

Implementation and Calibration of a Laser-Induced Fluorescence System in a Diesel Engine

by

Luis H. Palacios

Submitted to the Department of Mechanical Engineering in Partial
Fulfillment of the Requirements for the Degree of


BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

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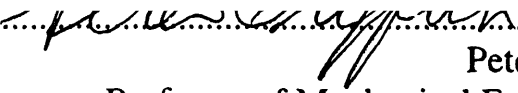
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1997

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Luis H. Palacios

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Abstract

The measurement of the oil film thickness between the piston and cylinder walls is important in understanding the lubricating behavior of oil under varying conditions. This knowledge is useful in trying to minimize oil consumption, power loss and wear from friction inside the engine.

For this purpose, the MIT Laser-Induced-Fluorescence (LIF) system was developed, which can measure the oil film thickness between the piston and cylinder wall during fired operation. The LIF system's components, operation and calibration procedures have reviewed and implemented for the first time in a production diesel engine.

Various methods for calibrating the raw LIF signals from voltage to actual oil film thickness have been used in the past, with varying degrees of success. In this experiment, unlike previous experiments, the piston did not contain the skirt tool marks that had been the preferred method for calibration. Instead, an etch mark was made on the piston skirt region. This region was measured with a Talysurf scan to try to match the LIF trace. The methodology of calibrating with the etch mark was developed and the possibility of automating the calibration procedure was investigated; The currently available data, however, presented too great a noise-to-signal ratio to permit actual calibration.

Thesis Supervisor:
Title:

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Acknowledgments

I would like to thank Dr. Victor Wong, who took a chance on a first-term sophomore three years ago. He gave me a chance to get much more exposure to real-world experimentation than most undergraduates ever get a chance to experience. This culminated in this thesis.

Mark Kiese¹ also deserves my gratitude, whose work for Caterpillar is the background for most of this thesis. He also very patiently explained all the questions that I was constantly asking. It was a real learning experience working with such a meticulous and resourceful experimentalist.

The group of people I'd like to thank next are the three Sloan Automotive graduate students whom I had the good fortune to get to know; Goro Tamai, Bouke Noordzij and Tian Tian. Goro Tamai was probably the hardest working student I met at MIT: when it was time for me to work 12-hour days, I had no justification to complain. Bouke Noordzij is the antithesis of the stereotypical engineering student, who could set up show-room quality experiments in record time. Tian Tian proved to me that it was possible for one person to almost know everything.

My parents, whom I consider two of my closest friends, have always encouraged and supported me in every decision I've made, and have made it possible for me to achieve my educational goals.

I am indebted to Sissela Park, whose support and affection through the later part of my MIT career made the most stressful moments bearable. I really don't know how I would have managed without her.

Finally, I want to thank all of the rest of the people that are responsible for most of my fond memories at MIT; my friends at Interphase, ZBT and Sloan Automotive Laboratories.

Luis Palacios
May, 1997

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Chapter 1: Introduction

1.1 Motivation

In the area of automotive engineering there is a great interest in understanding the lubrication between the piston ring pack and the cylinder wall under varying conditions. The goal is usually twofold; to decrease friction, thereby reducing engine wear and mechanical loss in the engine, and to reduce oil consumption. At the MIT Sloan Automotive Laboratories the Laser-Induced Fluorescence (LIF) system has been used for this purpose.

The LIF system has been through several iterations, as new ways to reduce noise and improve resolution have been developed. The LIF system components and methods of calibration have been documented in previous thesis, most recently by Ryan Bryla [1].

The implementation of the LIF system in the Kubota diesel engine has presented some unique calibration problems, as the piston lacked the tool marks used in previous experiments. There are other methods of calibration (each discussed in section 1.2), but an etch mark on the piston skirt was selected because of earlier success in the use of piston skirt tool marks for calibration [2].

1.2 Previous Work

The MIT LIF system was developed at Sloan Automotive Laboratories by Hoult, Lux, Wong and Billian[5]. The most recent implementations and adaptations have been by Bouke Noordzij[4] and Goro Tamai[1].

The calibration of the LIF signal to actual oil film thickness has been achieved by comparing the microgeometry of different piston components to the voltage readings acquired during the experiment. These different piston components used for the calibration are the upper and lower oil control rails and the piston skirt tool marks[2], and are briefly discussed below.

1.2.1 Upper Oil Control Rail Calibration Method

One calibration method is to use the slope of the upper oil control rail face (see Figure 1.1). The main drawback to the use of the oil control rails is the difficulty of obtaining an accurate Talysurf, and the exceptionally high resolution required for calibration [1]. Another problem arises due to the fact that the LIF signal has a finite width, which can end up spread over the steep side of the oil control rail, giving a false reading. This problem is discussed in detail in Tamai's thesis [2].

Also, this technique would have been especially cumbersome in this experiment, since oil control rails of different design were tested, which would have necessitated a Talysurf profile for each of the different sets of tests run.

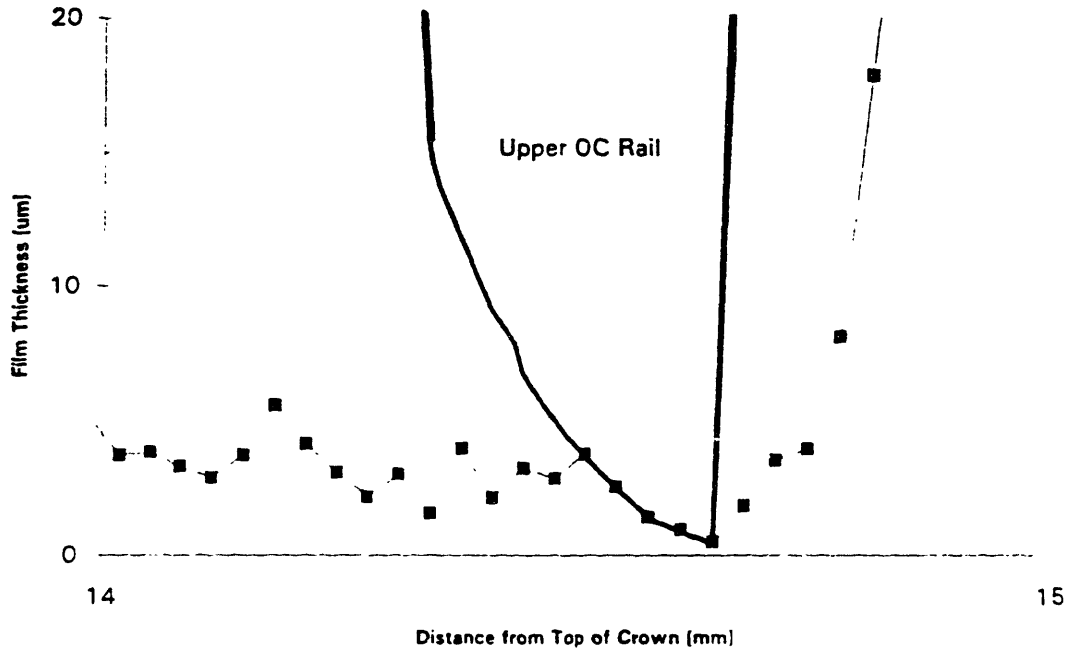


Figure 1.1: Upper OC rail fit into LIF trace for calibration

1.2.2 Lower Oil Control Rail Calibration Method

Calibration by use of the lower oil control rail was also attempted by Tamai [2], but it turned out to be of no use due to over flooding on both sides of the rail. As with the upper oil control rail, there are also difficulties in obtaining the accurate Talysurf required for calibration [1].

1.2.3 Piston Skirt Tool Marks

The most robust method for calibration is the use of piston tool marks. These marks are usually flooded with oil, and since the piston is barrel-shaped, very little wear occurs in the upper skirt region. This facilitates the use of the same Talysurf profile throughout an experiment. Goro found that even after 100 hours of operation, there was very little wear in this region (see Figure 1.2)

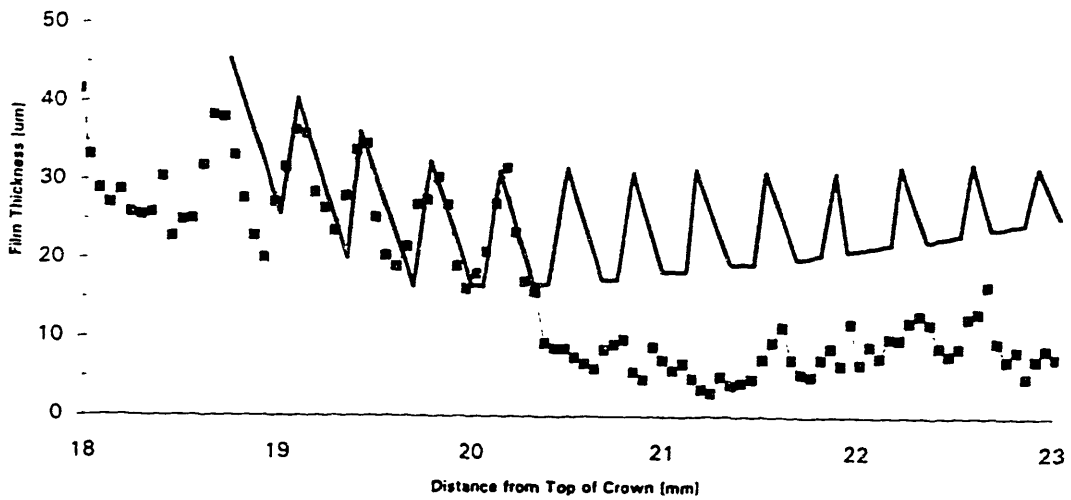


Figure 1.2: Talysurf of Kohler upper skirt machining marks.

1.3 Project Objectives

The LIF system was implemented to investigate the lubricating properties of different ring-pack designs in a Kubota single-cylinder Diesel engine. Based on previous work, the piston tool mark calibration method was selected as the preferred means of calibration. Since the piston lacked the piston skirt tool marks required for this calibration method, it was decided to etch a mark on the upper piston skirt region to emulate this technique. The first attempt in data acquisition resulted in a very noisy signal, so that it was not possible to successfully calibrate the data. However, the calibration techniques and the possible reasons for the unacceptable noise in the signal are documented for future reference.

CHAPTER 2: Experimental Apparatus

2.1 Laser-Induced-Fluorescence (LIF) System

The purpose of the LIF system is to measure the oil film thickness between the piston and cylinder wall during normal operation of the engine and with varying conditions. A simple schematic of the LIF system is shown below in Figure 2.2. In its essence, the LIF system consists of a laser beam (from a 14mW Liconix Helium-Cadmium Laser with a frequency of 492 nm) that is aimed through a quartz window, where it impinges on the oil film between the piston and cylinder wall. The laser excites the film of oil, which has been doped with a coumarin-based dye, and causes it to fluoresce at a different frequency. A photo-multiplier tube (PMT) picks up this fluorescence and converts it to an electrical signal. This signal is amplified and recorded by the data acquisition system.

The PMT voltage amplification setting is crucial, as higher voltages lead to a greater LIF trace. However, with an increase in amplification there is also an increase in noise. Typically, a maximum PMT setting of 700 is recommended [2]. Voltages above this range show a dramatic increase in noise (see figure 2.1). For this experiment, the PMT voltage was varied in order to provide a constant LIF trace. [3].

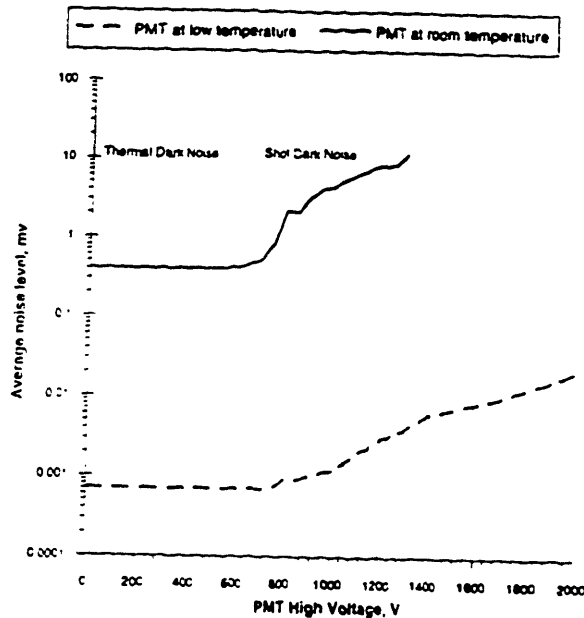


Figure 2.1: PMT signal noise v.s. PMT voltage

2.1.1 LIF Focusing Probes

The LIF housing was manufactured to fit through the water jacket (see Appendix A). The focusing assembly lenses were manufactured by Oriel corp. They are made of high purity fused silica, and which gives a low coefficient of thermal expansion and high thermal conductivity. This helps prevent breakage during the temperature extremes it is subjected to. The specifications are listed in Table 1:

Table 1: Focusing Probe Lens Specifications

Diameter (mm)	Focal Length (mm)	Back Focal Length (mm)	Center Thickness (mm)	Edge Thickness (mm)
6.35	12.7	11.6	1.6	0.6

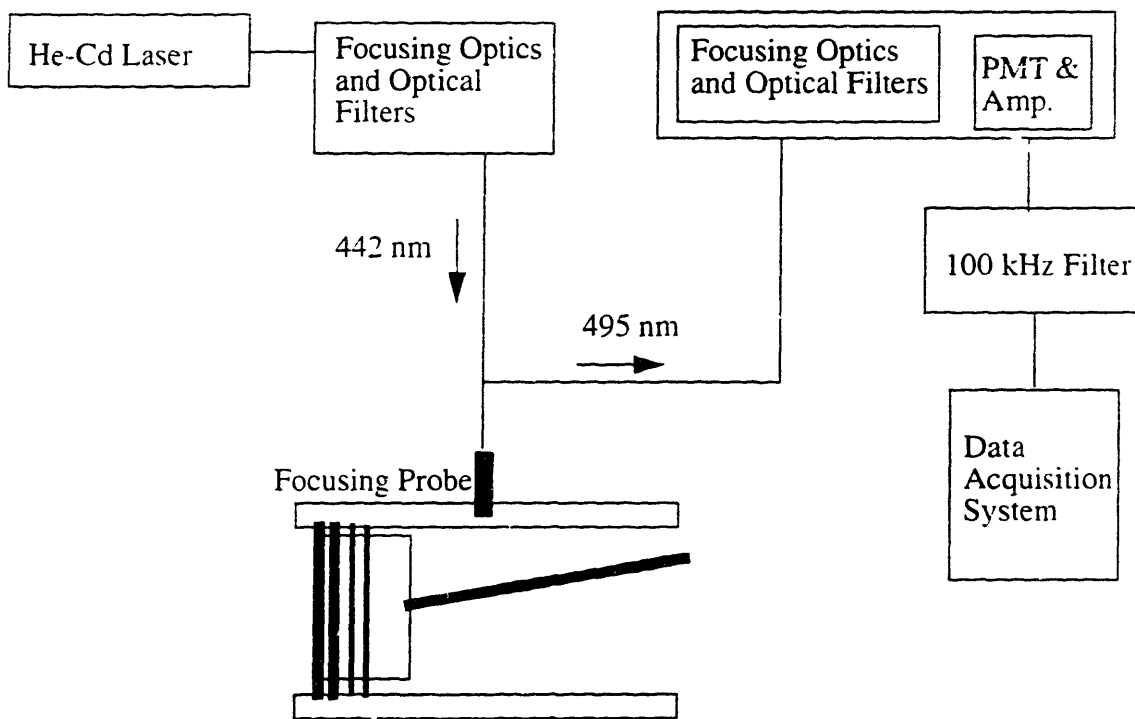


Figure 2.2 Schematic of the Laser Induced Fluorescence System

2.2 Engine setup

A production Kubota Diesel, single cylinder engine was used in the experiment. The

engine's features a horizontal displacement of the piston, which made the installation of the single LIF probe on the anti-thrust side much more feasible. In order to look at the ring characteristics at maximum speed, the mid-stroke section was chosen for the LIF window. Engine specifications are given below in Table 2.

The engine, which is normally cooled with a water radiator, was retrofitted with a water jacket so that the coolant temperature could be controlled. The pump that provided flow through the water jacket was regulated by an electronic controller, which kept the coolant at 90° C.

Table 2: Engine Specifications

Model	Kubota EA300-NB1
Type	Horizontal, water-cooled, 4-cycle diesel engine
Number of Cylinders	1
Bore x Stroke	75mm x 70mm
Displacement	309 cc
Combustion System	Precombustion Swirl Chamber
Fuel	SAE No. 2 Light Diesel Oil

2.3 Test Procedure

The tests began with the firing of the engine until the coolant temperature reached 90° C. This temperature was maintained by the coolant pump, which automatically began circulating the coolant through an heat exchanger when the temperature started to rise.

A set of data was then taken, at each of three different speeds, 1000 rpm, 1600 rpm and 3000 rpm. The engine was also run under different loads: no load, mid load and full load.

In order to minimize the effects of different oil on ring-pack performance, the oil was not changed from the beginning of the test, after which time the data analysis began.

2.4 Data Acquisition System

The data acquisition system used for the LIF and pressure transducer signals was a DAS-58 unit from Keithley Megabyte. The DAS-58 unit was installed in an IBM PC 486-33 clone. The data acquisition system was inherited from previous work, and is documented by Tamai [2] and Noordzij [4]. In this experiment only two channels, the LIF and cylinder pressure, were recorded.

The DAS-58 is triggered by an optical shaft encoder mounted on the engine. The shaft encoder measures 2000 points per revolution. Since an engine cycle consists of two revolutions of the crankshaft, the encoder was mounted on a 2:1 reduction pulley, so that one engine cycle would correspond to one revolution of the encoder. This was done to insure that data acquisition would begin on the same stroke each time, and therefore facilitate data analysis later on. This reduction also resulted in a lesser resolution, but it was not believed at the beginning of the experiment that this would adversely affect results [3].

The LIF system typically includes a 100 kHz filter. Several sets of data were taken without the physical filter, to see if it was causing any unwanted attenuation of the signal. It was hoped that by filtering the data digitally instead (by the use of software), greater resolution could be achieved.

2.5 Piston Skirt Etch Mark

As was noted earlier, the piston upper skirt calibration method was the preferred method of calibration [2]. In the Kubota engine, however, the piston did not contain the tool marks used in the past. It was decided, instead, to create a microgeometry that could be used for calibration. For this purpose, a metal punch was used to score the side of the piston upper skirt. A simple jig was made that would ensure an etch mark perpendicular to the center line of the piston (see figure 2.3).

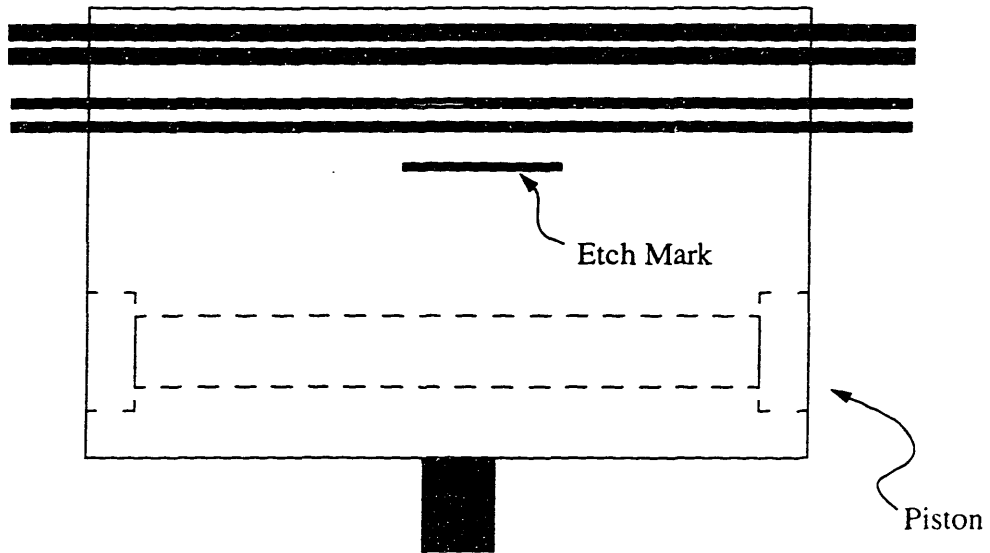


Figure 2.3 Horizontal etch mark

A talysurf was then taken of the score mark (see Figure 2.4). Just like in the upper skirt tool mark calibration, it was hoped that by matching the magnitude of the LIF trace to the known depth of the piston etch mark, a calibration constant (volts per micron) could be calculated. The LIF trace could then be converted to a known oil film thickness.

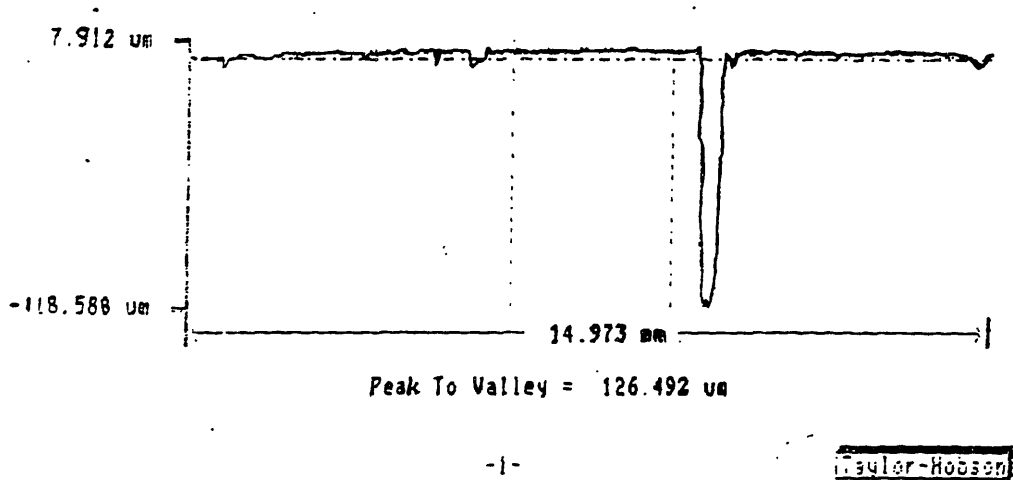


Figure 2.4: Talysurf of etch mark

CHAPTER 3: Data Processing

3.1 Raw LIF data

For each operating condition, two sets of data were taken. The first was done with the 100kHz filter in place, and the second without this filter. It was done to see if there was any attenuation of the signal due to this filter, and if the resolution could be improved with a digital (software) filter in the analysis stage (see Figure 3.1).

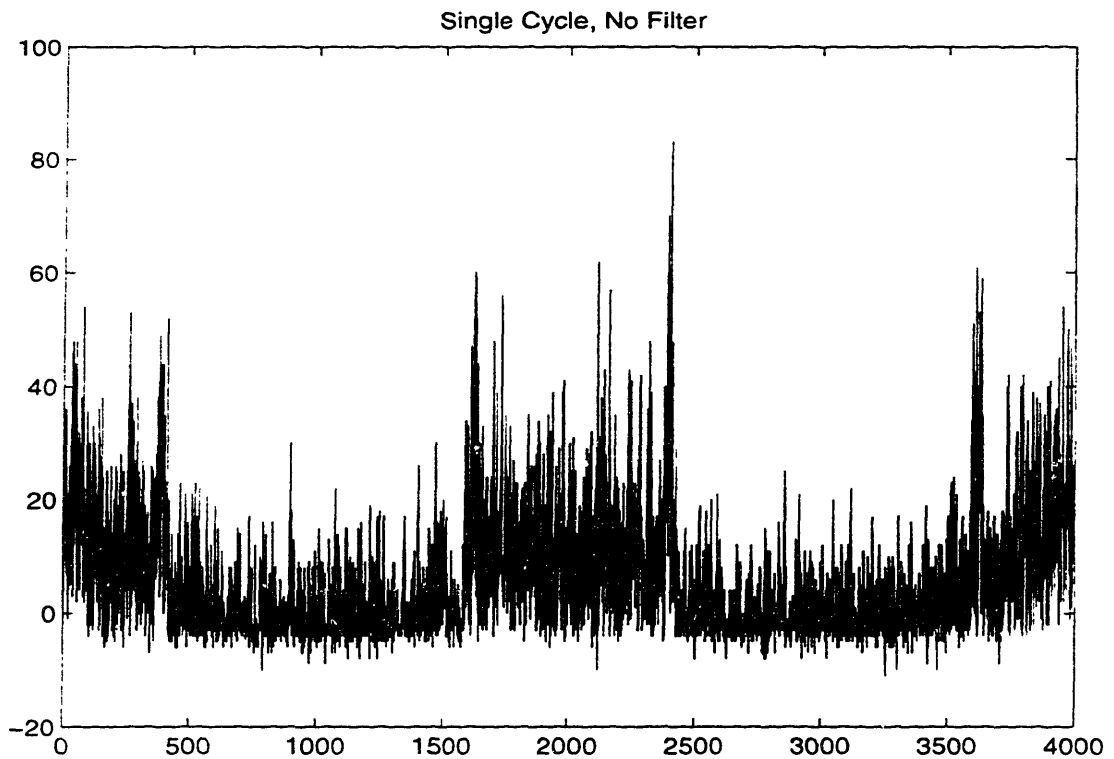


Figure 3.1: Single LIF trace, no filter

In Figure 3.2, we see the effects of the 100kHz filter. This signals trace shows much less noise, though in this case, the noise level is still too great to distinguish the effects of the etch mark on the LIF trace.

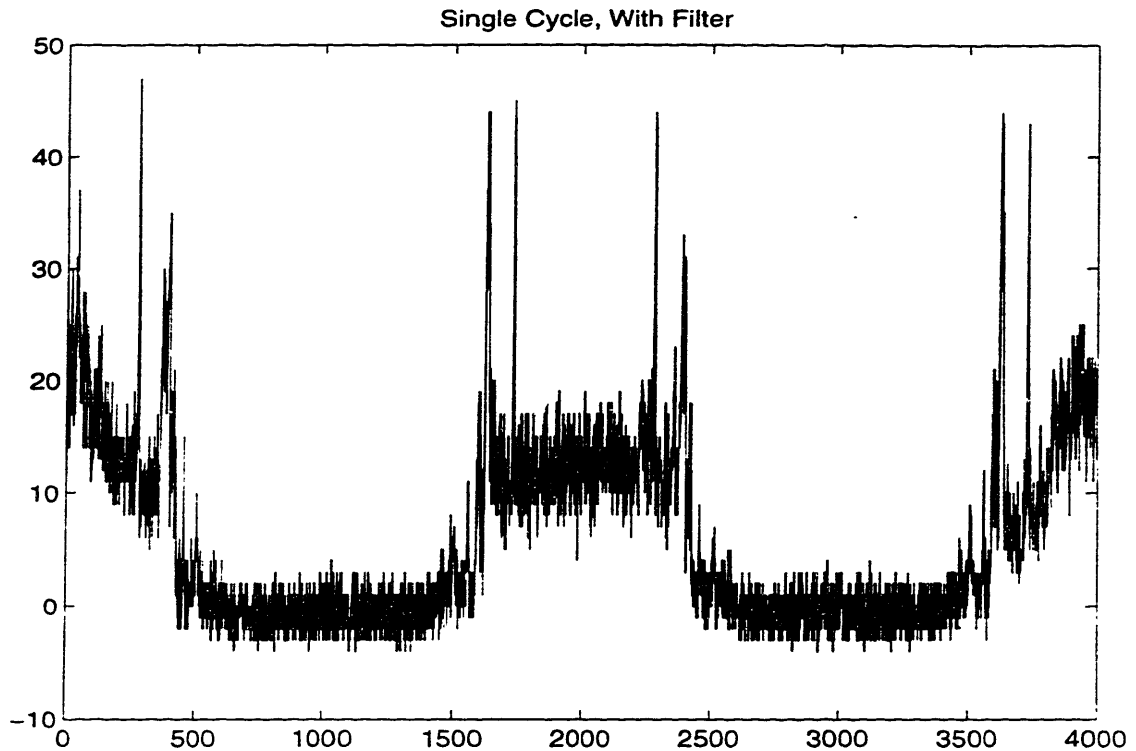


Figure 3.2: Single LIF trace, with 100kHz filter

3.2 Data Smoothing

The way in which data has been smoothed in the past is by averaging the ten cycles of data comprising each data set. This is done by using another Fortran program. Once a data set is averaged, the calibration constant determined from the single cycles is applied to the averaged cycles (see Figure 4.1 -4.2).

Both of the Fortrand programs used are documented in Noordzij [4]

3.2.1 Post-Test Filtering

In an attempt to recover data from the noisy signals acquired, the unfiltered single LIF trace was processed using Matlab. The fluctuation was gradually reduced until there were no discernible features in the LIF trace (see Figures 3.3 to 3.6). Any features due to the etch in the piston were lost in the random noise at this point.

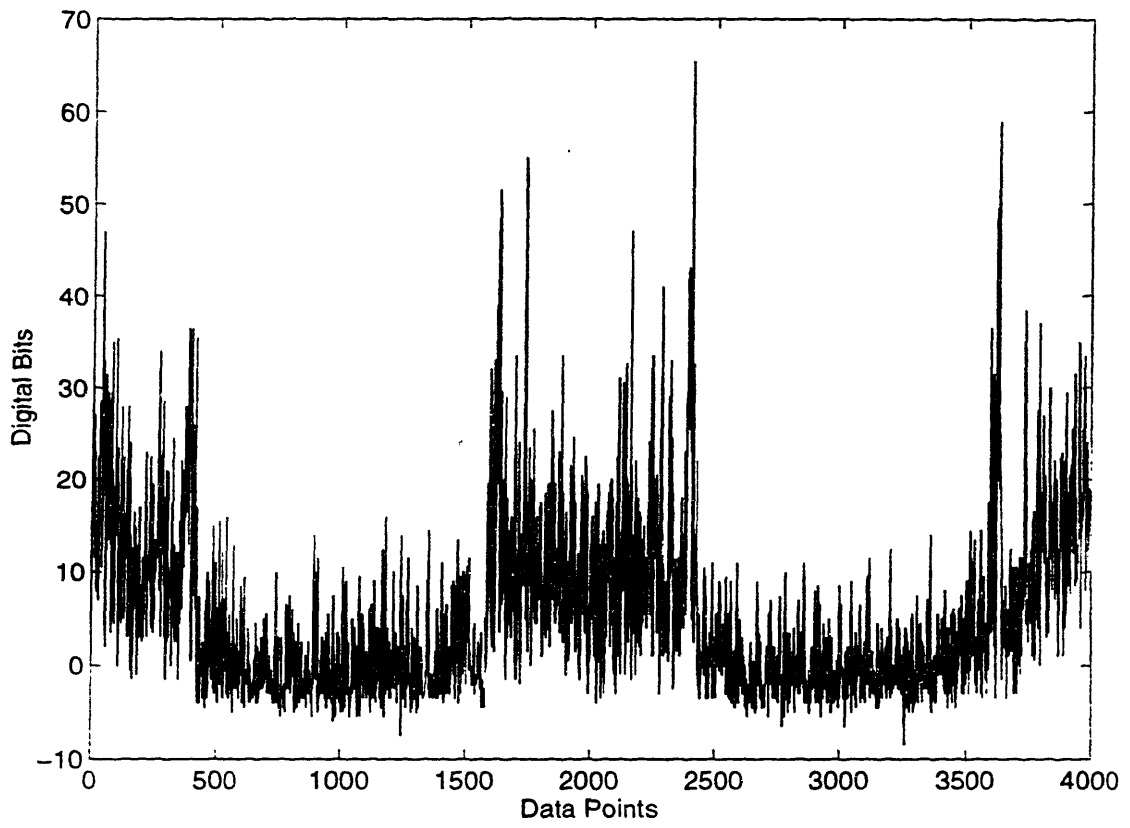


Figure 3.3: Processed LIF signal (1)

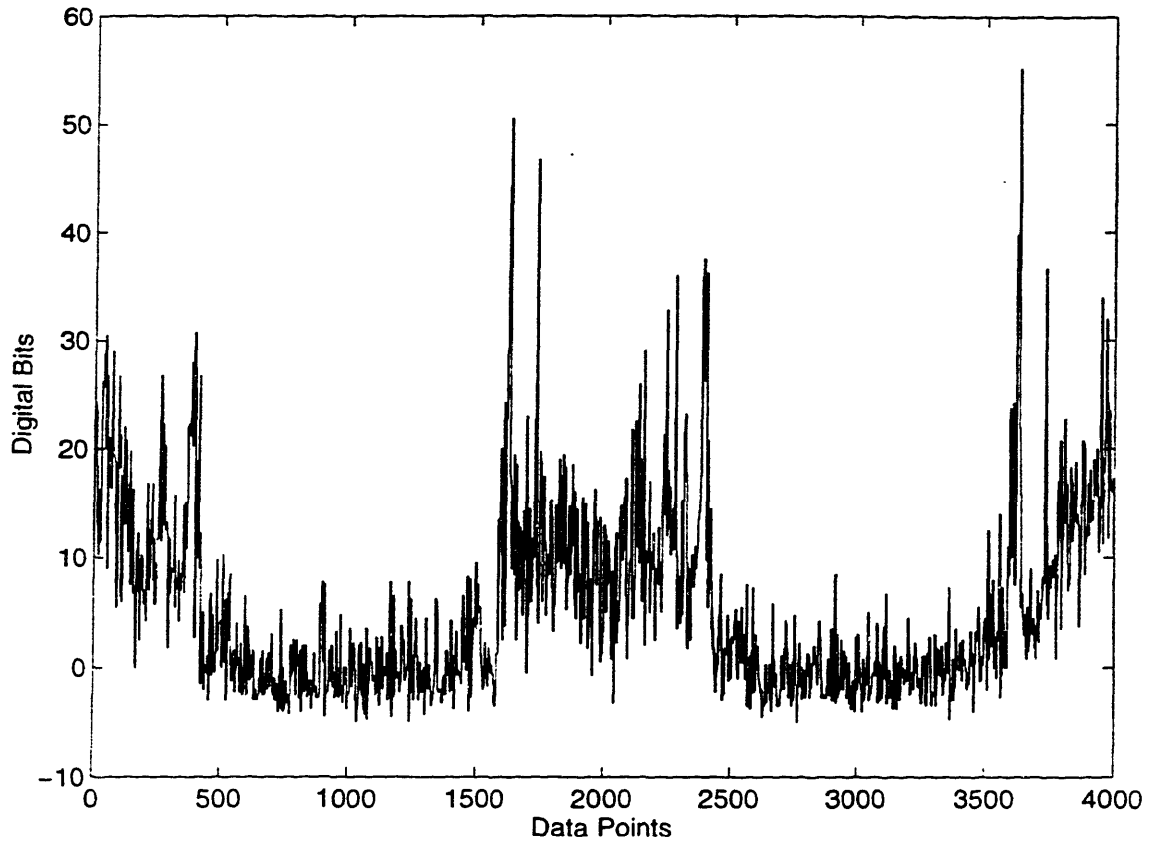


Figure 3.4: Processed LIF signal (2)

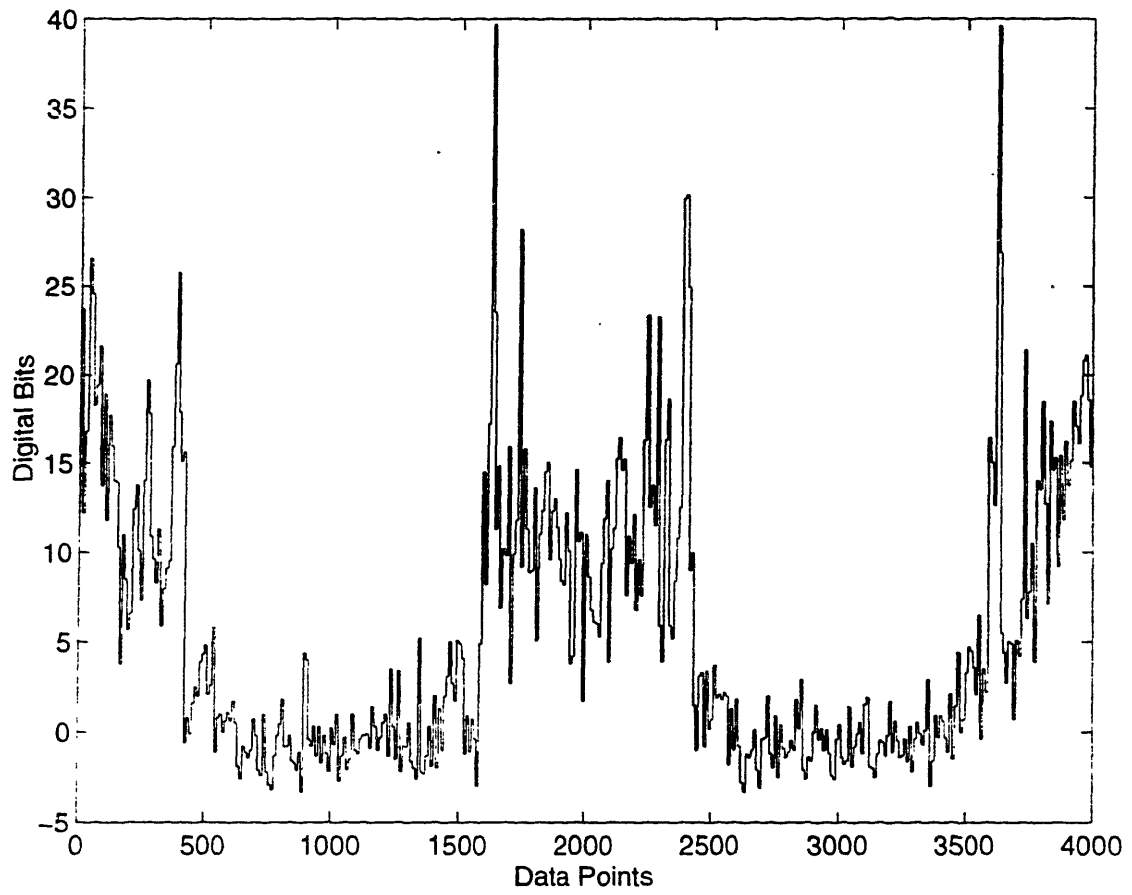


Figure 3.5: Processed LIF signal (3)

3.3 LIF Oil Film Calibration

The purpose of the oil film calibration procedure is to convert the voltage signal into an oil film thickness. In the calibration of LIF data, the first step is to take the ten-cycles of data for each data set and break it up into individual cycles. These individual sets are then used to determine the calibration constant. Since this calibration procedure is very time-consuming [2], an attempt to automate the this part of the data analysis was planned.

3.3.1 Automated LIF Oil Film Calibration

In this case, if data with enough resolution had been acquired, the proposed method of calibration would have taken advantage of the square nature of the piston skirt etch mark (see Figure 3.6).

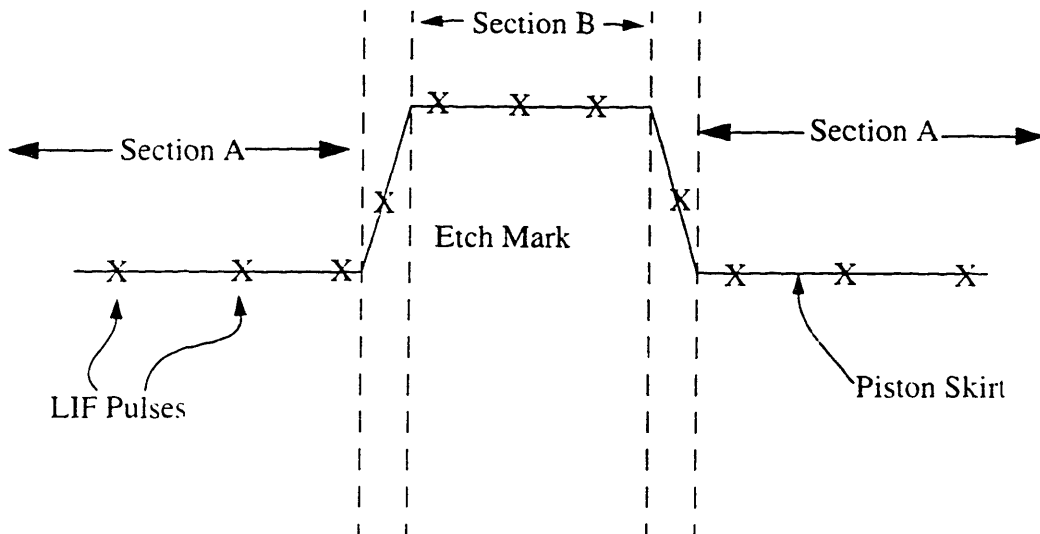


Figure 3.6: Automated calibration scheme

The approximate position of the etch mark versus LIF pulse number is easily be determined from the kinematic equation:

Where 's' is the distance between crank axis and piston pin axis, 'a' is the crank radius,

and ' l ' is the connecting rod length.

A computer program would have been written to locate the bottom (and level) section of the etch mark (Section B), as well as the piston skirt region surrounding the etch mark (Section A). The exact locations of the LIF pulses in these regions would have been determined manually at first, since the kinematic equation would probably not be able to provide the exact locations. Once known, the LIF pulses in each section could then be averaged, and the distance from the skirt of the piston to the bottom of the etch mark could be compared to the actual geometry, and a calibration constant determined.

This automated procedure depends on the square nature of the notch. Since the tool marks yield sharp 'peaks' in the LIF trace, determining what should be used as the maximum value of the signal, or even if the tool marks are fully flooded and usable, would require a much more complicated automation technique.

3.3.2 Manual LIF Oil Film Calibration

Had the automated calibration technique not proved feasible, then each single LIF trace would have been manually matched to the etch mark in the same way that the LIF signal was matched to the piston tool marks in previous experiments, much like Tamai[2] or Noordzij [4]

CHAPTER 4: Conclusions

1) The 100 kHz filter provided great improvement in the averaged data (Figures 4.1 and 4.2), although it was not as vast an improvement as in the single cycle case (Figures 3.1 and 3.2). The filter was also suspected of causing unwanted attenuation of the LIF signal, though this did not turn out to be the case.

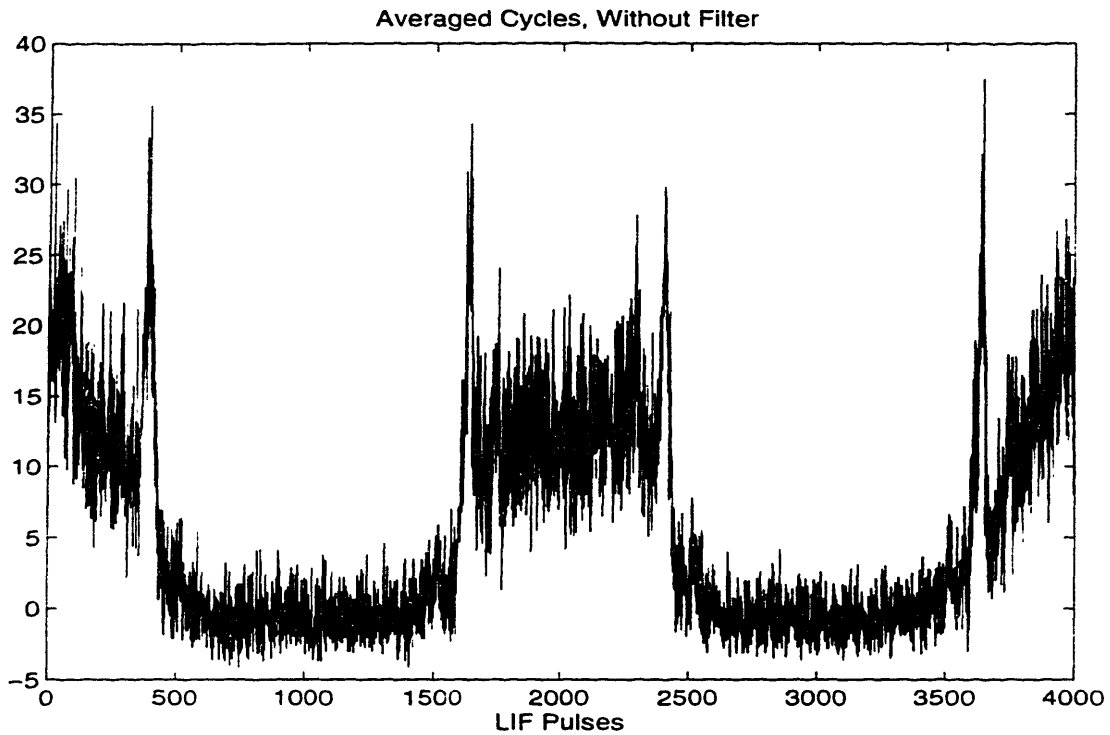


Figure 4.1: Averaged LIF trace, without filter

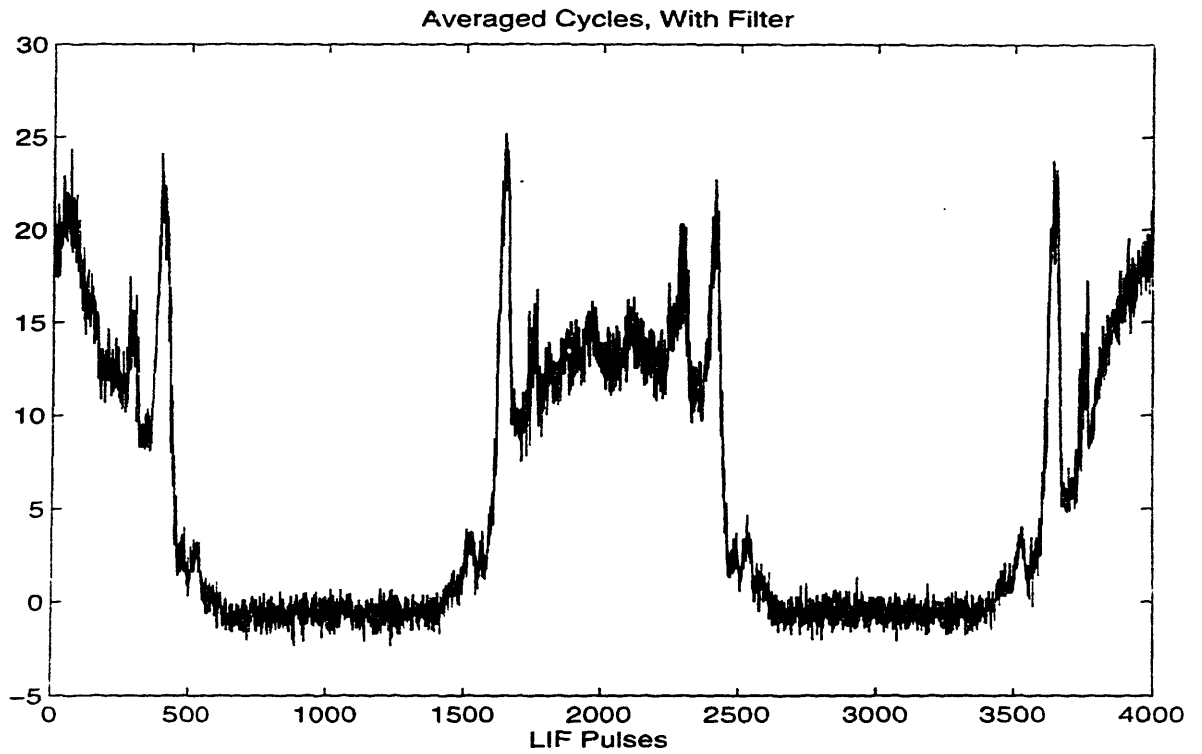


Figure 4.2: Averaged LIF trace, with filter

2) The oil's fluorescent properties in diesel engines decays much faster than in gasoline engines, and needs to be changed with great frequency. In the table below, we see then PMT voltage required to maintain the LIF signals at a constant level.

Table 3: PMT Voltage Required for Constant LIF

Time (min)	PMT (V)	Speed	Load
0	500	1600	no
80	500	2300	no
100	500	1600	mid
130	550	2300	mid
150	600	1600	full
175	620	2300	full
220	570	3000	mid
240	570	3000	no

There was a noticeable temperature effect on the relative strength of the LIF signal recorded, but the effects of wear on the fluorescence of the oil, even after only four hours, are evident here. In this experiment, this gradual decay in signal intensity required increasingly high PMT voltages (near the 700 volt maximum range), which lead to the unacceptable noise in the LIF trace.

3) There was no obvious advantage in filtering the data in the analysis stage. The 100kHz filter works well: it does not seem to cause any unwanted attenuation of the signal, but does prevent unnecessary noise. Post-test filtering only added to the amount of effort required to analyze the data.

CHAPTER 5: Recommendations

- 1) The variability of the calibration constant from test to test, without varying the PMT voltage, should be investigated. If it proves to be stable enough, it may not be necessary to re-calibrate every single LIF trace within a single run.
- 2) For LIF measurements in a Diesel engine, frequent changing of the oil is crucial. It is believed that the poor quality of the data obtained is mostly due to extended use of the oil, and the increasingly high PMT voltage required.
- 3) If the automated calibration technique is to be attempted, a wider groove would be desirable. With such a profile, it would be easier to determine if the groove is fully flooded, and can be used for calibration. Also, the etch profile should be machined as square as possible. Slight variations in the etch surface could cause off-set errors (as this profile is averaged) that would necessitate manual calibration instead.

References

[1] Bryla, Ryan, "The Use of Laser Induced Fluorescence For Measurement of Engine Oil Film Thickness," MIT Bachelor's Degree Thesis, May 1996.

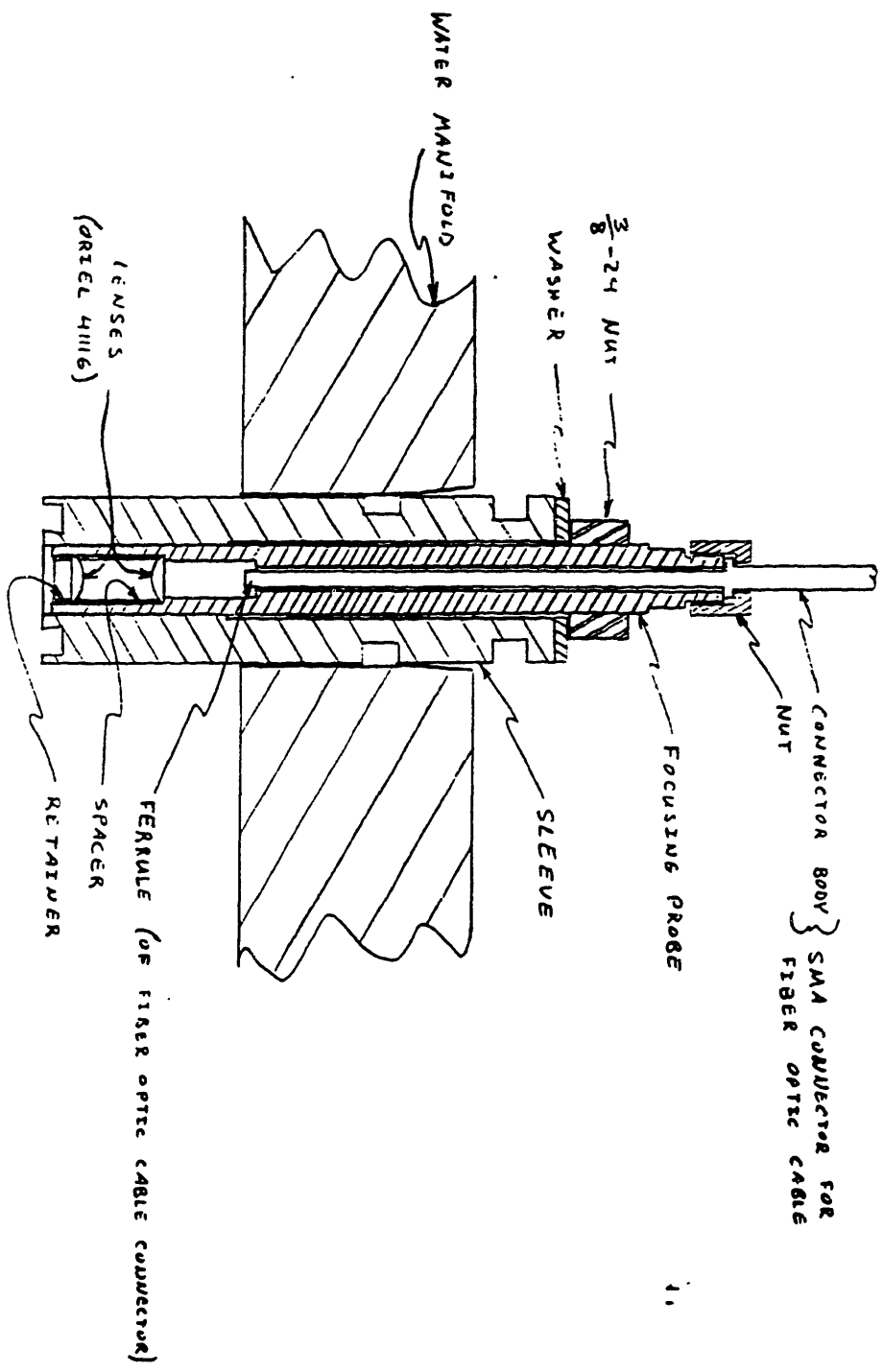
[2] Tamai, Goro, "Experimental Study of Engine Oil Film Thickness Dependence on Linear Location, Oil Properties, and Operating Conditions," MIT Master's Degree Thesis, August 1995.

[3] Private Conversation with Mark Kiesel at MIT

[4] Noordzij, Bouke, "Measurement and Analysis of Piston Inter-Ring Pressures and Oil Film Thickness and their Effects on Engine Oil Consumption," MIT Master's Degree Thesis, June 1996.

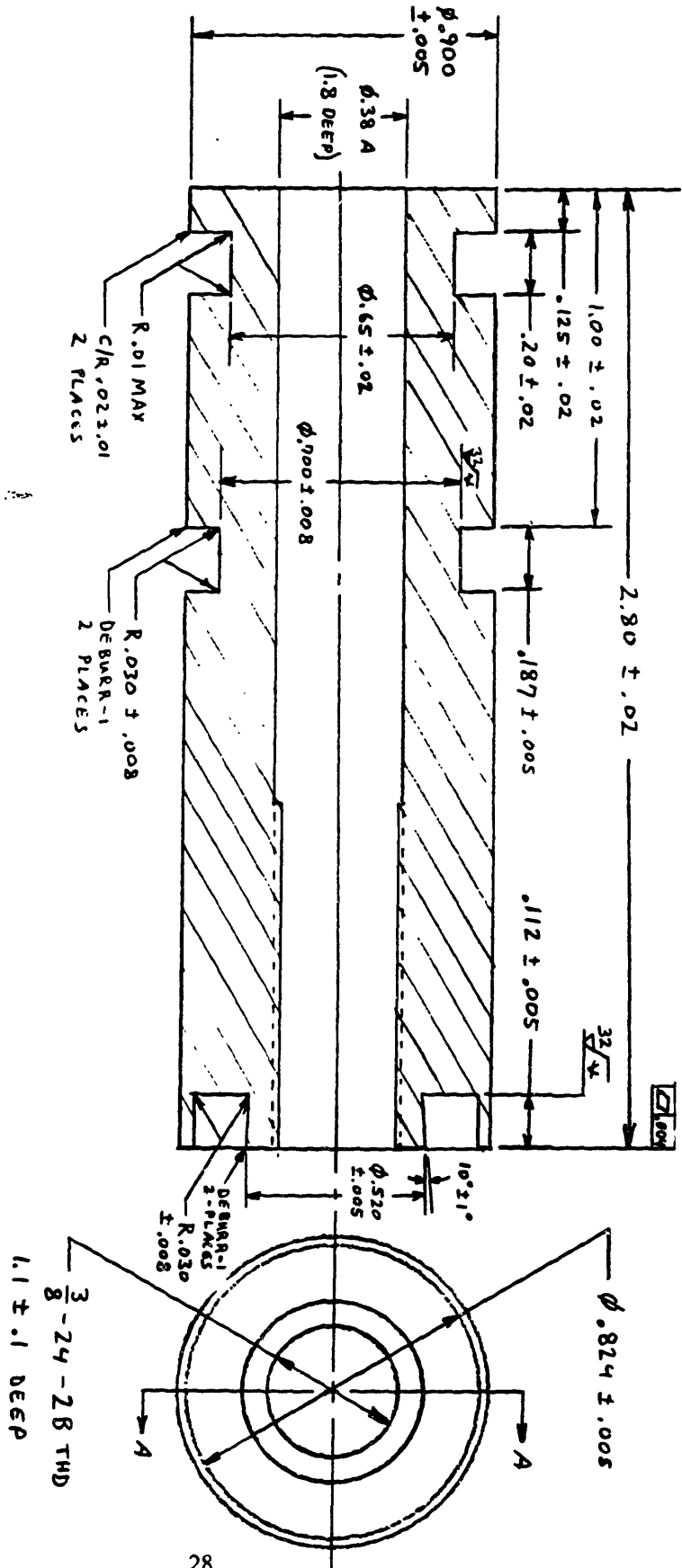
[5] Houtt, D.P., Lux, J.P., Wong, V.W., Billian, S.A., "Calibration of Laser Fluorescence Measurements of Lubricant Film Thickness in Engines", SAE paper #88157, 1988

Appendix A: LIF Probe Housing Drawings



LIF PROBE ASSEMBLY
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 MARK J. KIESEL
 (617) 253-8725

Appendix A (cont'd): LIF Probe Housing Drawings

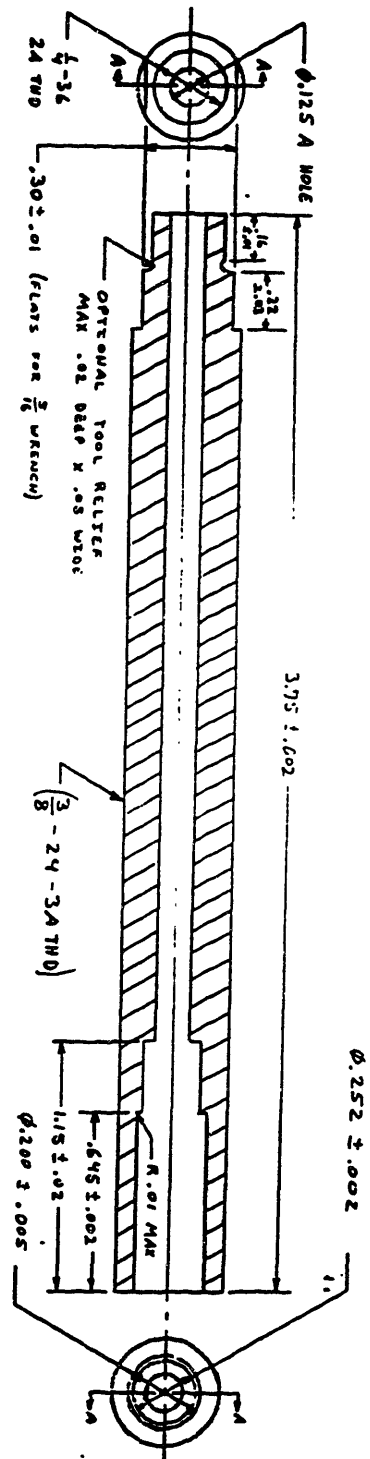


SCALE 2:1

MATERIAL: STAINLESS STEEL

SLEEVE
 24 OCT 95
 MARM J. KIESSEL
 (617) 253-8725

Appendix A (cont'd): LIF Probe Housing Drawings



SECTION A-A

SCALE 2:1

MATERIAL: TO BE MACHINED FROM
 3/8 - 24 GRADE 8 BOLT
 (PROVIDED)

FOCUSING PROBE
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