Design and Development of a Camshaft Inspection Machine

Author

Arslan Hayat

Roll/Registration Number

00000203444

Supervisor

Prof. Dr Riaz Ahmed Mufti

DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

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Author

ARSLAN HAYAT

Registration Number

00000203444

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Thesis Supervisor:

Prof. Dr. Riaz Ahmed Mufti

Thesis Supervisor's Signature: ____

DEPARTMENT OF MECHANICAL ENGINEERNG

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY, ISLAMABAD

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ARSLAN HAYAT

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Abstract

Camshaft plays a crucial role in the efficiency of reciprocating engines. As it controls the opening and closing of cylinder valves, any flaw in a camshaft translates directly into decreasing the efficiency and life of the engine. Emissions are also increased because of inadequacy of the camshaft. Testing a camshaft, thus becomes an important task. Modern engines with high fuel efficiency require automatic tested camshafts before they can be assembled. A camshaft inspection machine was designed and developed to perform this task. This machine is equipped with highly sensitive linear variable differential transducer (LVDT) which has a resolution better than 0.5µm. Camshafts of Fiat Iveco engine 8035.05 and 8045.05 were inspected on this machine. Their design parameters were measured and logged into a computer system using LabVIEW. The results were studied to validate the accuracy of the developed camshaft inspection machine and found to be satisfactory.

Key Words: *Camshaft, Camshaft design, Camshaft Inspection machine*

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CHAPTER 1: INTRODUCTION

The research work in this dissertation has been presented in chronological order of the phases in the development of the camshaft inspection machine. It will start with the introduction about camshaft designs, its nomenclature, and different parameters then it will go into detail about all the phases of developing a system which can inspect the OEM defined parameters of a camshaft. Moreover, design and all the components of the inspection machine developed will be explained in detail.

Background, Scope and Motivation

The first known use of camshaft mechanism dates to 1206 when a Turkish engineer named Al-Jazri described and employed it in water raising machines and tower clock. The first camshaft in car engine was used by Alexander Craig in 1902.[1][2] The function of the camshaft in internal combustion, reciprocating engine is to operate poppet valve which in turn controls the intake and exhaust of gases from the engine cylinder. Modern camshafts have come so far from their early Iterations. Today, the camshafts are manufactured with high precision CNC machining and grinding. Camshaft are mostly made of chilled cast iron or of billet steel for high end applications. [3] These camshafts go through highly meticulous testing phase before they are put into the engine. Camshafts are present almost all the reciprocating internal combustion engines that are running on road or producing electricity. Some cam-less engines are present in the market but currently they are not as reliable, economical, or widespread as camshaft operated valve engines. In the meantime, more research is being carried out in making camshafts more efficient and versatile in their operation.

Currently, camshafts are mass produced by manufacturing company with ever increasing efficiency and accuracy. These accuracies are mostly achieved by CNC grinders and surface finishing techniques.[4] As camshaft is a critical component of the engine, it is made sure that it performs its function without any failure or losing its efficiency and function for the entire engine life. In more recent time, this is done by a camshaft inspection machine.

A camshaft inspection machine measures the different parameters of a camshaft. These parameters determine whether the camshaft is well made and thus, can be put into the engine. The idea behind this research and development is to improve locally manufactured engines and give them international quality standards. Some of the advantages of a camshaft inspection machine are listed below.

1.1.1 Engine Manufacturing Industry

Engine manufacturing industries produce engine parts in a very large quantity and are always in need to ensure their products quality. Camshaft is one of the crucial parts of the engine and need and very thorough inspection which cannot be done without a specialized inspection machine. Most industries in Pakistan opt to buy an inspection machines from outside of the country spending thousands of dollars for a very low-resolution inspection machine. A locally build camshaft inspection machine will not only be a cheaper yet will have a better resolution than the machine imported four times the price of this machine.

1.1.2 Engine research

Pakistan lags most other nations in engine research because the lack of experiment equipment. This is because they are too expensive for universities and researchers to buy. A camshaft design parameter can only be properly studied on a camshaft inspection machine. This machine allows engine researchers to make modifications to camshaft and study the results, thus giving an opportunity to researcher and manufactures to improve the overall efficiency of locally manufactured engines.

1.1 Problem statement

"Design and develop a camshaft inspection machine which gives precise and accurate measurement of its cam lift, cam profile, cam duration and cam lobe separation angle."

Due to high demand and competition among engine manufacturers, they want to produce cheaper yet durable and highly efficient engine parts. Furthermore, ever increasing environmental laws require engines to meets a set emission values. To meet these goals, engine manufactures have a need to test most critical engine parts they produce. This not only ensures the product quality but also create opportunities for its improvement. Most nations in the world require certain international or national certifications for a product to be imported/exported and a certificate cannot be obtained without testing equipment. Testing equipment usually costs thousands of dollars and if you include shipping and importing tax cost, the total sum goes to millions. Building test/inspection machines locally becomes the logical choice.
There are many camshaft inspection machines available in the international market though none of them are available in Pakistan. Acquiring an automatic camshaft inspection machine with high resolution cost hundred thousands of dollars. Building a camshaft inspection machine will not only improve overall efficiency of locally manufactured engines but also make them internationally certifiable for export.

1.2 Objectives

- Develop a camshaft inspection machine according to resolution and specification required.
- Use easily available components and manufacture locally.
- Make the product world market competitive yet keep the cost low.

CHAPTER 2: LITERATURE REVIEW AND DESIGN CONCEPTS

In this chapter, literature studied for this project and different design iterations of camshaft inspection machine will be discussed. Significant publications (research papers, books) and designs concepts will be referred to. A summary of the findings will be presented at the end.

2.1 Camshaft

A camshaft is a straight cylindrical rod machined and grinded to make journals and ovoid shape cam. Camshaft in an engine operated the poppet valve of the engine which let air/fuel mixture into the engine cylinder and let out the burnt gases to the atmosphere in a timely and synchronized manner. The length, size, number of journals and number of cams of a camshaft vary from engine to engine, but it is an indispensable part of a reciprocating internal combustion engine. A four-cylinder camshaft is shown in figure 1.

Figure 1 Four-cylinder camshaft

2.1.1 Working principal of a camshaft

The main function of the camshaft is to open and close intake and exhaust valves of the engine. For this, a camshaft is rotated using a timing belt and sprockets on camshaft and crankshaft. The angle of the cam lobe with respect to a reference point/line is determined for each cam according to the intake/exhaust valve it is intended to operate. From the intake valve air/fuel or just the air come into the engine cylinder where it is burnt during the power stroke and then burnt gases are exhausted through the exhaust valve.

There are many different mechanisms to drive the intake and exhaust valves but the most common are OHC (overhead cam) and OHV (overhead valve). The camshaft, valves and their driving mechanism is collectively valve train. Working principle of a camshaft (OHC) is shown figure 2

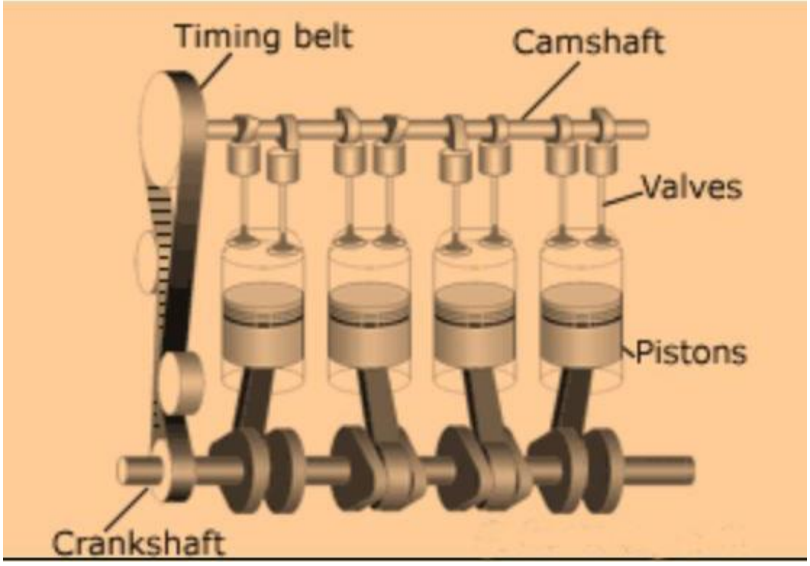

Figure 2 Working principle of a camshaft

2.1.2 Valve train mechanism

A valve train mechanism consists of components that control the opening and closing of intake and exhaust valves. There are many types of valve train mechanism. All of them consist of a camshaft, a valves, valve spring and a valve guide. Other types include a hydraulic lash adjuster, a rocker arm, or a direct acting bucket. Valve train mechanism with hydraulic lash adjuster and a rocker is shown in figure 3

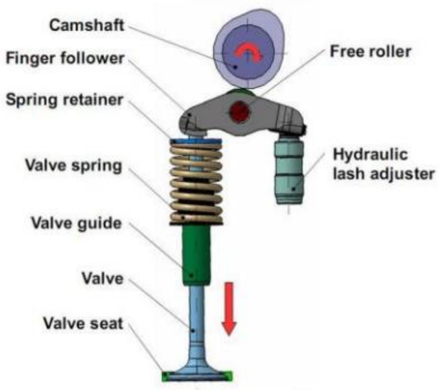

Figure 3 Valve train mechanism

2.1.3 Design and specification of a camshaft

A camshaft is a cylindrical rod with cams along its length. These cams have ovoid shape which is intended to operate intake and exhaust valve of the internal combustion engines. There are different types of valve train mechanisms but according to their design, there are only two main types of cam lobes used in the engine (a)flat tappet and (b)roller camshafts. This shown in figure 4

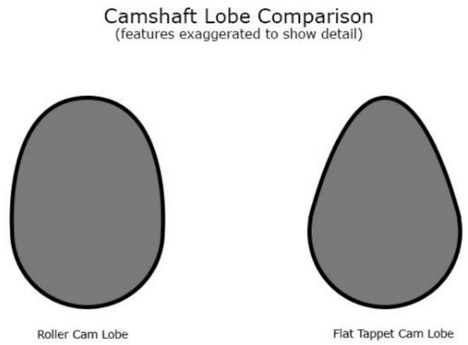

Figure 4 Cam lobe types

Efficiency and durability of an engine is directly related to the performance of its camshaft. A flawed or underperforming cam will affect dynamic performance, cause noise, economy and nuance for the user and company. These are the most common parameter camshaft manufacturers used to define the design of the camshaft shown in figure 5[5]

- The **Base circle** of the cams is a circle that can be made inside the cam touching its round edge where t
- **Cam lift** is the maximum distance a lifter is pushed by the cam lobe. The actual valve lift may vary according to the valvetrain mechanism used in the engine.
- **Cam profile** is the line running along the camshaft perimeter which make the actual shape of the cam.
- **Cam duration** is the time passed when a cam starts to lift the valve to time it completely closes it.
- **Camshaft lobe separation angle** is the angle between the progressive lobe peaks of a camshaft shown in figure 6

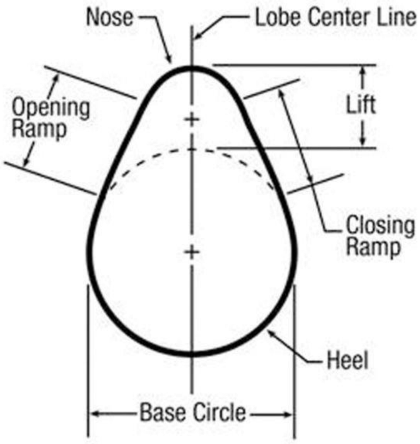

Figure 5 Cam diagram

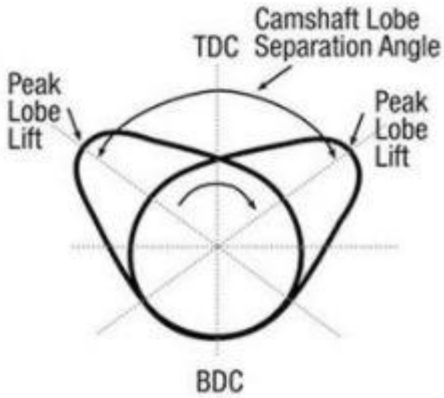

Figure 6 Camshaft lobe separation angle

2.2 Camshaft Inspection Machine

A camshaft inspection machine studies the parameter of a camshaft to determine the quality of camshaft produced by the camshaft manufacturer. Without inspection, the performance of a camshaft in an engine becomes a guess work which is very undesirable. Following are some of the camshaft inspection machines designs considered according to their performance, resolution, mechanisms, and affordability.

2.2.1 V-block stand camshaft inspection machine

This was the first design studied and it is also the simplest one. It consists of two precisely machine v-blocks which give good concentricity are tightened to a smooth surface or a t-slot table. [6] They are then aligned, and a camshaft is placed on the v-blocks. A vertical assembly is present on which a lvdt (linear variable differential transducer) is attached to take reading of the camshaft. the lvdt assembly is placed on the cam lobe or journal to take a reading manually and then cam is rotated by hand to take a reading. The camshaft is also attached to a rotary encoder which takes reading of the angular position of the camshaft. Readings from the lvdt and rotary encoder are synchronized, and a program is made to show the measurements taken to determine the quality of the camshaft. Though this inspection machine is most basic and does not give high resolution or most parameters like velocity, acceleration, and jerk diagrams of the camshaft but it does give an idea of what is the basic principle of building a camshaft inspection machine.
Some of things we learned from this machine is that a high resolution lvdt and a rotary encoder is a must in a camshaft inspection machine. Furthermore, an assembly is required to fix the camshaft is an aligned position, but it still needs to rotate about its own axis. A proper assembly to fix lvdt synchronized to a rotary encoder is required to take measurements of the cam lobes. The biggest flaw of this machine is that it’s totally manual and requires an experienced operator to take its measurement. Also, the manual operation makes it time consuming and infeasible for industrial applications. Figure 7 shows a v-block camshaft inspection machine.

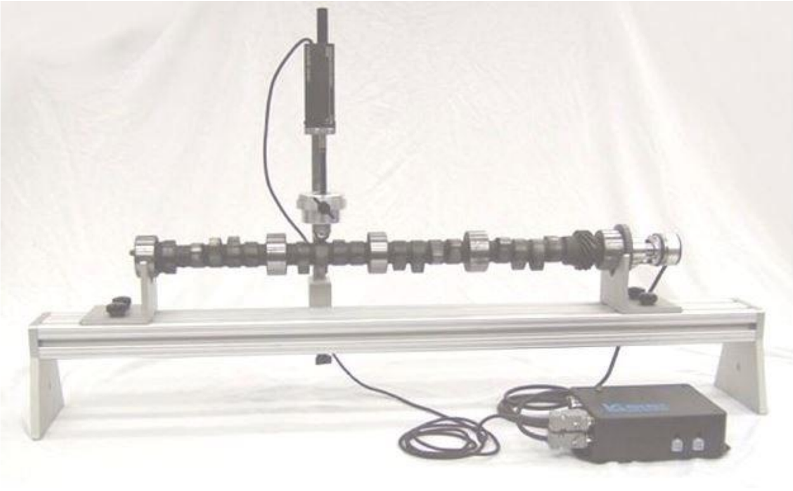

Figure 7 V-block camshaft inspection machine

2.2.2 A lathe chuck and a tail stock

Another design we studied had a camshaft held between lathe chuck and a tailstock live/dead center like a work piece. This assembly has very easy drive mechanism and a lot of options to install rotary encoder synchronized with a camshaft. Where this design lags, is that a mechanical chuck holds the work piece with maximum 0.03mm concentricity and does not have a good repeatability. Since camshaft is already centered during its grinding so a chuck and tailstock assembly cannot hold a camshaft concentrically and will give different readings during each test. If the required resolution of the camshaft measurement is not too high, then this is assembly is a very good candidate for our final design. Figure 8 show this type of camshaft inspection machine

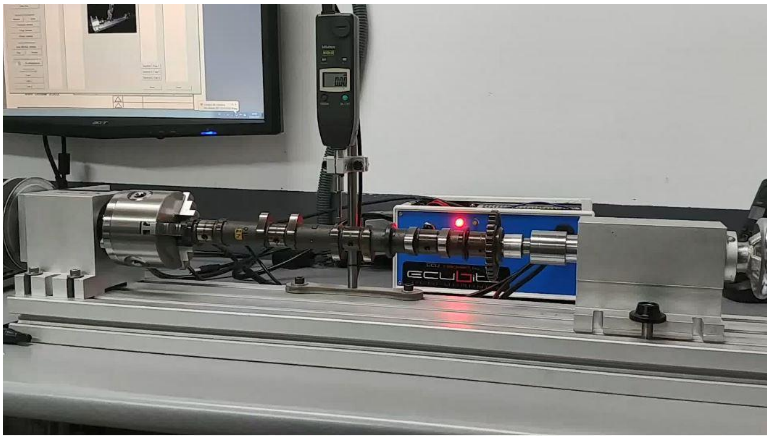

Figure 8 A lathe and chuck driven camshaft inspection machine

2.2.3 Live Centers on Both Ends

In this design, camshaft is held tightly between two live centre of a tailstock. One of the tailstock is attacked to a motor assembly which rotates the love centre. Since camshaft is held between the two live centers, it rotates due to friction between the life centre and the camshaft. The live centers are usually coated with anti-wear agents that keeps the coefficient of friction high. LVDT is used from the side rather than from the top. The biggest flaw in this design is that we cannot be sure of no-slip condition between the camshaft and the live centre. This is undesirable because the rotary encoder is connected to one of the live centre, thus it will not be able to register the rotation of camshaft during a slip condition between the camshaft and the live center.[7] This is shown in Figure 9

Figure 9 Camshaft driven between two live centers

2.2.4 Optical camshaft inspection machine

Optics has made a lot of improvement in this century. Optical measurement devices are on the rise which has led engineers to build Optical camshaft inspection machines. Their prices are still too high to be market competitive and they lack the reliability of direct camshaft measuring machines. Moreover, the optical sensors they use don’t work perfectly in an industrial environment because of electromagnetic pollution present there that interferes in their function. Studying this machine, we concluded that optical sensors are a poor choice for multi-purpose camshaft inspection machine. Though, optical sensor does have an advantage in a laboratory settings where perfect isolation form electromagnetic noise can be provided. [8] Such type of optical camshaft inspection machine is shown in the figure 10

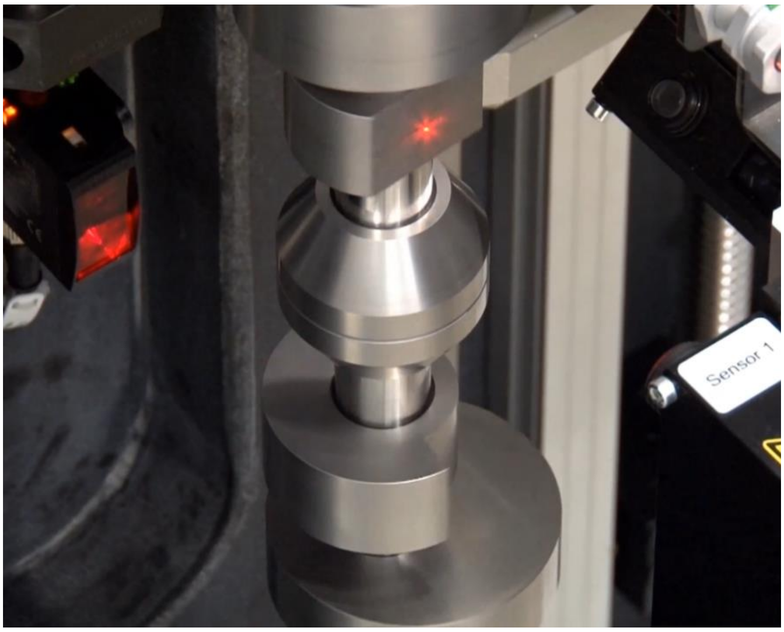

Figure 10 Optical camshaft inspection machine

2.3 Linear Variable Difference Transducer(lvdt)

A linear variable differential transducer is a device or an electrical transformer that converts linear position of an object into an electrical signal. This signal then can be processed and calibrated to produce an accurate measurement of the distance. It consists of three solenoid coils and placed around a cylindrical tube. An alternating current is provided on the center primary coil which induces a voltage across the two secondary coils. Range of the frequency is usually between 1-10khz. Since the core is linked to primary and the secondary coil, when is moves it changes the induced voltage across both secondary coil. This change is measured, and the value is calibrated to the corresponding position. When the cylindrical metal tube is between the centre of both the secondary coils, the voltage difference between the coils is zero. There is a small quadrature error owing to the residual voltage present due to phase shift which can be minimized using a precise full bridge rectifiers. Linear variable differential transducers have a very reliable operation with theoretically infinite cycles. It can give high accuracy in systems ranging from satellites, ship engines, aircraft turbine to automotive and to simple lab measurement equipment. Figure 11 shows basic construction of a lvdt.

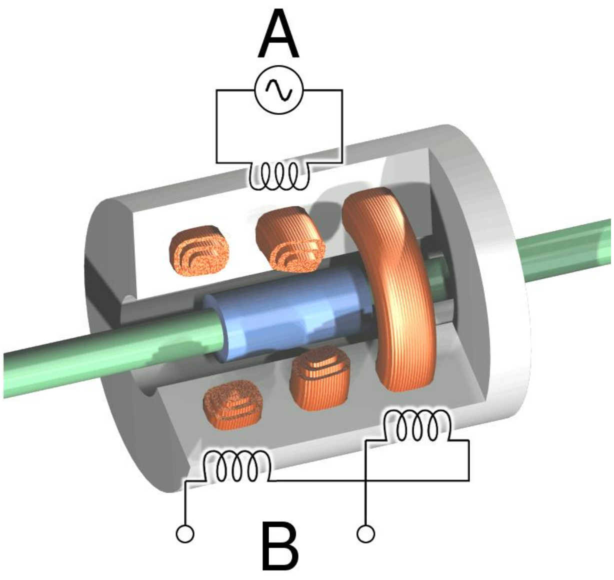

Figure 11 Linear variable differential transducer

2.4 Rotary encoders

A rotary encoder is an electromechanical device which converts the angular position of an axel or shaft into an output signal of either digital or analogue kind. In practice, optical encoders are used widely. They have metal disc which has slits along its circumference. There is a light source on one side of the disc and a light detector on the other side. A signal is generated when light hit the detector and stops when light is blocked by the slits on the metal disc. The slits are designed to give an angular position of the shaft couple with the metal disc. This is shown in figure 12

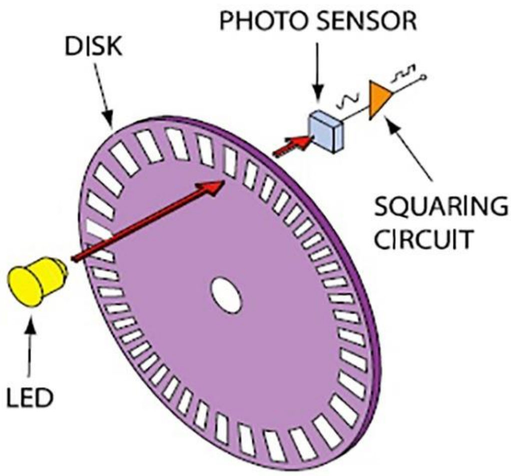

Figure 12 Working diagram of a rotary encoder

Rotary encoders are further divided into the two type according to their data they produced about the angular position of the rotating assembly it is attached to.

- Incremental rotary encoders
- Absolute rotary encoders

Incremental rotary encoders give change in position rather than the absolute position of the rotating device attached to it. They are robust, as they produce a signal immediately when a change in position is registered. This makes them effective to determine positional accuracy at even very high speed. Resolution of the incremental rotary encoder is not as limited as absolute rotary encoders and it is easy to find incremental rotary encoder with resolution 10,000 or more. It generates two square form wave A and B which indicate movement and direction. A leads and B trail in clockwise direction. In anti-clockwise direction, B leads and A trail. There is also usually a Z signal which indicate a complete rotation and act as an index. This is represented in figure 13.

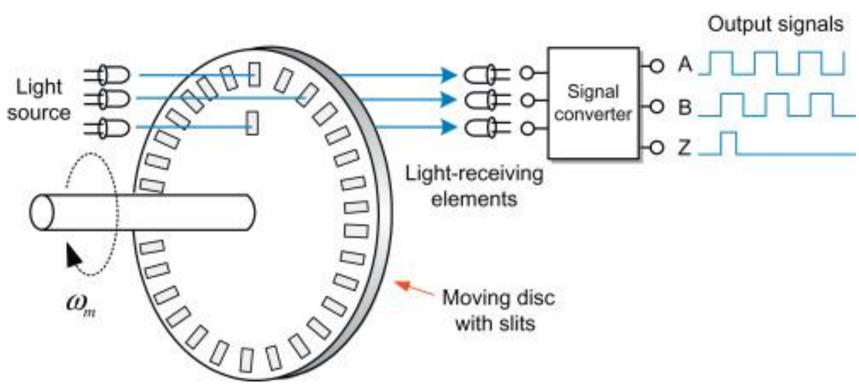

Figure 13 Incremental rotary encoder

Absolute encoders save the information about the position of the rotating device even when power is removed from the system. This is because each position on the rotary encoder is unique due to the fact there are multiple row of slits on the metal disc of the encoder. Absolute encoders can operate at high speed but mostly they are used in applications where positional information in vital. E.g. in robotic arms, windmills. These type of encoders uses a coding format known as gray code which is a variation of binary codes. As it uses only one “bit” changes on the disc between the adjacent line. This is represented in figure 14 and figure 15

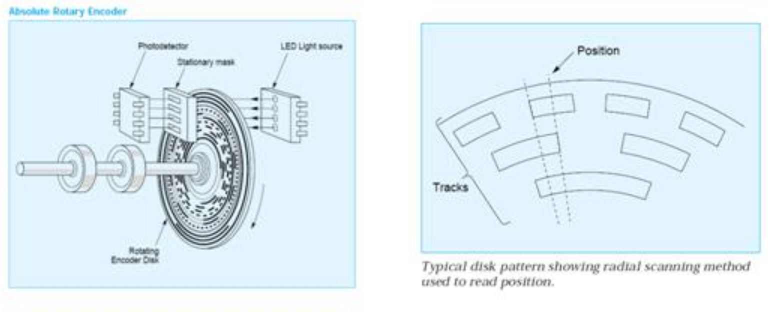

Figure 14 Absolute encoder working diagram

Gray code by bit width

2-bit	4-bit
00	0000
01	0001
11	0011
10	0010
	0110
3-bit	0111
000	0101
001	0100
011	1100
010	1101
110	1111
111	1110
101	1010
100	1011
	1001
	1000

Figure 15 Gray code bit width

2.5 Tailstock

A tailstock is a component of a metal lathe. It is usually used to support the tail end or longitudinal end of the work piece held in the chuck of the lathe. It comes with a live center and a dead centre. A dead center provides better concentricity than a live centre due to the fact the live centers uses bearing which have internal clearances. This is the reason the dead centers are used in grinding of shafts to produce high concentricity and surface finish on journals of a shaft. A metrological instrument known as concentricity test bench uses two tailstock with dead centers aligned to test the concentricity cylindrical object. Concentricity test benches give accuracy of about 5-20 microns. Figure15 shows a tailstock on concentric test bench

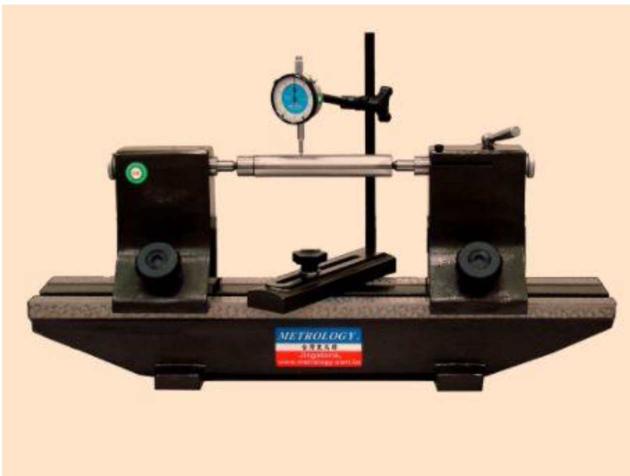

Figure 16 Tailstock with dead centers on Concentric test bench

2.6 Stepper motor

A stepper motor is a type of electro-mechanical device which converts electrical energy into rotational motion of its shaft. Stepper motor is also a type of brushless DC motor and as a name suggest it rotates in steps. It divides the full rotation in equal number of steps. Usually the size of these steps in 1.8 degrees, though it can be further divided into more than 1.8/1600 steps using a stepper motor driver. Stepper motor is unique in its function as it can move to a specified position and hold it without the use of any positional sensor. This is of course if the motor is properly and carefully chosen for its operation according to its torque and speed. Speed of a stepper motor is very easy to control using a stepper motor driver. Around a central rod, a multiple toothed electromagnet acts as a stator which are energized by the external drive circuit. These electromagnets are given power in a synchronous manner to produce rotation or lock the shaft in place. Figure 17 shows such assembly

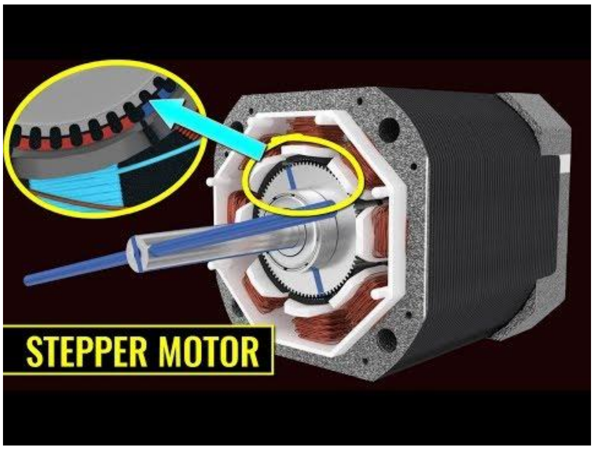

Figure 17 A stepper motor with its geared stator

2.7 Conclusion

After extensively studying the design and workings of various machine and components, we concluded that the best way to design a camshaft inspection machine that can be manufactured locally is by using tailstocks with dead centers. High resolution incremental rotary encoder and linear variable differential transducer are crucial measuring components for this machine. A rigid and accurate electric slider will be used to move linear variable differential transducer across the camshaft length which it is mounted between the two dead centers. Rotary encoder will be attached in such a way that shaft of rotary encoder should move with the camshaft or in synchronization with the camshaft. Stepper motors will be used to rotate camshaft with the help of a pulley attached to the camshaft rotating mechanism of the machine. Further design adjustment will be needed along the development phase, but basic design idea will be the same.

CHAPTER 3: METHODOLOGY

Design detail of the whole system will be discussed in this chapter. It will include the detail of the specific component used and the reasoning behind its selection. At the final design will be presented.

3.1 Design Approach

Camshafts with design specification were given to us by an OEM. These camshaft were for 4-cylinder engines and 3- cylinders engines and their manufacturing designs as well as lift data was included in the package given to us. The design goals were,

- Inspect camshaft and cross reference it with the given data.
- Keep the cost within budget given.
- Use easily available component.
- 1-micron lift accuracy and 0.025-degree cam lobe separation angle accuracy.
- Easily scalable for both camshafts.

3.2 Parameter of the camshafts under consideration

As explained earlier there are two camshaft under consideration. One id for 4-cylinder and the other is for 3-cylinder. The engine uses a rocker arm valve train mechanism. The design parameters for both camshafts are well defined in the engineering drawing provided to us. The lift data for intake valve cam and exhaust valve cam is different but same for both the camshafts.

3.2.1 Four-Cylinder Camshaft

One of the camshaft provided for the inspection is of a four-cylinder in-line diesel engine with firing order of 1-4-3-2. Length of this camshaft is 518.5mm±0.2. It has three journal and 8 cams, one intake and exhaust for each cylinder. There is a notch slit before the first journal which acts as an index for the timing pulley and cam lobe separation angle. Figure 18 show the diagram of the camshaft. Table 1 show the cam lobe separation angles for this camshaft.

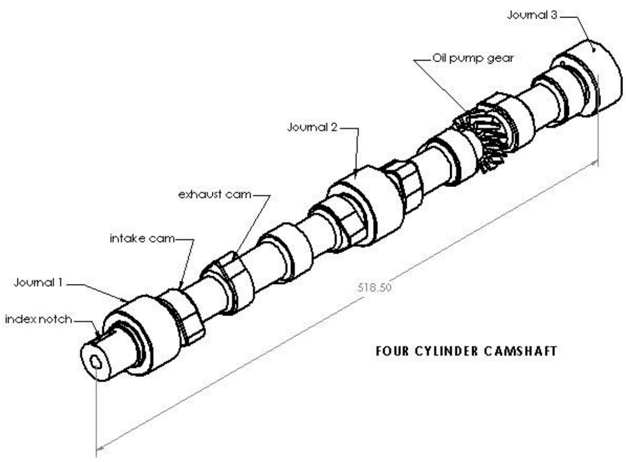

Figure 18 Four-cylinder camshaft

Table 1: Camshaft lobe separation angles for 4-cylinder camshaft

Cams from notch side	Angle with respect to notch in clockwise direction ±0.5 degrees
1st exhaust	111°
1st intake	5°
2nd exhaust	201°
2nd intake	95°
3rd exhaust	21°
3rd intake	275°
4th exhaust	291°
4th intake	185°

3.2.2 Three-cylinder camshaft

This camshaft is of three cylinder in-line diesel engine with firing order 1-2-3. The length of this camshaft is 403.5mm±0.2. Like four-cylinder camshaft it has three journals but 6 cams instead of four. Notch slit before first journal acts as index for timing pulley and cam lobe separation angle. Figure 19 shows the camshaft diagram and table 2 shows the lobe separation angle of this camshaft.

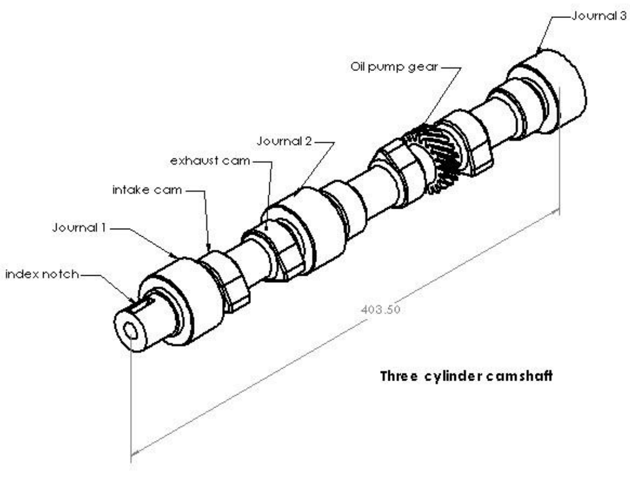

Figure 19 Three-cylinder camshaft

Table 2: **Cam lobe separation angles for Three-cylinder camshaft**

Cams from notch side	Angle with respect to notch in clockwise direction ±0.5 degrees
1st exhaust	111^0
1st intake	5^o
2nd exhaust	351^o
2nd intake	245^o
3rd exhaust	231^o
3rd intake	125^o

3.2.3 Lift data of the camshafts

Table 3: Exhaust cam opening lift data

Angle (degree)	Lift (mm)	Angle (degree)	Lift(mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)
0	6.25000	9	6.05906	18	5.48961	27	4.55130	36	3.25894
0.5	6.24941	9.5	6.03729	18.5	5.44704	27.5	4.48864	36.5	3.17711
1	6.24764	10	6.01435	19	5.40333	28	4.42488	37	3.09425
1.5	6.24469	10.5	5.99025	19.5	5.35849	28.5	4.36004	37.5	3.01036
2	6.24056	11	5.96498	20	5.31252	29	4.29411	38	2.92544
2.5	6.23525	11.5	5.93854	20.5	5.26541	29.5	4.22710	38.5	2.83950
3	6.22876	12	5.91094	21	5.21718	30	4.15901	39	2.75254
3.5	6.22109	12.5	5.88218	21.5	5.16782	30.5	4.08985	39.5	2.66455
4	6.21224	13	5.85226	22	5.11734	31	4.01961	40	2.57556
4.5	6.20221	13.5	5.82118	22.5	5.06574	31.5	3.94830	40.5	2.48556
5	6.19101	14	5.78894	23	5.01302	32	3.87593	41	2.39461
5.5	6.17863	14.5	5.75555	23.5	4.95918	32.5	3.80249	41.5	2.30286
6	6.16507	15	5.72100	24	4.90423	33	3.72800	42	2.21055
6.5	6.15033	15.5	5.68531	24.5	4.84817	33.5	3.65244	42.5	2.11795
7	6.13443	16	5.64846	25	4.79100	34	3.57583	43	2.02540
7.5	6.11734	16.5	5.61046	25.5	4.73273	34.5	3.49818	43.5	1.93320
8	6.09909	17	5.57132	26	4.67335	35	3.41947	44	1.84168
8.5	6.07966	17.5	5.53103	26.5	4.61288	35.5	3.33973	44.5	1.75116

Angle(degree)	Lift(mm)	Angle(degree)	Lift(mm)
45	1.66193	66	0.02730
45.5	1.57429	66.5	0.02023
46	1.48851	67	0.01442
46.5	1.40486	67.5	0.00978
47	1.32358	68	0.00623
47.5	1.24489	68.5	0.00364
48	1.16898	69	0.00188
48.5	1.09604	69.5	0.00080
49	1.02620	70	0.00024
49.5	0.95959	70.5	0.00003
50	0.89628	71	0.00000
50.5	0.83635		
51	0.77892		
51.5	0.72668		
52	0.67691		
52.5	0.63045		
53	0.58719		
53.5	0.54703		
54	0.50980		
54.5	0.47534		
55	0.44345		
55.5	0.41390		
56	0.38644		
56.5	0.36082		
57	0.33675		
57.5	0.31395		
58	0.29210		
58.5	0.27089		
59	0.25000		
59.5	0.22920		
60	0.20857		
60.5	0.18830		
61	0.16854		
61.5	0.14947		
62	0.13123		
62.5	0.11395		
63	0.09775		
63.5	0.08273		
64	0.06897		
64.5	0.05652		
65	0.04542		
65.5	0.03569		

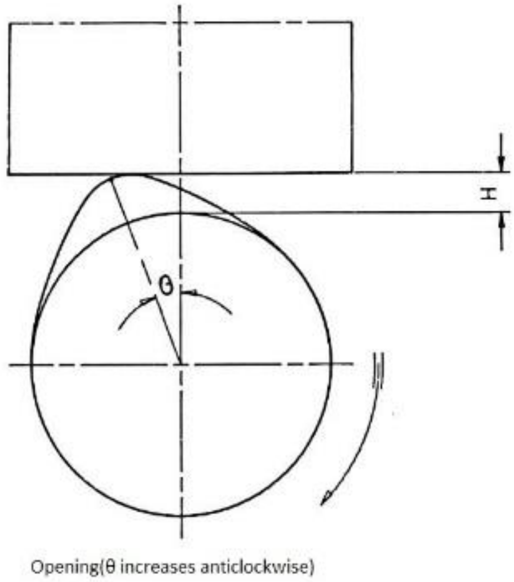

Figure 21 Exhaust/Intake cam opening

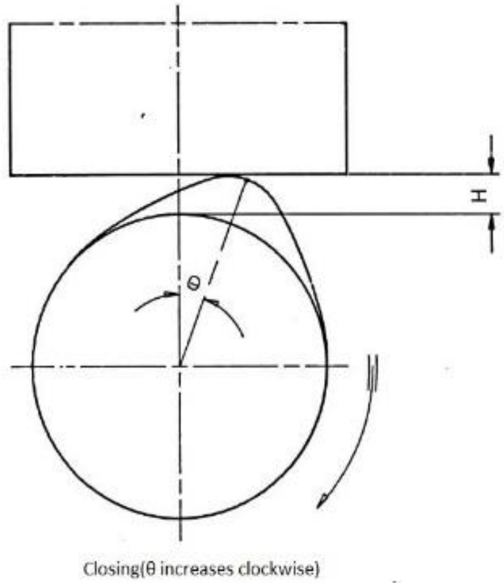

Figure 20 Exhaust/Intake cam closing

Table 4: Exhaust cam closing dwell data

Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)
0	6.25000	20.5	5.26491	41	2.40029	61.5	0.29819	82	0.01759
0.5	6.24941	21	5.21662	41.5	2.31365	62	0.28753	82.5	0.01517
1	6.24764	21.5	5.16721	42	2.22741	62.5	0.27755	83	0.01298
1.5	6.24469	22	5.11666	42.5	2.14176	63	0.26809	83.5	0.01099
2	6.24056	22.5	5.06499	43	2.05685	63.5	0.25896	84	0.00921
2.5	6.23525	23	5.01220	43.5	1.97285	64	0.25000	84.5	0.00763
3	6.22876	23.5	4.95829	44	1.88992	64.5	0.24107	85	0.00623
3.5	6.22109	24	4.90326	44.5	1.80820	65	0.23216	85.5	0.00501
4	6.21224	24.5	4.84711	45	1.72786	65.5	0.22328	86	0.00396
4.5	6.20221	25	4.78985	45.5	1.64902	66	0.21444	86.5	0.00306
5	6.19101	25.5	4.73147	46	1.57183	66.5	0.20565	87	0.00231
5.5	6.17862	26	4.67199	46.5	1.49642	67	0.19693	87.5	0.00169
6	6.16506	26.5	4.61141	47	1.42290	67.5	0.18830	88	0.00119
6.5	6.15033	27	4.54971	47.5	1.35138	68	0.17976	88.5	0.00800
7	6.13442	27.5	4.48692	48	1.28198	68.5	0.17133	89	0.00500
7.5	6.11733	28	4.42303	48.5	1.21478	69	0.16302	89.5	0.00290
8	6.09908	28.5	4.35804	49	1.14978	69.5	0.15484	90	0.00015
8.5	6.07965	29	4.29196	49.5	1.08732	70	0.14681	90.5	0.00006
9	6.05904	29.5	4.22479	50	1.02720	70.5	0.13894	91	0.00002
9.5	6.03727	30	4.15654	50.5	0.96956	71	0.13123	91.5	0.00000
10	6.01433	30.5	4.08719	51	0.91444	71.5	0.12370	92	0.00000
10.5	5.99022	31	4.01677	51.5	0.86188	72	0.11636		
11	5.96494	31.5	3.94526	52	0.81189	72.5	0.10921		
11.5	5.93849	32	3.87268	52.5	0.76448	73	0.10226		
12	5.91089	32.5	3.79902	53	0.71966	73.5	0.09553		
12.5	5.88212	33	3.72429	53.5	0.67740	74	0.08920		
13	5.85218	33.5	3.64849	54	0.63769	74.5	0.08273		
13.5	5.82109	34	3.57163	54.5	0.60048	75	0.07667		
14	5.78884	34.5	3.49370	55	0.56573	75.5	0.07085		
14.5	5.75543	35	3.41471	55.5	0.53339	76	0.06527		
15	5.72086	35.5	3.33466	56	0.50337	76.5	0.05994		
15.5	5.68515	36	3.25356	56.5	0.47561	77	0.05485		
16	5.64827	36.5	3.17143	57	0.45002	77.5	0.05001		
16.5	5.61025	37	3.08830	57.5	0.42650	78	0.04542		
17	5.57108	37.5	3.00425	58	0.40493	78.5	0.04108		
17.5	5.53077	38	2.91937	58.5	0.38521	79	0.03699		
18	5.48931	38.5	2.83378	59	0.36721	79.5	0.03315		
18.5	5.44671	39	2.74761	59.5	0.35080	80	0.02956		
19	5.40296	39.5	2.66101	60	0.33584	80.5	0.02621		
19.5	5.35808	40	2.57415	60.5	0.32219	81	0.02310		
20	5.31206	40.5	2.48718	61	0.30969	81.5	0.02023		

Table 5: Intake cam opening lift data

Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)
0	5.97149	20.5	4.84389	41	1.66090	61.5	0.12710
0.5	5.97079	21	4.78885	41.5	1.57565	62	0.11666
1	5.96874	21.5	4.73255	42	1.49224	62.5	0.10649
1.5	5.96535	22	4.67498	42.5	1.40981	63	0.09663
2	5.96061	22.5	4.61617	43	1.32921	63.5	0.08710
2.5	5.95451	23	4.55610	43.5	1.25111	64	0.07792
3	5.94706	23.5	4.49478	44	1.17545	64.5	0.06913
3.5	5.93825	24	4.43223	44.5	1.10258	65	0.06075
4	5.92808	24.5	4.36843	45	1.03262	65.5	0.05282
4.5	5.91657	25	4.30341	45.5	1.96576	66	0.04535
5	5.90370	25.5	4.23716	46	0.90208	66.5	0.03838
5.5	5.88948	26	4.16969	46.5	0.84202	67	0.03193
6	5.87391	26.5	4.10101	47	0.78534	67.5	0.02602
6.5	5.85699	27	4.03111	47.5	0.73243	68	0.02067
7	5.83873	27.5	3.96001	48	0.68291	68.5	0.01590
7.5	5.81912	28	3.88772	48.5	0.63700	69	0.01173
8	5.79816	28.5	3.81423	49	0.59428	69.5	0.00818
8.5	5.77586	29	3.73955	49.5	0.55465	70	0.00525
9	5.75222	29.5	3.66369	50	0.51793	70.5	0.00296
9.5	5.72724	30	3.58666	50.5	0.48400	71	0.00132
10	5.70093	30.5	3.50846	51	0.45252	71.5	0.00034
10.5	5.67328	31	3.42909	51.5	0.42353	72	0.00000
11	5.64429	31.5	3.34857	52	0.39638		
11.5	5.61398	32	3.26691	52.5	0.36923		
12	5.58233	32.5	3.18409	53	0.34476		
12.5	5.54936	33	3.10015	53.5	0.32325		
13	5.51507	33.5	3.01507	54	0.30374		
13.5	5.47945	34	2.92887	54.5	0.28827		
14	5.44252	34.5	2.84156	55	0.27441		
14.5	5.40427	35	2.75313	55.5	0.26305		
15	5.36471	35.5	2.66343	56	0.25314		
15.5	5.32384	36	2.57278	56.5	0.24133		
16	5.28167	36.5	2.48092	57	0.22956		
16.5	5.23819	37	2.38847	57.5	0.21766		
17	5.19341	37.5	2.29546	58	0.20582		
17.5	5.14734	38	2.20230	58.5	0.19405		
18	5.09997	38.5	2.10995	59	0.18234		
18.5	5.05132	39	2.01637	59.5	0.17095		
19	5.00134	39.5	1.92545	60	0.15977		
19.5	4.95016	40	1.83556	60.5	0.14868		
20	4.89766	40.5	1.74754	61	0.13778		

Table 6: Intake cam closing dwell data

Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)	Angle (degree)	Lift (mm)
0	5.97149	20.5	4.84860	41	1.68454	61.5	0.09663
0.5	5.97082	21	4.79382	41.5	1.59957	62	0.08523
1	5.96883	21.5	4.73778	42	1.51636	62.5	0.07436
1.5	5.96547	22	4.68049	42.5	1.43411	63	0.06405
2	5.96076	22.5	4.62196	43	1.35362	63.5	0.05437
2.5	5.95468	23	4.56218	43.5	1.27554	64	0.04535
3	5.94724	23.5	4.50117	44	1.19982	64.5	0.03705
3.5	5.93847	24	4.43892	44.5	1.12678	65	0.02950
4	5.92834	24.5	4.37545	45	1.05655	65.5	0.02274
4.5	5.91686	25	4.31076	45.5	0.98931	66	0.01681
5	5.90404	25.5	4.24486	46	0.92513	66.5	0.01174
5.5	5.88987	26	4.17774	46.5	0.86443	67	0.00754
6	5.87436	26.5	4.10942	47	0.80701	67.5	0.00427
6.5	5.85751	27	4.03990	47.5	0.75321	68	0.00190
7	5.83931	27.5	3.96919	48	0.70268	68.5	0.00049
7.5	5.81977	28	3.89729	48.5	0.65563	69	0.00001
8	5.79889	28.5	3.82422	49	0.61164	69.5	0.00000
8.5	5.77668	29	3.74996	49.5	0.57065		
9	5.75313	29.5	3.67454	50	0.53246		
9.5	5.72824	30	3.59796	50.5	0.49695		
10	5.70203	30.5	3.52022	51	0.46381		
10.5	5.67448	31	3.44133	51.5	0.43307		
11	5.64561	31.5	3.36130	52	0.40410		
11.5	5.61541	32	3.28013	52.5	0.37512		
12	5.58389	32.5	3.19784	53	0.34873		
12.5	5.55105	33	3.11442	53.5	0.32591		
13	5.51689	33.5	3.02989	54	0.30361		
13.5	5.48142	34	2.94426	54.5	0.28608		
14	5.44464	34.5	2.85752	55	0.27002		
14.5	5.40655	35	2.76969	55.5	0.25608		
15	5.36715	35.5	2.68060	56	0.24361		
15.5	5.32645	36	2.59058	56.5	0.22935		
16	5.28445	36.5	2.49936	57	0.21516		
16.5	5.24115	37	2.40756	57.5	0.20100		
17	5.19657	37.5	2.31522	58	0.18693		
17.5	5.15069	38	2.22271	58.5	0.17322		
18	5.10353	38.5	2.13006	59	0.15977		
18.5	5.05509	39	2.03813	59.5	0.14648		
19	5.00537	39.5	1.94779	60	0.13348		
19.5	4.95438	40	1.85842	60.5	0.12080		
20	4.90212	40.5	1.77083	61	0.10850		

3.2.4 Data Description:

The cam lift data shown here is an ideal camshaft lift profile as it has an accuracy of 0.1 micron which is impractical and very difficult to achieve. Accuracy to 1-micron is more practical and achievable using a highly sensitive LVDT, provided that the mechanical system build is accurate and has a high repeatability. It is concluded here form the data, that the exhaust cam starts to open 71 degrees before its fully open and takes another 92 degrees before it is totally closed. So, exhaust valve opens for the of 163 degrees rotation of the camshaft. Similarly, intake cam starts to open 72 degrees before it is fully open and fully closes by rotating another 69.5 degrees. This makes the inlet valve open for total 141.5-degree rotation of the camshaft.

3.3 Components selected and their specification

The component selected for this machine is will be discussed in detail. Their selection was based on the previously discussed topics in chapter 2. Moreover, these components were selected with respect to their cost effectiveness without compromising on their resolution, durability, and repeatability. The component selected are as follows:

- Base plate (Bed)
- Pneumatic tailstock
- Drive head
- Linear electric ball screw slider
- Linear slider
- Spring return pneumatic actuator
- Solartron feather touch probe
- Hollow shaft rotary encoder

3.3.1 Base plate (bed)

Base plate as the name suggest is the plate on which every component of this is mounted it is a simple 930x240x40mm aluminum alloy plate with T-slots in it. This type of plate is usually used in a CNC engraving or cutting machine. It has a surface accuracy of 20-50 microns. Not ideal but can be compensated using shims.

Figure 22 Base plate

3.3.2 Pneumatic tailstock

Tailstock is a very crucial component of a lathe or a machine which performs a turning operation according to cylindrical workpiece center. It is basically a square block which is horizontally moveably on the lathe bed and has a round point coming out from one of its side which its center. This tailstock we selected for this project has a dead center (does not move with the workpiece) and is operated by a pneumatic cylinder. As it has a dead center, it has an accuracy of 1-micron

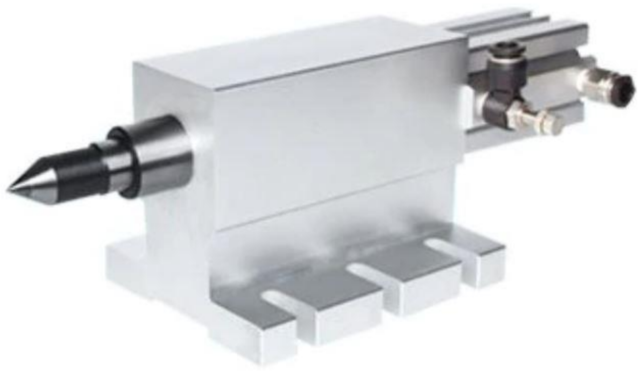

Figure 23 Pneumatic tailstock

3.3.3 Drive head(stock)

Drive stock or drive head performs the same function in this machine as a driving head does in a lathe machine. It drives the component or workpiece held in a jaw chuck or a dog attached to the head. Many driving heads are available in the market with different load and work rating and with different clearances. Selecting a very precise drive head was a difficult task because of the options and price range. The heads shown in the figure was selected owing to fact that it has 0-TIR. Though, upon inspection the runout was around 8-11 microns.

Figure 24 Drive head (stock)

3.3.4 Linear electric ball screw slider

This type or sliders are widely used in the automation, packaging, precision manufacturing and logistic industries. There precision ratings might vary according to its intended use. The electric slider used here is a high precision slider which used 12mm diameter ball screws with 5mm pitch and provides 20-30-micron positional accuracy. It also has high load bearing capacity which further reduces clearances in its linear slider bearings. Testing this component against a granite surface plate reveals its vertical parallelism to be around 3-microns across 600mm stroke length. It can carry 30kg load in vertical setting and 50kg load in horizontal setting.

Figure 25 Electric ball screw slider

3.3.5 Linear SMC slider

The slider used for the insertion of follower for the camshaft is a modified SMC mxq-12-50. It is a high precision slider table produced by SMC. Though it has a parallelism of 10-20µm, it has a less than 0µm rattle, which very ideal for high precision operations. The table and tube of this component provides lots of locations for mountings desired assembly or multiply assemblies. Certain modifications were necessary to use this component for this machine. It comes with a pneumatic operate valves which had to be removed for required operation smoothness. The movement of this component translates directly to the lift of the cam lobes. Furthermore, the stroke of the slider is selected long enough so it does not interfere with any other component or part of the machine except the camshaft under inspection.

Figure 26 Linear SMC slider

3.3.6 Spring return pneumatic actuator

This component as the name suggest is a pneumatically operated linear actuator. This type of actuator comes with multiple operation like spring return, double acting, single acting, spring extended. The spring return type is used here. It has an interna bore of 10mm and a stroke length of 50mm. it accuracy is of no concern as it will just to be used for the retraction and extending of measuring slider (linear SMC slider). The end shaft of this slider is provided with m4 thread screws. It model number is CDJ2B10-50-S

Figure 27 Spring return pneumatic actuator

3.3.7 Solartron feather touch probe

This probe is a precise LVDT with a resolution better than 1µm and repeatability of 0.05µm. It is main measuring component which translates linear movement of the linear SMC slider to the electrical signal for data acquisition system. The model number is Solartron at/5/p. It can be operated by the pneumatic action or by spring loading the moving rod. It is made of high strength stainless steel with high durability. It comes with a removeable round tip. The wire it comes with has a IP50 sealing which provides good insolation to electrical noise.

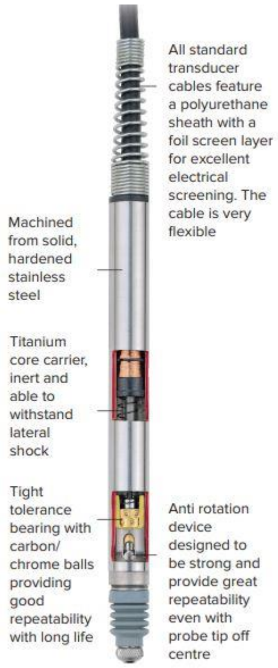

Figure 28 Solartron feather touch probe

3.3.8 Hollow shaft rotary encoder

A rotary encoder is electro-mechanical device which measures the angular motion and position of a shaft of a rotating component. They come in multiple configuration and sizes with wide range of pulse per revolution(ppr) and r.p.m ratings. The widely used rotary encoders are incremental encoders which is used here. It is also of hollow shaft type. It has a 14400 ppr and 4000 r.p.m rating. It fits a shaft of 18mm in diameter with h7 tolerance. It operates on an 8-30v DC voltage and gives out a 5v digital output.

Figure 29 Hollow shaft Optical Rotary encoder

3.4 Designed and manufactured assemblies

Despite tedious selection of components for the camshaft inspection machine, a lot of parts and assemblies needed to be carefully designed and precisely manufactured for this machine. The parts and assemblies manufactures are as follows.

- Probe and slider assembly
- Drive plate
- Drive pin
- Encoder shaft
- Electric slider holder

3.4.1 Probe and slider assembly

For the camshaft inspection machine to perform its intended operation there is a need to have an assembly which translate vertical motion of the cam lobe to the lvdt very precisely. The assembly designed does exactly that using SMC linear slider. It is shown below

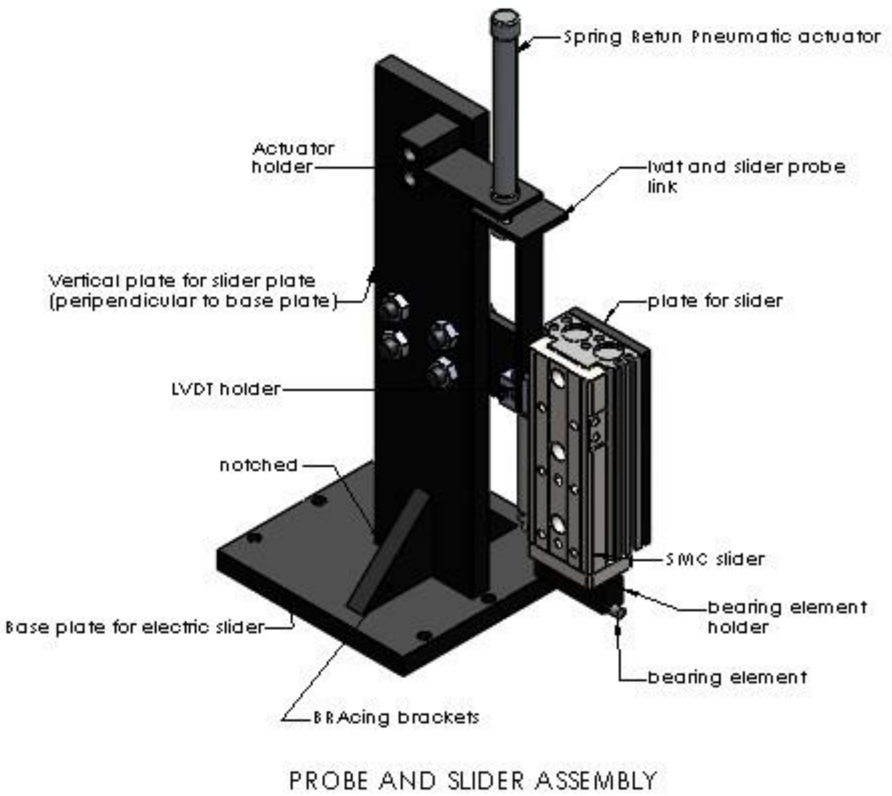

Figure 30 Probe and slider assembly (CAD model)

Figure 31 Probe and slider assembly (Manufactured and assembled on the electric slider)

3.4.2 Drive plate

In a lathe machine mostly the work piece is held in a jaw chuck. In an operation where the concentricity of the workpiece is necessary the chuck is removed, and the workpiece is rotated between two centers. Here, for the development of this machine we did exactly that to keep the camshaft concentric between two centers. The chuck of the head stock was removed and replaced with a drive plate which also has a hole for a drive pin.

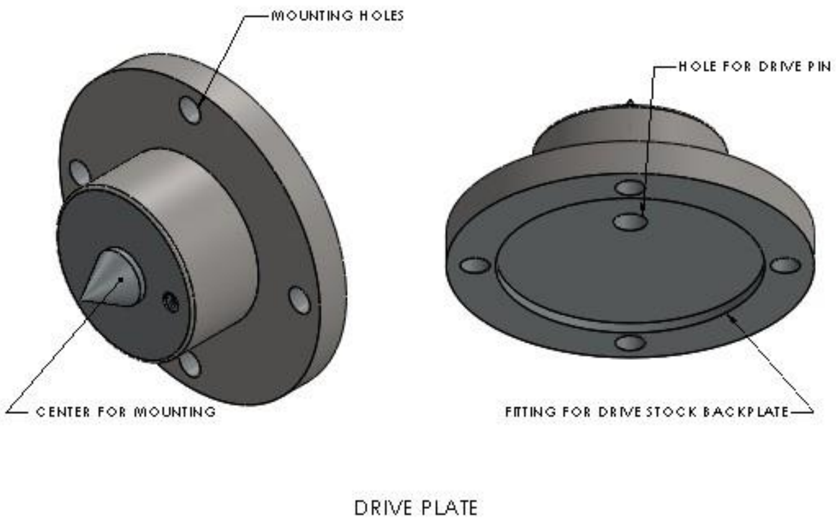

Figure 32 Drive plate (CAD model)

Figure 33 Drive plate (Manufactured and assembled on the drive stock)

3.4.3 Drive pin

Most camshafts have a hole in the last bearing journal. Its position is arbitrary at a fixed radius from the central axis of the camshaft. The camshafts selected for this machine had this hole which can be used to drive them. A drive pin was designed and manufactured for this. It was manufactured using a M6 Allen bolt.

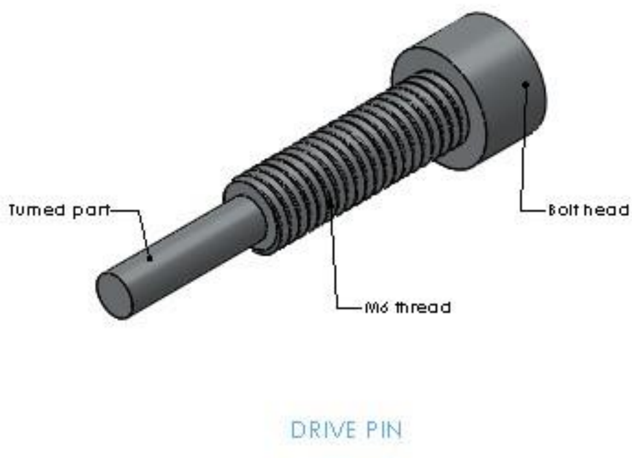

Figure 34 Drive pin (CAD model)

3.4.3 Encoder shaft

Rotary incremental encoder performs best when they are directly coupled with the shaft, they are supposed to measure the angular motion of. The head stock was selected keeping this in mind as it has provision to couple things on the backside of its pulley. An encoder shaft was designed for this purpose.

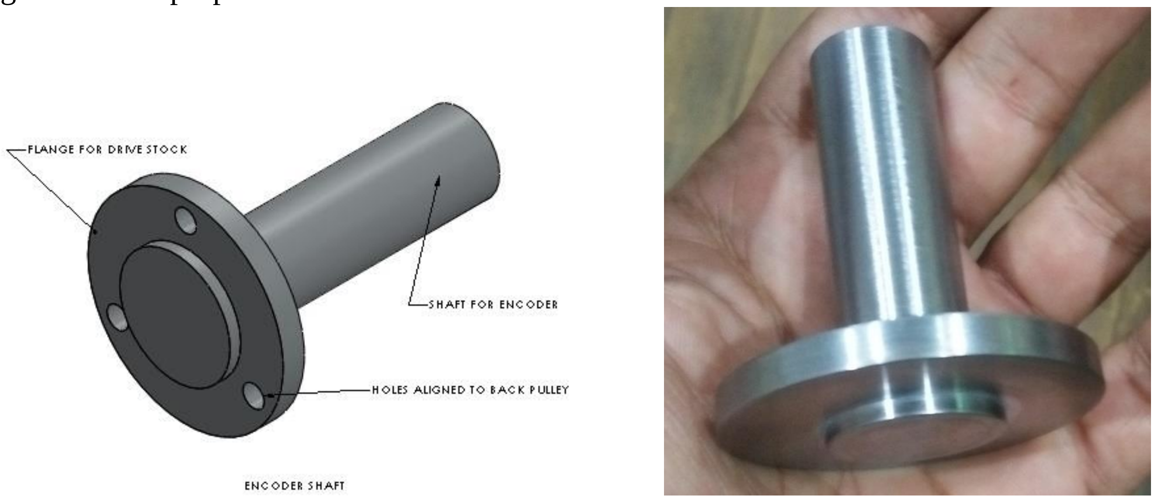

Figure 35 Encoder shaft (CAD model and manufactured part)

3.4.4 Electric slider holder

When it came to fixing electric slider on the base plate. The simplest way was to fix it from the side of both the base plate and the electric slider. At first, the holders were made by bending them which upon completion did not give desired results, so a machine holder were made with much better dimension accuracy. Two of these holders were made of mild steel. Their dimensions were kept within the tolerance range of ±0.05mm.

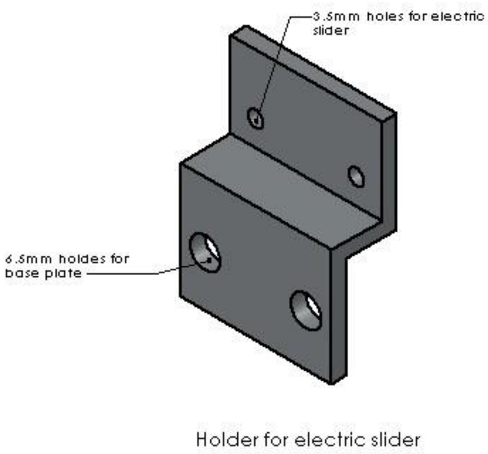

Figure 36 Electric slider holder (CAD model)

3.5 Final design of camshaft inspection machine

In practice, all the parts were selected and manufactured after countless design iteration and tests to reach this stage. The finalized was then approved and procurement of the selected components started. In the meantime, the parts and assemblies were designed and manufactured according to the operation intended. The final CAD model and the actual machine is shown here.

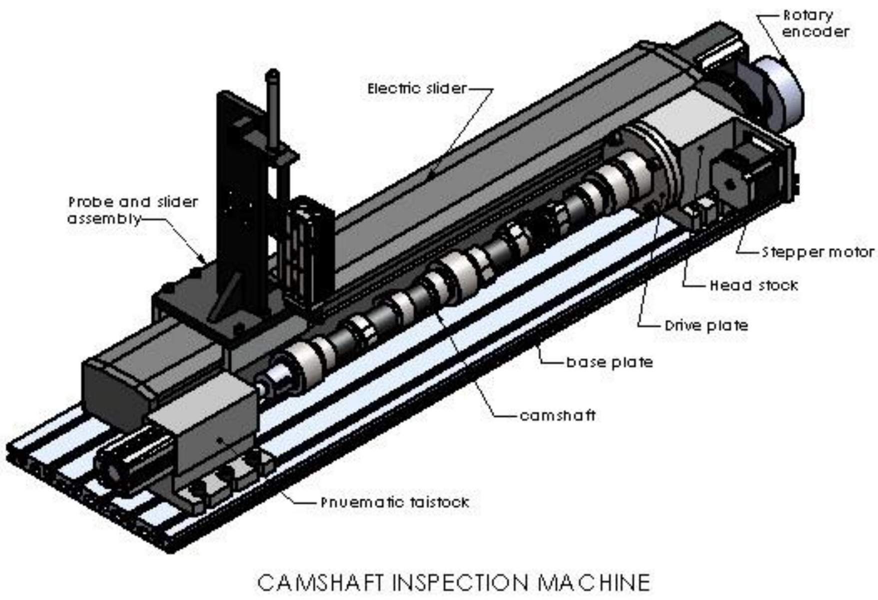

Figure 37 Camshaft inspection machine (CAD model)

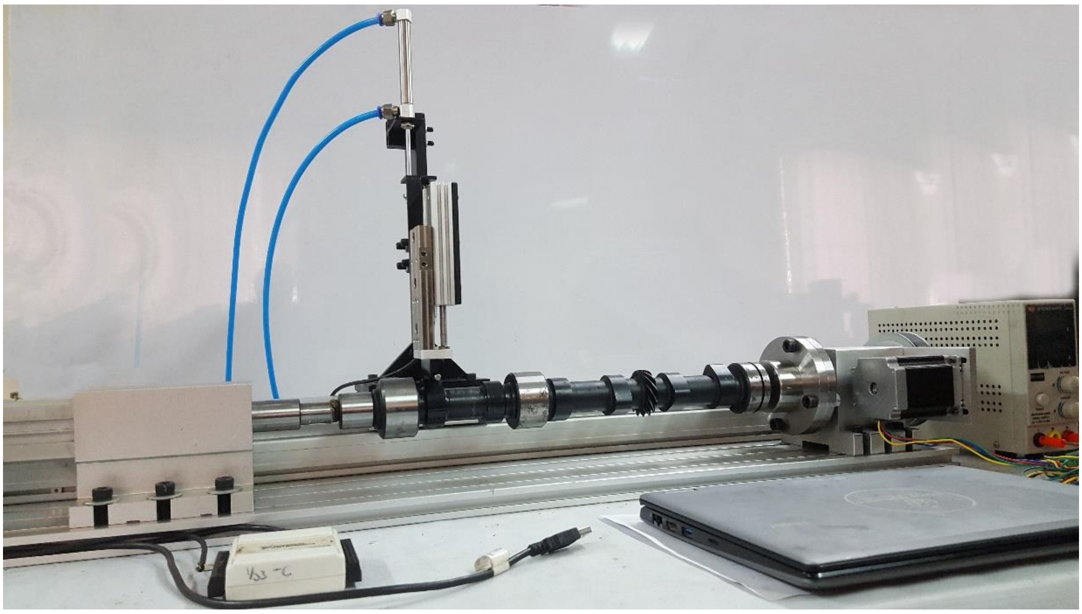

Figure 38 Camshaft inspection machine (manufactured and assembled)

CHAPTER 4: DATA ACQUISITION AND ELECTRONICS

Camshaft inspection machine measures camshaft using highly sensitive electronic devices. These devices generate signals which can be interpreted by data acquisition system to produce meaningful output data. Data acquisition system used in this machine will be discussed in this chapter.

4.1 Data acquisition

Data aquation is a process in which a physical quantity is measured using a sensor which transmits a signal to a device which amplifies or clean the signal for electrical interference and feed the signal to another device which converts that analogue signal to a digital signal. This digital signal is then sent to a computer program for further analysis and reporting back to the user. For short a data acquisition is also referred to as DAQ.

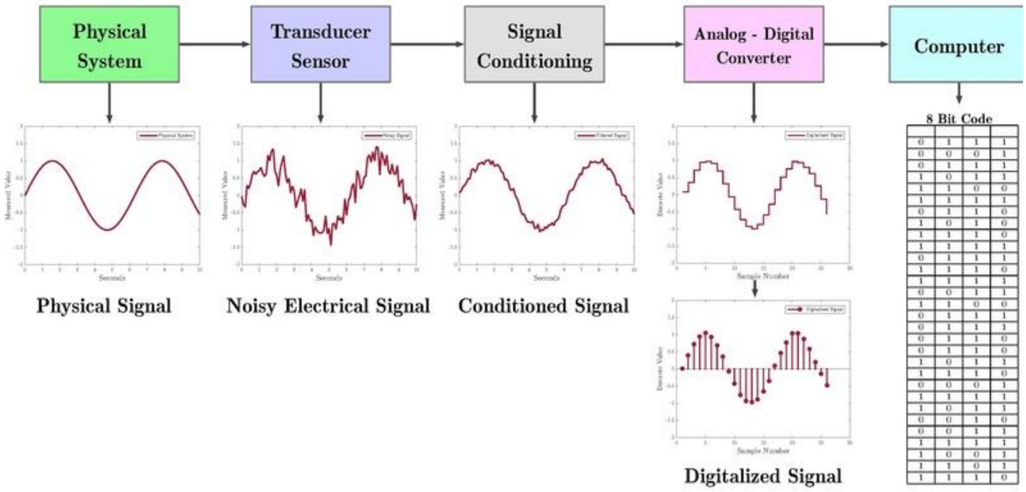

Figure 39 Digital data acquisition system

4.2 Data acquisition system

A data acquisition system consists of following unis

- Sensors
- Condition unit
- DAQ card/module
- LabVIEW

4.2.1 Sensor

A sensor is a device which measures the physical quality and correspond that value to an electrical signal. A sensor is also known as a transducer. In our case, we had a linear variable differential tanseducer (LVDT) which converts physical changes in length into a change in electrical voltage. LVDT is also known as length gauge. The Solartron LVDT model at/5/p selected was the main sensor in our camshaft inspection machine. It has a resolution of 0.5µm and repeatability better than 0.05µm.

Figure 40 Solartron AT/5/p installed on the machine

4.2.2 Conditioning unit

The objective of a conditioning unit in a data acquisition system is to clean, amplify or attenuate the noisy signal coming from the sensor installed in a system. Signal generated by the sensor after taking the measurement of a physical quantity is mostly very noisily due to electrical optical or mechanical interference. Sometimes, like in our case the signal is very from the sensor is very small related to the physical quantity. So, to solve both problem a conditioning unit is used for the amplification and cleaning the signal. The conditioning unit used with our sensor is a boxed in-line conditioning module (BICM) which runs on a bipolar DC supply of ±15v. The BICM comes calibrated with LVDT sensor.

Figure 41 BICM with the Solartron LVDT

4.2.3 DAQ card/module

Data acquisition card or module is device which converts the electrical signal generated by the sensor or conditioning unit to a digital signal which can be read by the computer. A DAQ card or module has a built-in analogue to digital converter which converts analogue signals such as voltage or current to a corresponding digital signal. The DAQ module used in the machine we developed is a National Instruments USB ni-6009. It is a multifunction input and output device which provides 8 analogue inputs AI at 14-Bits and 48 kilo samples per second. It also provides 2 analogue output channels at 150Hz frequency. 12 digital input and output channels are also available on this device.

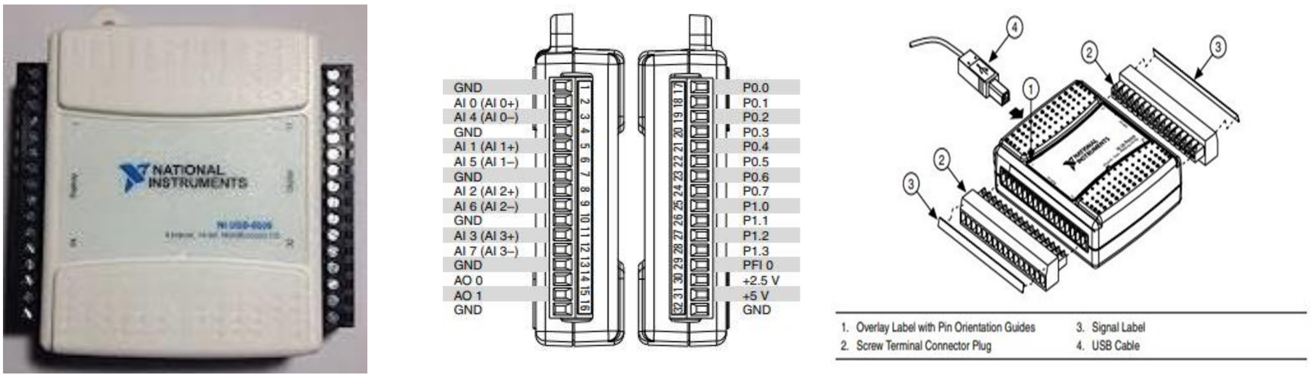

Figure 42 NI-6009 USB, Pin outs and components

4.2.4 LabVIEW

LabVIEW which is an acronym for Laboratory Virtual Instrument Engineering Workbench which is a graphical or visual programing language developed by the National Instruments. It is used to design and develop systems for data acquisition, instrument control and automation. This platform was selected for the operation or camshaft inspection machine for its ease of use and visual data flow representation. The platform has two windows, a block diagram window, and a front panel window. Most of the programming is done on the block diagram window while the front panel display the controls and the graphs of the readings. The following figure shows this

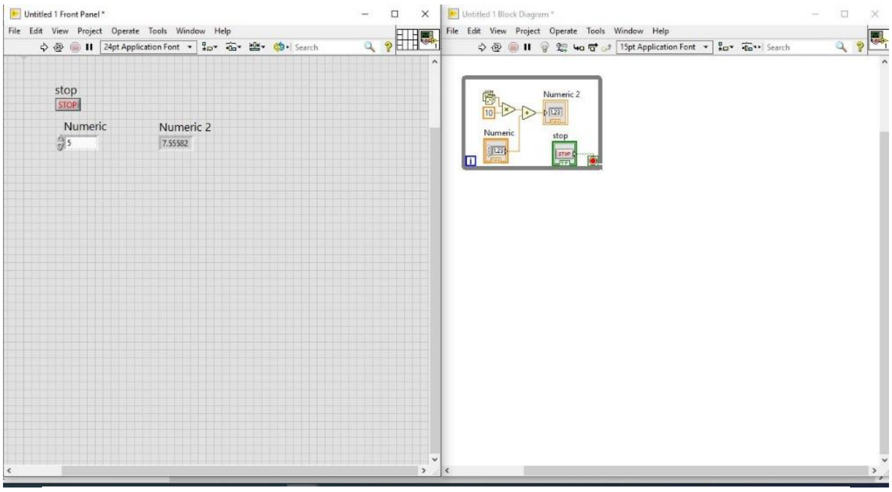

Figure 43 LabVIEW front panel and block diagram windows

4.3 Circuit diagram for data acquisition system

The following figure shows the circuit of the data acquisition system developed for the camshaft inspection machine.

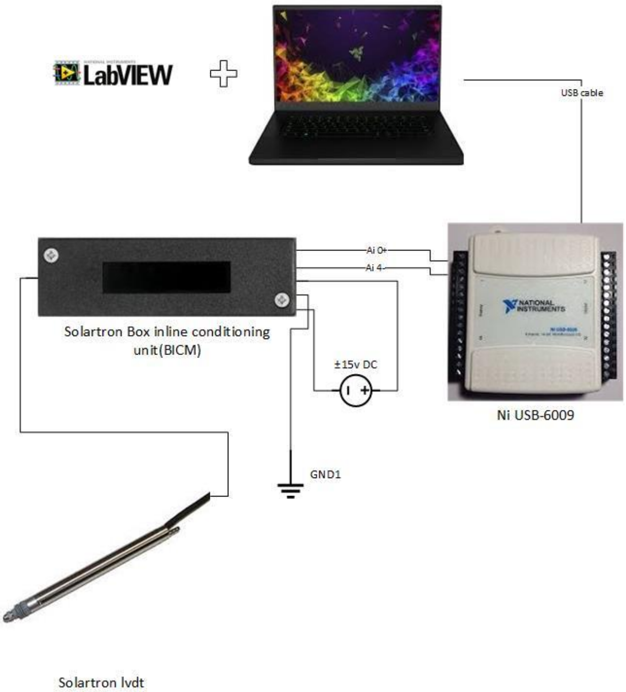

Figure 44 Circuit diagram for data acquisition system

4.4 LabView Block diagram of data acquisition system

The figure shown here is the block diagram of the data acquisition system which is the program that reads the digital data from the DAQ module and uses virtual instruments provided in the LabVIEW to represent the reading in the form of cam lift

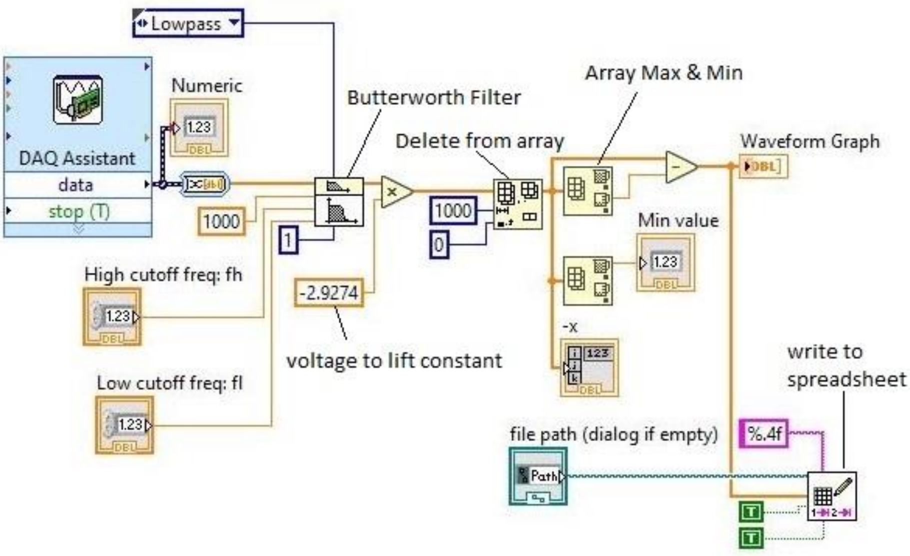

Figure 45 LabVIEW block diagram for camshaft inspection machine

4.4.1 Butterworth filter

It is a type of signal processing filter to flatten the frequency response as much as possible for the range of frequency or wavelength that passes through it. In this case, it was used in its lowpass setting and filtering was of first order where it filters out all the low and high frequency noise from the data we receive in the LabVIEW. The low and high cutoff frequencies were 3.25 and 22.45 respectively. The data was multiplied by -2.9274 as to calibrate/correspond the values of voltage and displacement. Negative sign was used because the LVDT give lift reading when its probe moves outside of its case.

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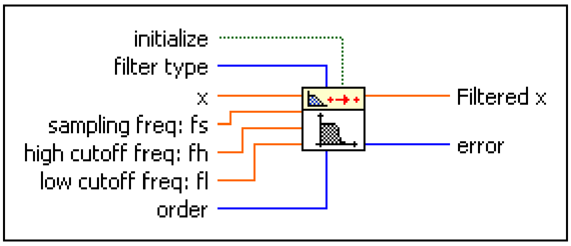

Figure 46 Butterworth filter in and out data

4.4.2 Delete from Array Function

From n-dimensional array of length elements starting at index, elements or sub-array is deleted using this function. The edited array is then returned as array w/ subset deleted. First thousand elements were deleted because there might be some error in them because of the start synchronization of the program and machine.

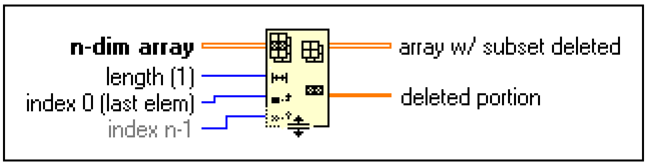

Figure 47 Delete from Array Function in and out data

4.4.3 Array Max & Min Function

The raw data from the DAQ card show the voltage generated by the LVDT to be in the negative and positive region. So, a max min function had to be used to show the lift data in just the positive region. The min valve was subtracted from the original valve and the since the min value was in negative region the whole valve showed just in the positive region of the graph.

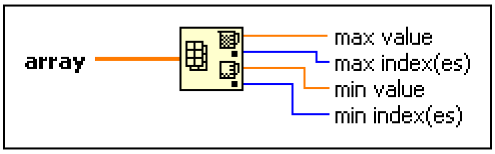

Figure 48 Array min max function in and out data

CHAPTER 5: RESULTS AND DISCUSSION

The gathering of cams lift data using the camshaft inspection machine and its analysis will be discussed in this chapter. Furthermore, the data will be compared to the given data of the intake and exhaust cams. The results and performance of the machine will be discussed in detail.

5.1 Operation parameter of the camshaft inspection machine.

The camshaft inspection machine was designed, developed, and assembled. Its data acquisition system was developed and tested to perform the required task. The machine is now in functional condition. 3-cylinder camshaft was mounted on the machine. The setting of the machine and the LabVIEW is shown in the table below.

Table 7: Camshaft inspection machine settings

R.p.m of the camshaft	15
Sampling frequency	6000
Number of samples taken	240000
Time out	500ms

5.1.1 Exhaust cam lift reading with a flat follower

The first lift reading was taken of exhaust cam. The electric slider was moved to the location of exhaust cam of the camshaft. Pneumatic actuator was operated using an air cylinder which made the probe mounted on the slider to get contact with the cam as shown in the figure

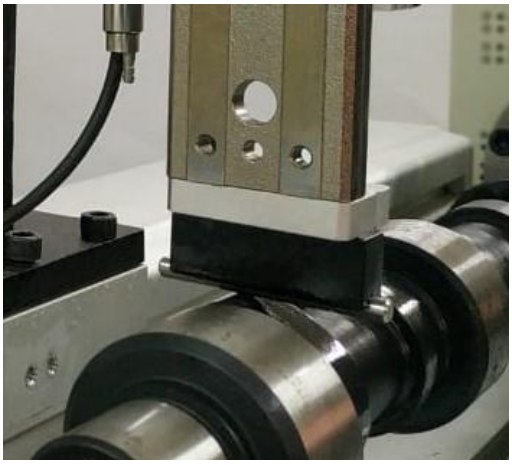

Figure 49 Probe in contact with cam

The setting of the camshaft inspection machine described in the previous section (5.1) were kept same. The following table shows the lift result compared with the design parameter of the exhaust cam described in the table 3 and table 4.

Table 8: Exhaust cam opening lift data (theoretical vs measured)

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
0	6.25000	6.15521	19	5.40333	5.42391	38	2.92544	3.20332
0.5	6.24941	6.15470	19.5	5.35849	5.38130	38.5	2.83950	3.12535
1	6.24764	6.15448	20	5.31252	5.33957	39	2.75254	3.04487
1.5	6.24469	6.15073	20.5	5.26541	5.29806	39.5	2.66455	2.96607
2	6.24056	6.14949	21	5.21718	5.25261	40	2.57556	2.88438
2.5	6.23525	6.14500	21.5	5.16782	5.20981	40.5	2.48556	2.80143
3	6.22876	6.13863	22	5.11734	5.16397	41	2.39461	2.71707
3.5	6.22109	6.13283	22.5	5.06574	5.11788	41.5	2.30286	2.63585
4	6.21224	6.12625	23	5.01302	5.07095	42	2.21055	2.55183
4.5	6.20221	6.11710	23.5	4.95918	5.02420	42.5	2.11795	2.47124
5	6.19101	6.10831	24	4.90423	4.97418	43	2.02540	2.38953
5.5	6.17863	6.09708	24.5	4.84817	4.92530	43.5	1.93320	2.30387
6	6.16507	6.08379	25	4.79100	4.87426	44	1.84168	2.22067
6.5	6.15033	6.07405	25.5	4.73273	4.82058	44.5	1.75116	2.13340
7	6.13443	6.05910	26	4.67335	4.76902	45	1.66193	2.04618
7.5	6.11734	6.04682	26.5	4.61288	4.71347	45.5	1.57429	1.95986
8	6.09909	6.03285	27	4.55130	4.65987	46	1.48851	1.87425
8.5	6.07966	6.01510	27.5	4.48864	4.60420	46.5	1.40486	1.78769
9	6.05906	5.99816	28	4.42488	4.54601	47	1.32358	1.70212
9.5	6.03729	5.97976	28.5	4.36004	4.48833	47.5	1.24489	1.61659
10	6.01435	5.96078	29	4.29411	4.43008	48	1.16898	1.53498
10.5	5.99025	5.94072	29.5	4.22710	4.37033	48.5	1.09604	1.45558
11	5.96498	5.91950	30	4.15901	4.31144	49	1.02620	1.37445
11.5	5.93854	5.89607	30.5	4.08985	4.25095	49.5	0.95959	1.29926
12	5.91094	5.87361	31	4.01961	4.18777	50	0.89628	1.22267
12.5	5.88218	5.84780	31.5	3.94830	4.12509	50.5	0.83635	1.14934
13	5.85226	5.82124	32	3.87593	4.05842	51	0.77892	1.07734
13.5	5.82118	5.79678	32.5	3.80249	3.99266	51.5	0.72668	1.00775
14	5.78894	5.76643	33	3.72800	3.92690	52	0.67691	0.94016
14.5	5.75555	5.73889	33.5	3.65244	3.85798	52.5	0.63045	0.87924
15	5.72100	5.70826	34	3.57583	3.79003	53	0.58719	0.82024
15.5	5.68531	5.67628	34.5	3.49818	3.71832	53.5	0.54703	0.76286
16	5.64846	5.64429	35	3.41947	3.64749	54	0.50980	0.71175
16.5	5.61046	5.61099	35.5	3.33973	3.57574	54.5	0.47534	0.66018
17	5.57132	5.57596	36	3.25894	3.50585	55	0.44345	0.61426
17.5	5.53103	5.54035	36.5	3.17711	3.43054	55.5	0.41390	0.56856
18	5.48961	5.50317	37	3.09425	3.35767	56	0.38644	0.52753
18.5	5.44704	5.46273	37.5	3.01036	3.28177	56.5	0.36082	0.48940

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
57	0.33675	0.45364
57.5	0.31395	0.41758
58	0.29210	0.38789
58.5	0.27089	0.35860
59	0.25000	0.33194
59.5	0.22920	0.30725
60	0.20857	0.27998
60.5	0.18830	0.25755
61	0.16854	0.23660
61.5	0.14947	0.21655
62	0.13123	0.19674
62.5	0.11395	0.17770
63	0.09775	0.15531
63.5	0.08273	0.13794
64	0.06897	0.12000
64.5	0.05652	0.10329
65	0.04542	0.08787
65.5	0.03569	0.06967
66	0.02730	0.05192
66.5	0.02023	0.03731
67	0.01442	0.02470
67.5	0.00978	0.01517
68	0.00623	0.00983
68.5	0.00364	0.00959
69	0.00188	0.00886
69.5	0.00080	0.00873
70	0.00024	0.00793
70.5	0.00003	0.00776
71	0.00000	0.00650

Table 9: Exhaust cam closing dwell data (theoretical vs measured)

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
0	6.25000	6.15521	20.5	5.26491	5.25494	41	2.40029	2.64224
0.5	6.24941	6.15470	21	5.21662	5.21246	41.5	2.31365	2.55906
1	6.24764	6.15343	21.5	5.16721	5.16742	42	2.22741	2.47780
1.5	6.24469	6.15311	22	5.11666	5.12112	42.5	2.14176	2.39317
2	6.24056	6.15084	22.5	5.06499	5.07406	43	2.05685	2.30878
2.5	6.23525	6.14581	23	5.01220	5.02654	43.5	1.97285	2.22533
3	6.22876	6.14119	23.5	4.95829	4.97448	44	1.88992	2.14224
3.5	6.22109	6.13379	24	4.90326	4.92437	44.5	1.80820	2.05740
4	6.21224	6.12584	24.5	4.84711	4.87141	45	1.72786	1.97608
4.5	6.20221	6.11699	25	4.78985	4.81743	45.5	1.64902	1.89556
5	6.19101	6.10548	25.5	4.73147	4.76407	46	1.57183	1.81687
5.5	6.17862	6.09283	26	4.67199	4.70714	46.5	1.49642	1.74181
6	6.16506	6.08117	26.5	4.61141	4.65138	47	1.42290	1.66526
6.5	6.15033	6.06697	27	4.54971	4.59604	47.5	1.35138	1.59295
7	6.13442	6.05176	27.5	4.48692	4.53758	48	1.28198	1.52107
7.5	6.11733	6.03752	28	4.42303	4.48249	48.5	1.21478	1.44814
8	6.09908	6.01897	28.5	4.35804	4.42354	49	1.14978	1.37823
8.5	6.07965	6.00200	29	4.29196	4.36170	49.5	1.08732	1.30737
9	6.05904	5.98477	29.5	4.22479	4.30106	50	1.02720	1.23957
9.5	6.03727	5.96329	30	4.15654	4.23821	50.5	0.96956	1.17440
10	6.01433	5.94445	30.5	4.08719	4.17649	51	0.91444	1.11024
10.5	5.99022	5.92069	31	4.01677	4.11306	51.5	0.86188	1.04982
11	5.96494	5.89652	31.5	3.94526	4.04916	52	0.81189	0.99307
11.5	5.93849	5.87247	32	3.87268	3.98276	52.5	0.76448	0.93786
12	5.91089	5.84548	32.5	3.79902	3.91566	53	0.71966	0.88590
12.5	5.88212	5.81971	33	3.72429	3.84717	53.5	0.67740	0.83727
13	5.85218	5.79248	33.5	3.64849	3.77756	54	0.63769	0.79064
13.5	5.82109	5.76263	34	3.57163	3.70883	54.5	0.60048	0.74628
14	5.78884	5.73271	34.5	3.49370	3.63569	55	0.56573	0.70240
14.5	5.75543	5.70333	35	3.41471	3.56383	55.5	0.53339	0.65857
15	5.72086	5.67180	35.5	3.33466	3.49108	56	0.50337	0.61888
15.5	5.68515	5.63883	36	3.25356	3.41382	56.5	0.47561	0.58191
16	5.64827	5.60655	36.5	3.17143	3.33999	57	0.45002	0.54553
16.5	5.61025	5.56973	37	3.08830	3.26341	57.5	0.42650	0.51263
17	5.57108	5.53580	37.5	3.00425	3.18812	58	0.40493	0.47903
17.5	5.53077	5.49706	38	2.91937	3.11364	58.5	0.38521	0.44713
18	5.48931	5.45836	38.5	2.83378	3.03442	59	0.36721	0.42080
18.5	5.44671	5.42056	39	2.74761	2.95828	59.5	0.35080	0.39449
19	5.40296	5.37921	39.5	2.66101	2.88085	60	0.33584	0.37405
19.5	5.35808	5.33859	40	2.57415	2.80123	60.5	0.32219	0.35508
20	5.31206	5.29718	40.5	2.48718	2.72288	61	0.30969	0.33464

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
61.5	0.29819	0.31718	82	0.01759	0.01608
62	0.28753	0.30063	82.5	0.01517	0.01582
62.5	0.27755	0.28563	83	0.01298	0.01403
63	0.26809	0.27472	83.5	0.01099	0.01353
63.5	0.25896	0.26222	84	0.00921	0.01350
64	0.25000	0.24953	84.5	0.00763	0.01316
64.5	0.24107	0.23856	85	0.00623	0.01302
65	0.23216	0.22656	85.5	0.00501	0.01292
65.5	0.22328	0.21789	86	0.00396	0.01278
66	0.21444	0.20884	86.5	0.00306	0.01254
66.5	0.20565	0.19925	87	0.00231	0.01136
67	0.19693	0.19120	87.5	0.00169	0.01127
67.5	0.18830	0.18418	88	0.00119	0.01020
68	0.17976	0.17727	88.5	0.00800	0.01008
68.5	0.17133	0.17203	89	0.00500	0.00998
69	0.16302	0.16609	89.5	0.00290	0.00975
69.5	0.15484	0.15810	90	0.00015	0.00892
70	0.14681	0.15144	90.5	0.00006	0.00889
70.5	0.13894	0.14367	91	0.00002	0.00871
71	0.13123	0.13577	91.5	0.00000	0.00813
71.5	0.12370	0.12959	92	0.00000	0.00788
72	0.11636	0.12058			
72.5	0.10921	0.11156			
73	0.10226	0.10455			
73.5	0.09553	0.09572			
74	0.08920	0.09068			
74.5	0.08273	0.08576			
75	0.07667	0.07894			
75.5	0.07085	0.07540			
76	0.06527	0.06898			
76.5	0.05994	0.06267			
77	0.05485	0.05823			
77.5	0.05001	0.05081			
78	0.04542	0.04517			
78.5	0.04108	0.03948			
79	0.03699	0.03248			
79.5	0.03315	0.02906			
80	0.02956	0.02501			
80.5	0.02621	0.02150			
81	0.02310	0.01980			
81.5	0.02023	0.01706			

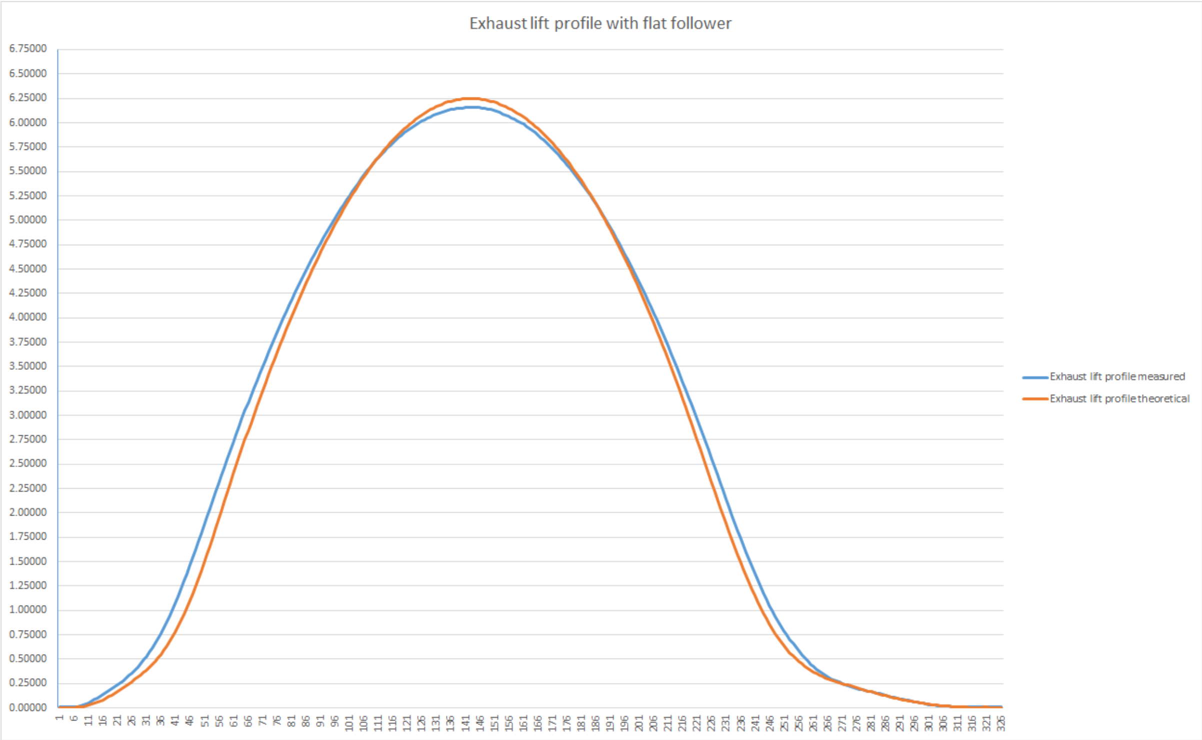

Figure 50 Exhaust cam lift profile graph (theoretical vs measured)

Description

From the tables and the graph, it can be noted that the measured cam has lesser lift than the designed value. Furthermore, there is almost 90-20µm error in the manufactured cam. The graph was plotted using Microsoft excel. Due to our sampling rate and the rpm of camshaft, the DAQ took 66 readings from the LVDT per degree rotation of the camshaft. since the data was given for every 0.5-degree, average of 33 values of the lift were taken against the value of every 0.5 degree.

5.1.2 Intake cam lift reading with a flat follower

Like the exhaust cam the electric slider was move to the intake cam. The pneumatic actuator was activated which made the probe to get in contact with intake cam. The machine setting was kept same as mentioned in the section 5.1 for the intake cam. The measured lift data was compared with given lift data of the intake cam as given in table 5 and table 6.

Table 10: Intake cam opening lift data (theoretical vs measured)

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
0	5.97149	5.94492	17.5	5.14734	5.10539	35	2.75313	2.56954
0.5	5.97079	5.94388	18	5.09997	5.05304	35.5	2.66343	2.47682
1	5.96874	5.94373	18.5	5.05132	5.00408	36	2.57278	2.38150
1.5	5.96535	5.94163	19	5.00134	4.95144	36.5	2.48092	2.28954
2	5.96061	5.93771	19.5	4.95016	4.89667	37	2.38847	2.19609
2.5	5.95451	5.93215	20	4.89766	4.83860	37.5	2.29546	2.10367
3	5.94706	5.92581	20.5	4.84389	4.78193	38	2.20230	2.00988
3.5	5.93825	5.92007	21	4.78885	4.72339	38.5	2.10995	1.91531
4	5.92808	5.91043	21.5	4.73255	4.66425	39	2.01637	1.82297
4.5	5.91657	5.90031	22	4.67498	4.59955	39.5	1.92545	1.73179
5	5.90370	5.88943	22.5	4.61617	4.53623	40	1.83556	1.64101
5.5	5.88948	5.87647	23	4.55610	4.47242	40.5	1.74754	1.55275
6	5.87391	5.86149	23.5	4.49478	4.41015	41	1.66090	1.46640
6.5	5.85699	5.84526	24	4.43223	4.34345	41.5	1.57565	1.38591
7	5.83873	5.82757	24.5	4.36843	4.27685	42	1.49224	1.30536
7.5	5.81912	5.80993	25	4.30341	4.20856	42.5	1.40981	1.22584
8	5.79816	5.78919	25.5	4.23716	4.14214	43	1.32921	1.14924
8.5	5.77586	5.76719	26	4.16969	4.07174	43.5	1.25111	1.07663
9	5.75222	5.74348	26.5	4.10101	3.99902	44	1.17545	1.00813
9.5	5.72724	5.71858	27	4.03111	3.92231	44.5	1.10258	0.94115
10	5.70093	5.69226	27.5	3.96001	3.84615	45	1.03262	0.87484
10.5	5.67328	5.66335	28	3.88772	3.76854	45.5	1.96576	0.81448
11	5.64429	5.63035	28.5	3.81423	3.69132	46	0.90208	0.75916
11.5	5.61398	5.59911	29	3.73955	3.60925	46.5	0.84202	0.70713
12	5.58233	5.56520	29.5	3.66369	3.52822	47	0.78534	0.65928
12.5	5.54936	5.53051	30	3.58666	3.44689	47.5	0.73243	0.61501
13	5.51507	5.49249	30.5	3.50846	3.36505	48	0.68291	0.57486
13.5	5.47945	5.45446	31	3.42909	3.28086	48.5	0.63700	0.53822
14	5.44252	5.41637	31.5	3.34857	3.19643	49	0.59428	0.50137
14.5	5.40427	5.37816	32	3.26691	3.11159	49.5	0.55465	0.46547
15	5.36471	5.33535	32.5	3.18409	3.02603	50	0.51793	0.43208
15.5	5.32384	5.29192	33	3.10015	2.93518	50.5	0.48400	0.40149
16	5.28167	5.24829	33.5	3.01507	2.84509	51	0.45252	0.37557
16.5	5.23819	5.20446	34	2.92887	2.75303	51.5	0.42353	0.35105
17	5.19341	5.15613	34.5	2.84156	2.66186	52	0.39638	0.32945

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
52.5	0.36923	0.31131
53	0.34476	0.29824
53.5	0.32325	0.28582
54	0.30374	0.27315
54.5	0.28827	0.25863
55	0.27441	0.24641
55.5	0.26305	0.23363
56	0.25314	0.22157
56.5	0.24133	0.20607
57	0.22956	0.19250
57.5	0.21766	0.18069
58	0.20582	0.17217
58.5	0.19405	0.16173
59	0.18234	0.15093
59.5	0.17095	0.14002
60	0.15977	0.13184
60.5	0.14868	0.11974
61	0.13778	0.10991
61.5	0.12710	0.09510
62	0.11666	0.08245
62.5	0.10649	0.07097
63	0.09663	0.06038
63.5	0.08710	0.04862
64	0.07792	0.03927
64.5	0.06913	0.03196
65	0.06075	0.02891
65.5	0.05282	0.02451
66	0.04535	0.02075
66.5	0.03838	0.01708
67	0.03193	0.01692
67.5	0.02602	0.01677
68	0.02067	0.01620
68.5	0.01590	0.01589
69	0.01173	0.01582
69.5	0.00818	0.01570
70	0.00525	0.01515
70.5	0.00296	0.01483
71	0.00132	0.01453
71.5	0.00034	0.01359
72	0.00000	0.01301

Table 11: Intake closing dwell data (theoretical vs measured)

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
0	5.97149	5.94492	20.5	4.84860	4.73962	41	1.68454	1.41707
0.5	5.97082	5.94431	21	4.79382	4.68127	41.5	1.59957	1.33366
1	5.96883	5.94375	21.5	4.73778	4.62019	42	1.51636	1.25517
1.5	5.96547	5.94227	22	4.68049	4.56132	42.5	1.43411	1.17835
2	5.96076	5.94131	22.5	4.62196	4.49985	43	1.35362	1.10621
2.5	5.95468	5.93685	23	4.56218	4.43653	43.5	1.27554	1.03691
3	5.94724	5.93119	23.5	4.50117	4.36742	44	1.19982	0.97029
3.5	5.93847	5.92086	24	4.43892	4.29977	44.5	1.12678	0.90464
4	5.92834	5.90891	24.5	4.37545	4.23126	45	1.05655	0.84519
4.5	5.91686	5.89671	25	4.31076	4.16342	45.5	0.98931	0.78590
5	5.90404	5.88563	25.5	4.24486	4.09114	46	0.92513	0.73346
5.5	5.88987	5.87168	26	4.17774	4.01956	46.5	0.86443	0.68003
6	5.87436	5.85458	26.5	4.10942	3.94731	47	0.80701	0.63282
6.5	5.85751	5.83657	27	4.03990	3.87225	47.5	0.75321	0.59153
7	5.83931	5.81786	27.5	3.96919	3.79532	48	0.70268	0.55237
7.5	5.81977	5.79785	28	3.89729	3.71865	48.5	0.65563	0.51305
8	5.79889	5.77512	28.5	3.82422	3.64020	49	0.61164	0.47830
8.5	5.77668	5.74855	29	3.74996	3.56204	49.5	0.57065	0.44756
9	5.75313	5.72372	29.5	3.67454	3.47695	50	0.53246	0.42047
9.5	5.72824	5.69679	30	3.59796	3.39448	50.5	0.49695	0.39102
10	5.70203	5.66748	30.5	3.52022	3.31166	51	0.46381	0.36510
10.5	5.67448	5.63683	31	3.44133	3.22781	51.5	0.43307	0.33976
11	5.64561	5.60600	31.5	3.36130	3.14035	52	0.40410	0.31780
11.5	5.61541	5.57378	32	3.28013	3.05267	52.5	0.37512	0.29530
12	5.58389	5.54044	32.5	3.19784	2.96550	53	0.34873	0.27477
12.5	5.55105	5.50315	33	3.11442	2.87953	53.5	0.32591	0.25798
13	5.51689	5.46634	33.5	3.02989	2.78972	54	0.30361	0.24370
13.5	5.48142	5.42843	34	2.94426	2.70000	54.5	0.28608	0.22783
14	5.44464	5.38764	34.5	2.85752	2.60906	55	0.27002	0.21413
14.5	5.40655	5.34373	35	2.76969	2.51893	55.5	0.25608	0.20157
15	5.36715	5.30023	35.5	2.68060	2.42485	56	0.24361	0.19091
15.5	5.32645	5.25586	36	2.59058	2.33096	56.5	0.22935	0.17913
16	5.28445	5.21186	36.5	2.49936	2.23671	57	0.21516	0.16609
16.5	5.24115	5.16260	37	2.40756	2.14479	57.5	0.20100	0.15355
17	5.19657	5.11290	37.5	2.31522	2.05011	58	0.18693	0.14337
17.5	5.15069	5.06319	38	2.22271	1.95690	58.5	0.17322	0.13003
18	5.10353	5.01281	38.5	2.13006	1.86231	59	0.15977	0.11691
18.5	5.05509	4.95872	39	2.03813	1.77194	59.5	0.14648	0.10544
19	5.00537	4.90385	39.5	1.94779	1.68109	60	0.13348	0.09511
19.5	4.95438	4.84889	40	1.85842	1.59086	60.5	0.12080	0.08470
20	4.90212	4.79558	40.5	1.77083	1.50201	61	0.10850	0.07389

Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured	Angle (degree)	Lift (mm) Theoretical	Lift (mm) Measured
61.5	0.09663	0.06398	64.5	0.03705	0.02444	67.5	0.00427	0.00713
62	0.08523	0.05754	65	0.02950	0.01868	68	0.00190	0.00663
62.5	0.07436	0.05006	65.5	0.02274	0.01373	68.5	0.00049	0.00641
63	0.06405	0.04180	66	0.01681	0.01135	69	0.00001	0.00609
63.5	0.05437	0.03413	66.5	0.01174	0.01033	69.5	0.00000	0.00522
64	0.04535	0.02907	67	0.00754	0.00810			

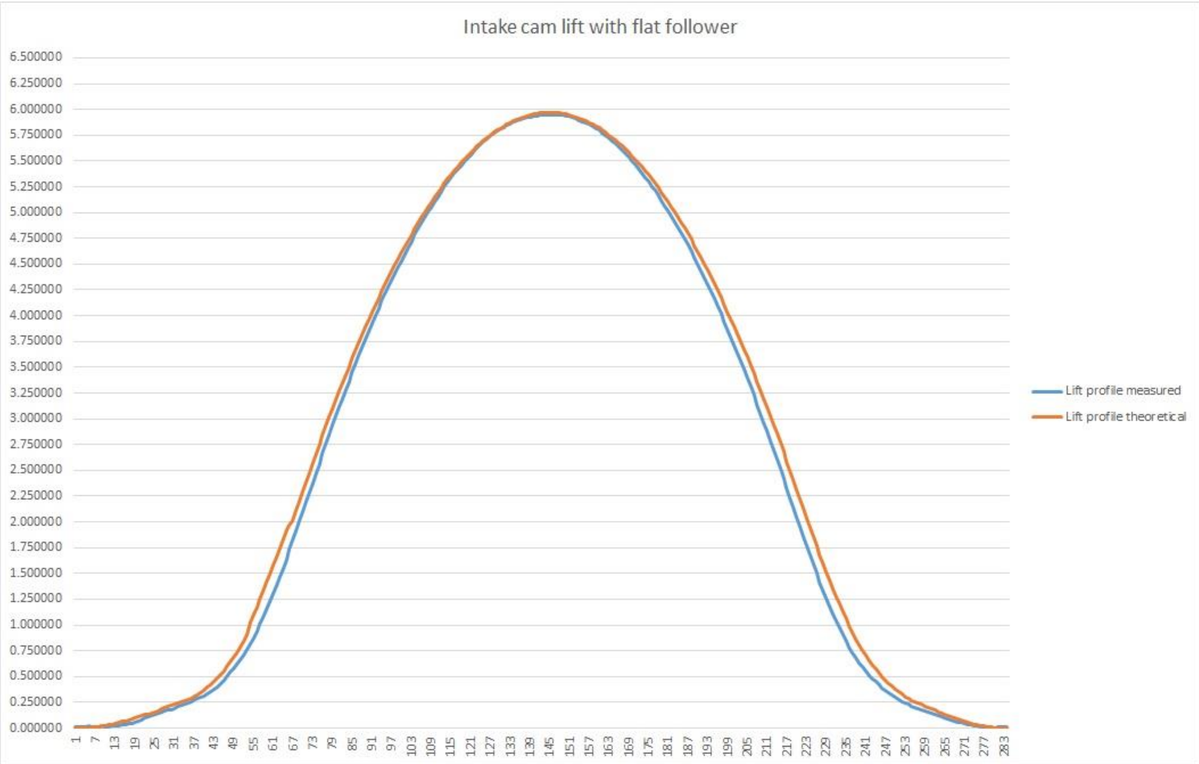

Figure 51 Intake cam lift profile graph (theoretical vs measured)

Description
From the tables and the graph, it can be noted that the measured cam has lesser lift than the designed value. Furthermore, there is almost 60-20µm error in the manufactured cam. The graph was plotted using Microsoft excel. Like exhaust cam, sampling rate and the rpm of camshaft was same (table 7), the DAQ took 66 readings from the LVDT per degree rotation of the camshaft. The data was given for every 0.5-degree, average of 33 values of the lift were taken against the value of every 0.5 degree.

5.2 Raw data of the cams

The data obtained from the LabVIEW was not in the analyzed and refined form. Rather, the data output from the LabVIEW was in CSV file (comma-separated value). The camshaft was running at a constant r.p.m and the LVDT probe was taking readings. The raw data shown on the LabVIEW front panel will be discussed here.

5.2.1 Exhaust cam raw data

The exhaust cam data shown on the front is shown in the figure below

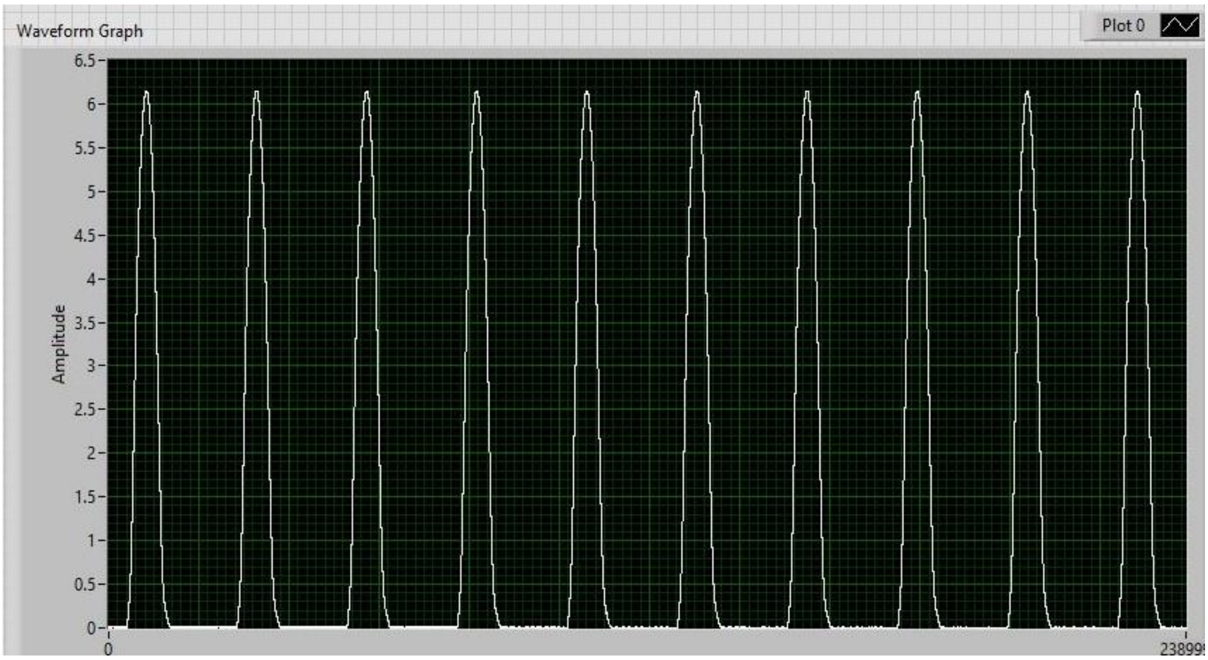

Figure 52 Exhaust cam lift data (LabVIEW front panel graph)

Each peak here shows the lift profile of the exhaust cam. The camshaft was running at 15 r.p.m and total 240000 samples were taken at 6000 samples per seconds with 500ms. The different here between the peaks is less than 3µm. A single lift profile was isolated in Microsoft excel. Lift values were taken separately for the rise and dwell of the exhaust cam corresponding to the given data.

5.2.2 Intake cam raw data

The exhaust cam data shown on the front is shown in the figure below

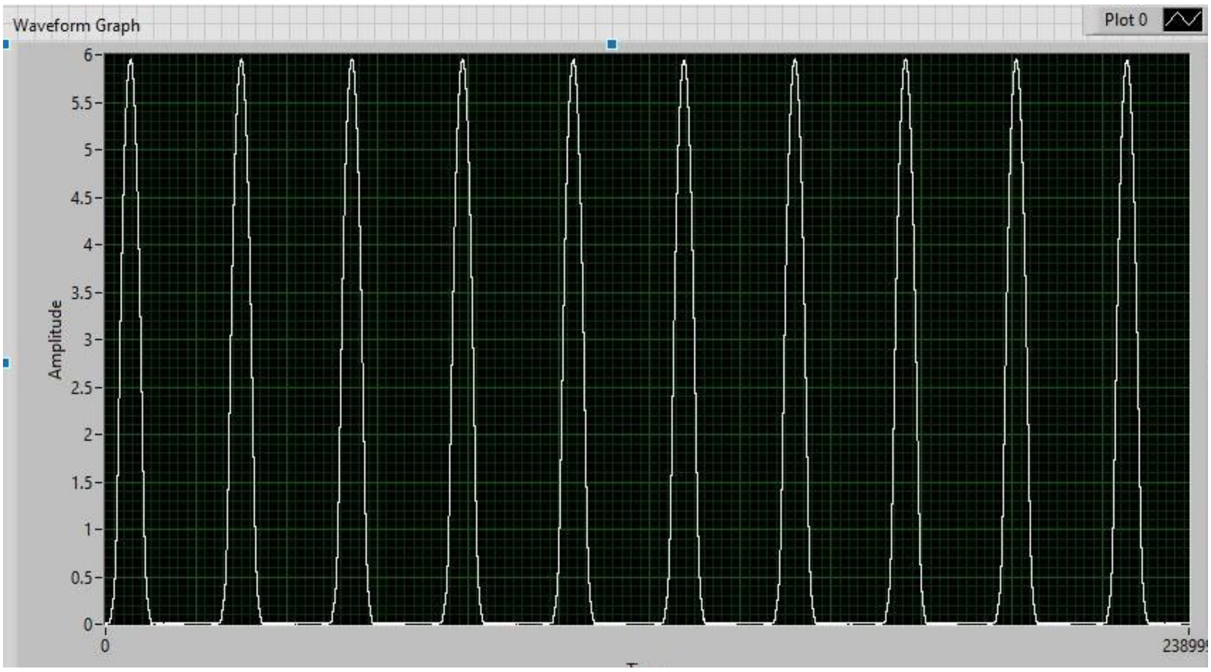

Figure 53 Intake cam lift data (LabVIEW front panel graph)

Like exhaust cam, each peak here shows the lift profile of the intake cam. The camshaft was running at 15 r.p.m and total 240000 samples were taken at 6000 samples per seconds with 500ms. The different here between the peaks is less than 3µm. A single lift profile was isolated in Microsoft excel. Lift values were taken separately for the rise and dwell of the intake cam corresponding to the given data.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

A comprehensive conclusion about the project and the result will be made in this chapter. Recommendation about the future project of similar nature and improvement that can be done in this machine will also be mentioned.

6.1 Conclusion

As mentioned earlier, after countless design iteration, testing and setbacks, a working camshaft inspection machine was developed and assembled. The parts selected and manufactured for the camshaft inspection machine performed exceptionally. Data acquisition system was challenging to develop but it gave clean output signal and worked fine. The data was collected on consecutive days with different settings, yet the output remained same. This tells us the durability and the repeatability of the machine is of industrial grade. The machine was tested to check any discrepancies in its output and there was none. The data collected was analyzed several times to see any shortcomings in the developed machine, but it prevailed every testing. The lift profile of the cams measured was in close approximation to the design data, but the machine still showed the manufacturing defects of the cams as it was the focus of our study. Overall, the project was a success yet as for every other project, room for improved remains.

6.2 Recommendations

Following are the recommendations for the further improvement in the machine

6.2.1 Design

The improvement of the design can be done by increasing the thickness of LVDT and probe slider link by 2mm. the current thickness of the link is 3mm which works well in translating probe slider motion to LVDT. The increase in its thickness will increase the resilience of machine to any nearby vibrations as it has a high resolution of 1µm which can translate to the LVDT and probe slider link. Furthermore, the whole probe and slider assembly should be encased in a metal box to shield it from dust and electrical interference. The last recommendation is to place the machine on a shock absorber assembly away from mechanical vibration and if possible, in a dust free environment.

6.2.2 Data acquisition

The module used in the data acquisition ni-6009 is a 14-bit USB which has just the right code width resolution. A better option for the data acquisition module would be the one with 16-bit resolution. A 16-bit data acquisition module will provide more flexibility in the programming and will provide data at better speed.

6.3 Future work

This camshaft inspection machine lags most in the development of its control and data acquisition system which can be improved. Inspection machines of similar nature can be developed using the same principle to measure the runouts of rotating shafts. An example would be of measuring journals runs out of the crankshaft. The principle of making such machine would be same of rotating the crank shaft between two dead centers. Most of the component used in this machine would be same. A new measuring assembly would have to be designed but is doable. Furthermore, machine of similar nature can be developed using the same principle. The future of research in this field of metrology would be develop a working coordinate measuring machine (CMM).

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