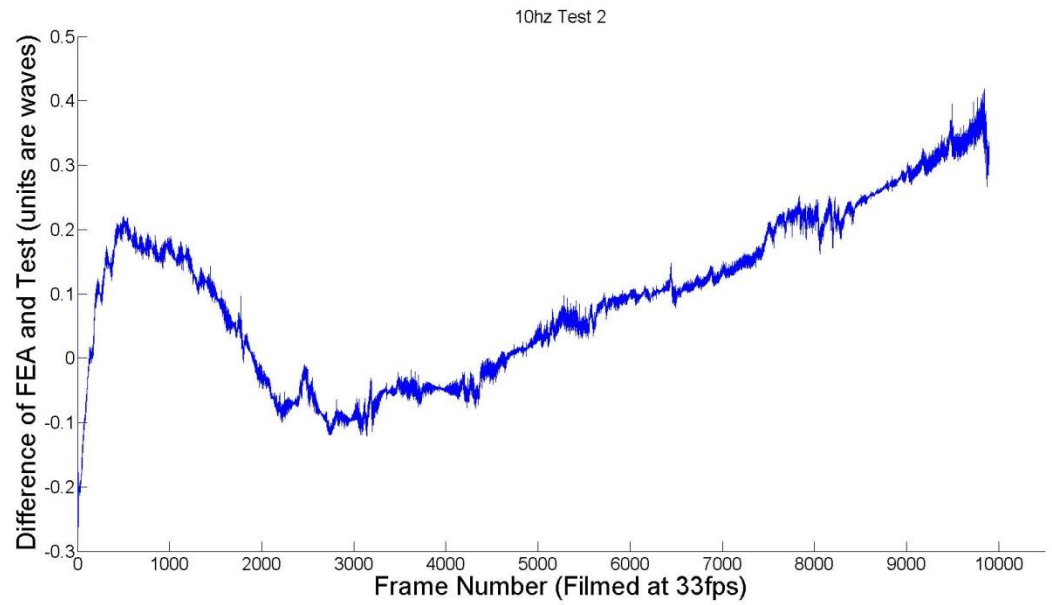


Figure 96: Difference of FEA and Test Data 10 Hz Pulse Rate Test 2

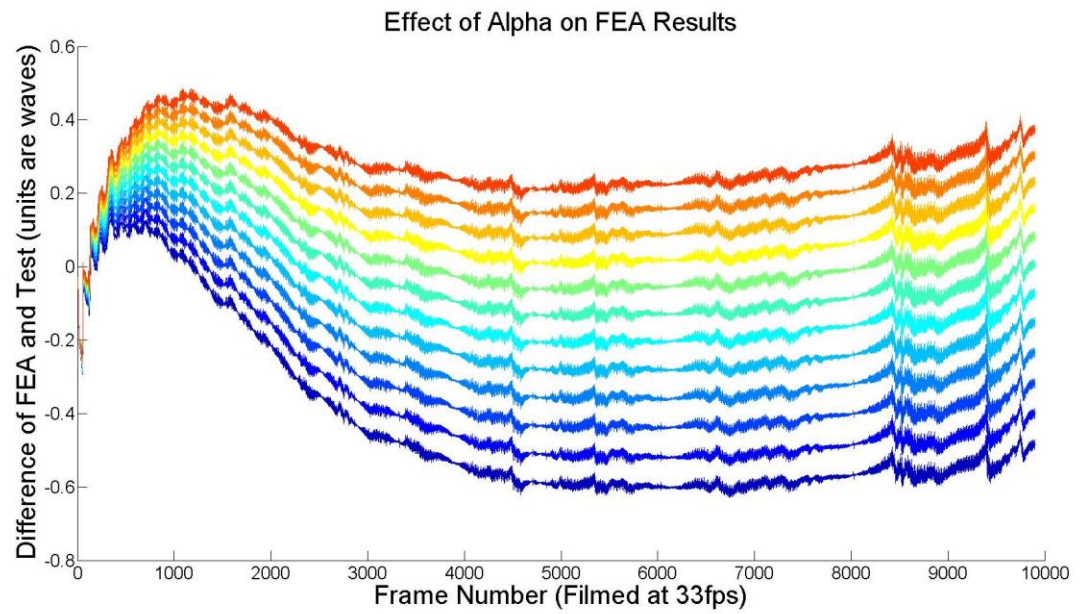


Figure 97: Effect of Varying Alpha on FEA Data, Difference of Experimental Data and FEA data for alpha ranging from $6\text{-}12\text{cm}^{-1}$ in 0.5cm^{-1} increments

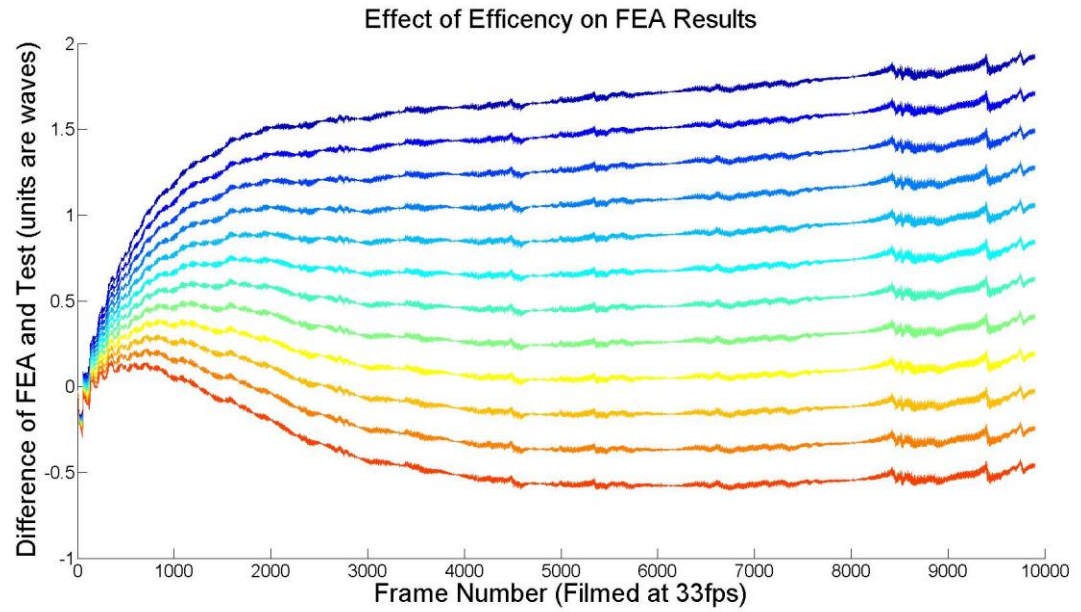


Figure 98: Effect of Varying Thermal Efficiency on FEA Data, Difference of Experimental Data and FEA data for eta ranging from 30-43% in 1% increments

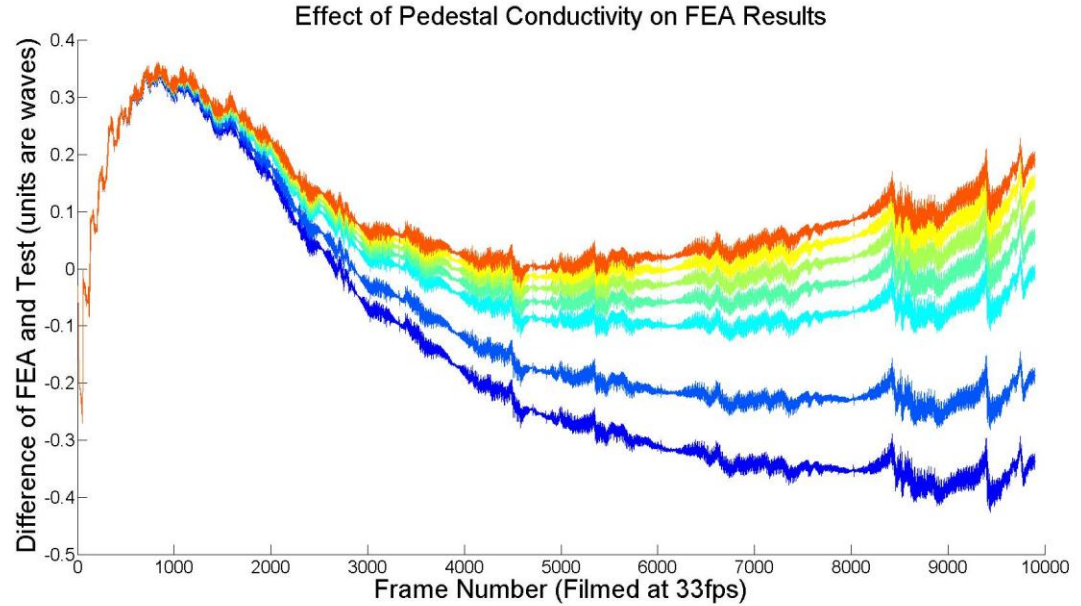


Figure 99: Effect of Boundary Conductivity on FEA Data, Difference of Experimental Data and FEA data for conductivity ranging from 2-22Wm⁻¹K⁻¹ in 2 Wm⁻¹K⁻¹ increments

APPENDIX L

STATISTICAL INFORMATION FOR STEADY

STATE EXPERIMENTAL DATA

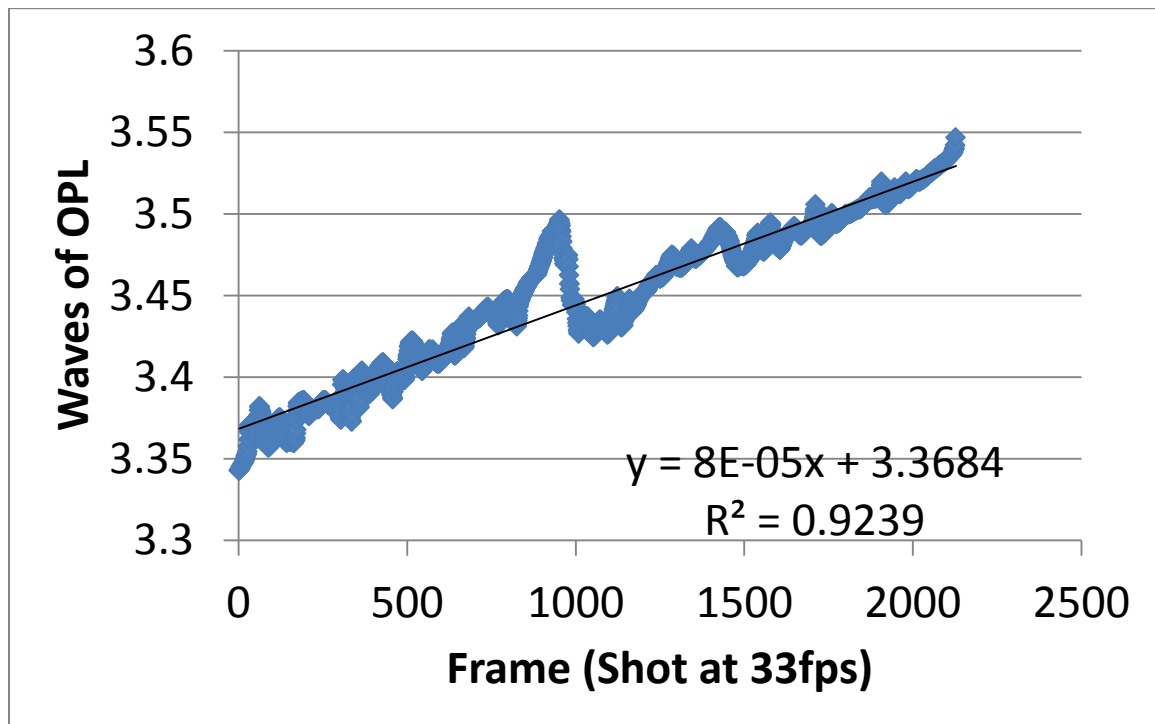


Figure 100: Statistical Data for 1 Hz Steady State diode off, RMS error 0.013 waves

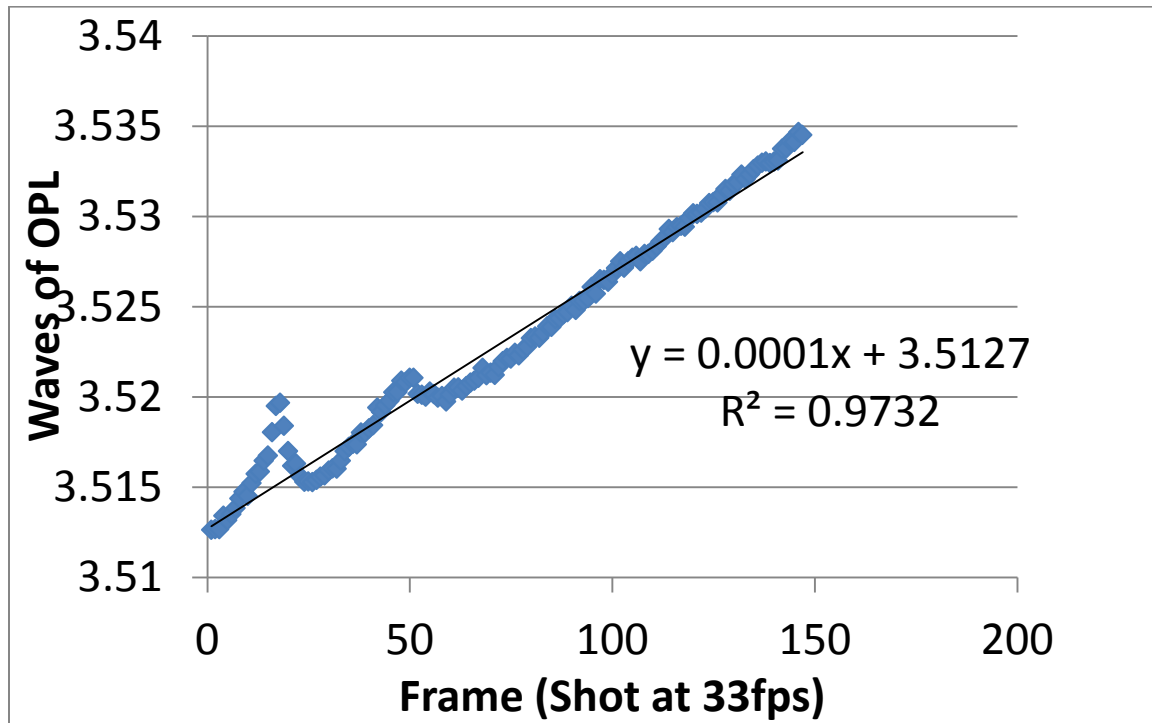


Figure 101: Statistical Data for 2 Hz Steady State diode off, RMS error 0.001 waves

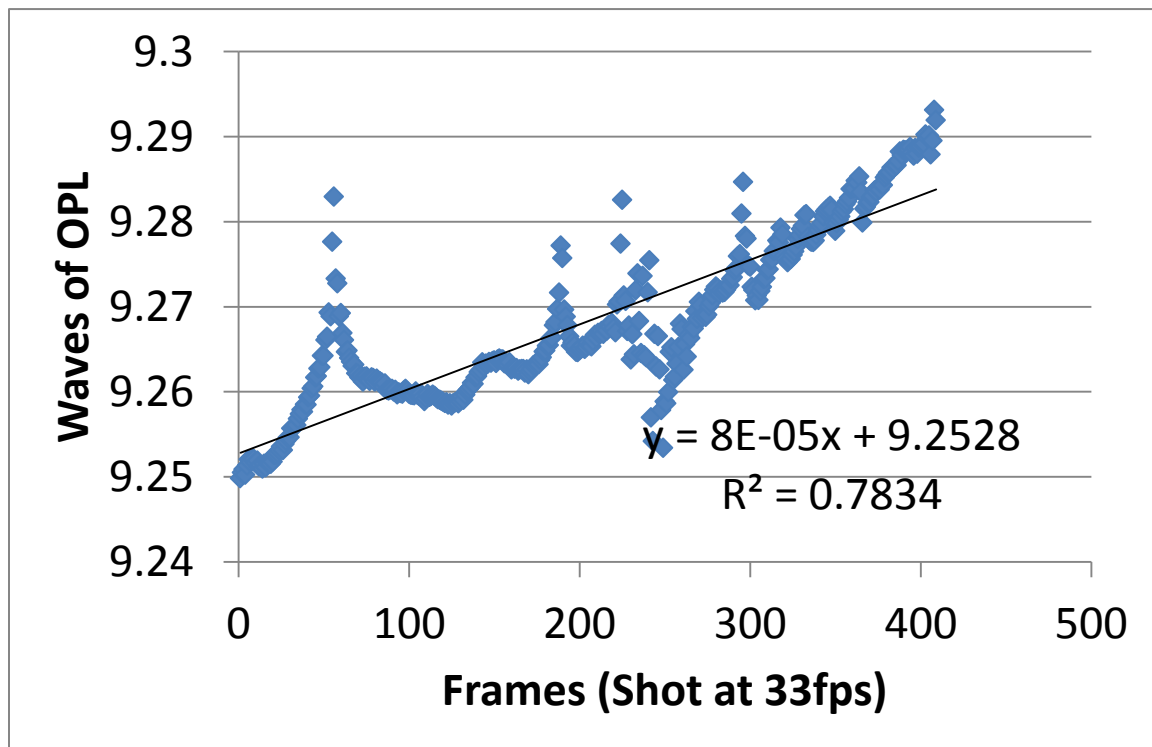


Figure 102: Statistical Data for 2 Hz Steady State diode off, RMS error 0.004 waves