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THEORETICAL AND FINITE ELEMENT ANALYSIS TO DETERMINE CONTACT PRESSURE, VONMISSES STRESSES AND WEAR IN CAM AND FOLLOWER FOR VARIOUS CAM ROTATIONAL ANGLES IN IC ENGINE

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ABSTRACT

The contact between the cam and follower that exists in the valve strain system of IC engine influences wear. The dynamic analysis of cam and follower system in carried to find the normal compressive force for various cam rotational angles. Based on this compressive force on the cam, the hertz contact stresses and surface wear are calculated theoretically. Finite element analysis was carried out in the three critical portions of the cam such as cam nose region, cam tangent region and cam base circle region to compare the results. The results showed that cam rotational angle directly affects the contact pressure. The max contact pressure occurs in the nose end of the cam. The results showed that principle stress and wear also increases with cam rotational angle.

Keywords: *Cam &Follower, Valve train, Diesel engine, Contact Pressure, Von misses stress and Wear*

1. Introduction

The internal combustion engine that engineers are always concerned about how to predict and extend the service life of the Camshaft. Variables like material and lift profile of the cam, valve trains system and manufacturing procedure is responsible for the fatigue life of the camshaft. High values of stress in the peak of the cam are the main responsible of cam damage. Cams are mainly used in opening and closing of valves in internal combustion engines. Both valves inlet and outlet are regulated using cam and follower. Pitting, polish, scuffing, and scoring are the kinds of modes cam and follower wear occurs from the surface due to the highcontact stresses that are present between cam and roller follower contact. Pitting most often occurs in a follower type timing gear system with the camshaft inside the engine block. It is a failure of surface manifested by break out of small roughly triangular portions of a material surface due to compressive stresses causing fatigue at a point below a surface. Scuffing is a local welding process, followed by tearing apart of the welded material. It starts at high stressed zone and poor surface finish. Polishing wear is because of the general attrition of contacting surfaces. Scoring is a defect of scratches in the surface. It is believed that the present work including both theoretical analyses and finite element analysis using Ansys has improved the understanding of the tribological performance of the cam and follower.

2. Literature Review

Lindholm et al. (2003) Conducted experimental study on characterization of wear on a cam follower system in a diesel engine. Their main concern was wear analysis of cam and follower. In their study includes investigation of the running in of the most important contact surfaces of a modern diesel cam follower system. The running in is investigated by analyzing the changes in topography of the roller, pin and rocker arm of the fuel injector arm. In their study, the surface is assumed to be smooth. The aim of the test was to observe the behavior of the wear of standard components of an automobile engine before performing a test with coated components. During the tests moulds of the surface of the cam and the shaft were created.

J. Michalski et al. (2005) Conducted experimental method to investigate the characterization of wear on a cam follower system in a diesel engine. The investigation focused on the effect of cam and follower materials and their thermal and thermochemical treatment on cam and follower functional properties. Cam wear was defined by comparing the profile lifts of the cams. It often concerns cams mating with a roller follower where the wear may be increased, particularly due to the occurrence and

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propagation of cracks. With respect to the geometry and kinematics of combustion engine valve gear, it is generally assumed that the value of Hertzian pressure has a direct effect on the pitting wear value. In the analysis Camshafts result shows the formation of a nitride layer on the hard and thick martensitic bainitic matrix of cams C5 ensures its small radial wear. The cam undergoes smooth abrasive wear. Follower also undergoes smooth abrasive wear of a small value.

3. Problem Definition

In valve strain system of IC engines, the cam and roller follower are the higher pairs and hence they are subjected to frequent wear. Due to the valve timing has been changed resulting in improper functioning of IC engines. In order to reduce wear in cam and roller follower system, it is essential that the effect of normal force, contact pressure, von misses stresses and the amount of wear have to be calculated theoretically and the critical areas in the tangent cam have to be identified. The normal force acting on the cam is caused due to inertial force (F_I weight of the moving parts), valve spring force (F_V) and friction force (F_F). Once the normal force acting on the cam is determined, it can be controlled by reducing weight of moving components (inertial force), reducing the stiffness of the spring (spring force) and applying lubricants on the contact (friction force). Surface between the cam and follower

Normal Force $F_N=F_I+F_V+F_f$(1)

The diagram of valve train system of tangent cam and roller follower system is shown in fig 1.

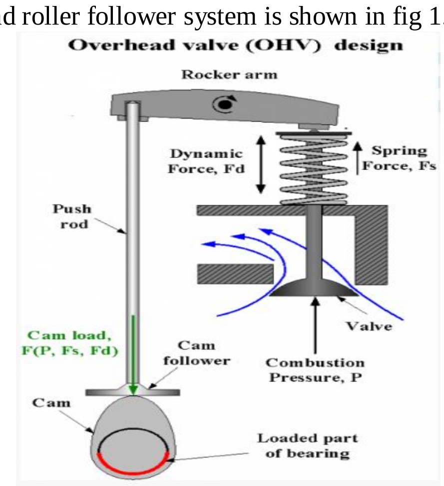

Fig. 1 Over head valve and roller follower configuration

The contact pressure between the cam and follower can be determined using the following equation.

4. Theoretical Analysis

4.1 Dynamic analysis

Displacement

A simple displacement diagram illustrates the follower motion at a modified harmonic motion rise followed by a similar return with a dwell in between as depicted in figure

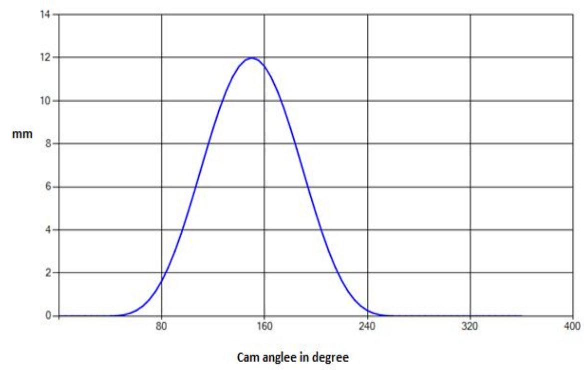

Fig. 2 Cam angle vs. Displacement

Velocity

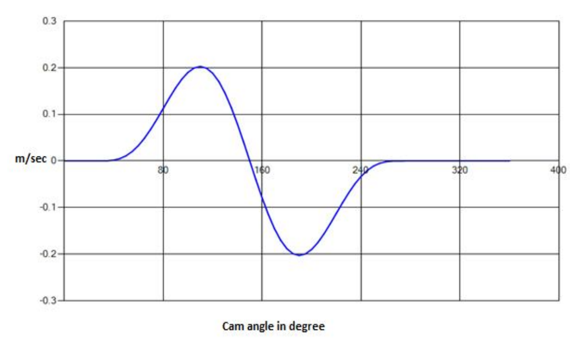

Fig. 3 Cam angle vs. velocity

Acceleration

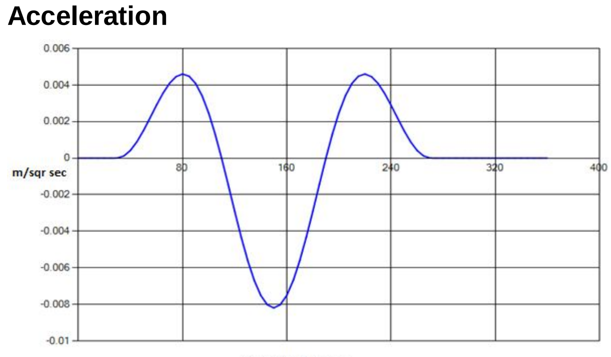

Fig. 4 Cam angle vs. Acceleration

Pressure angle

If the pressure angle is more than 30 degree there will be jumping of the follower with the bushing. The variation pressure angle with cam rotation is shown in fig (5).

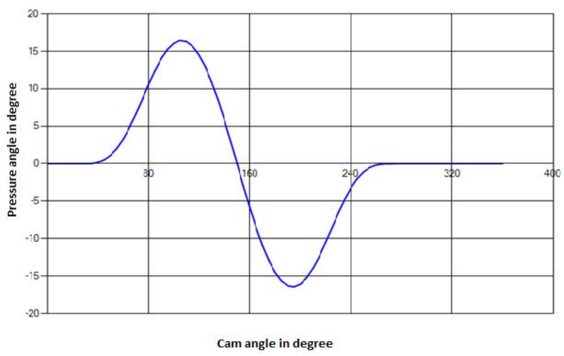

Fig. 5 Cam angle vs. pressure angle

Table 1 Dynamic analysis of cam and follower

cam angle θ	Displacement mm	Velocity m/sec	Acceleration m/sqr sec	Jerk m/cube sec
0	0	0	0	0
30	0	2.20E-05	8.78E-06	1.22E-05
60	0.25736	0.033109	0.0029037	0.00013586
90	3	0.15663	0.0040889	-0.0001072
120	8.7426	0.1884	-0.0029037	-0.00028746
150	12	-2.83E-16	-0.0081954	7.32E-18
180	8.7426	-0.1884	-0.0029037	0.00028746
210	3	-0.15663	0.0040889	0.0001072
240	0.25736	-0.033109	0.0029037	-0.00013586
240	0.25736	-0.033109	0.0029037	-0.00013586
270	0	-2.20E-05	8.78E-06	-1.22E-05
300	0	0	0	0
330	0	0	0	0
360	0	0	0	0

The forces acting against the direction of motion of follower can be broken down in to four components; these are the frictional forces, the inertial force, the spring force and the normal load.

4.2 Force Analysis

Friction force

Friction force of the cam and roller follower

$$F_f = \mu N^1 + \mu N^2 \qquad (2)$$

Inertial force

Inertial force of the cam and roller follower

$$I_{inertial} = \frac{W \times a}{g} \qquad (3)$$

Spring Force

The functional role of the spring in cam and follower designs engine is to ensure a constant contact between the cam and the follower.

$$Fs = K\Delta\,(y) \qquad (4)$$

$$\Delta y = Y_2 - Y_1 \qquad (5)$$

Normal Compressive Force

This normal compressive force and dynamic load depending on the cam angle, we estimated normal compressive force applied on the cam surface and is plotted with cam angle. Blow table shown the spring force, inertial force and normal force.

$$F_n = \left(\frac{F_s + F_{inertial}}{(\cos\theta)}\right) \qquad (6)$$

Table 2 Forces on the cam and follower

cam angle θ	spring force N	Inertial Force N	Normal Force N
0	980	542	1522
30	806	192	1153
60	500	270	808
90	353	192	552
120	340	58.56	418
150	340	58	344
180	340	58	344
210	340	58	344
240	340	58.56	418
270	353	192	552
300	500	270	808
330	806	192	1153
360	980	542	1522

4.3 Hertz Contact Stress and Surface Wear

To express the contact between two elastic bodies contact hertz proposed the contact between two parallel cylinders is presented in line contact.

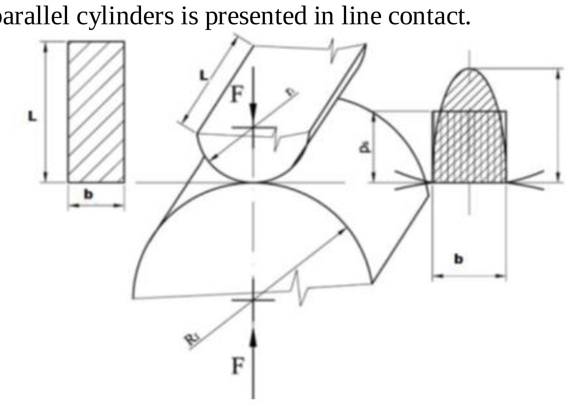

Fig. 6 Contact area of two cylindrical contacts

As depicted above in figure the pressure developed is elliptical distribution with respect to the normal load andit can be expressed as a function of normal load as

$$P_0 = \frac{2Fn}{\pi bl} \qquad (7)$$

The half width b depends on the geometry of contacting cylinders and for two cylinders of unequal diameter and unlike materials, the half width is:

$$b = 2\sqrt{\frac{2F}{l\pi}\frac{F\left(\frac{(1-\mu_1)}{E1}+\frac{(1-\mu_2)}{E2}\right)}{\left(\frac{1}{d1}+\frac{1}{d2}\right)}} \quad (8)$$

Table 3 Contact width and pressure distribution for cam and follower

cam angle θ	Contact width m	Maximum Pressure Mpa
0	0.0001174	896.506
30	0.0001014	779.15
60	0.0000831	674
90	0.0000676	565
120	0.0000587	493
150	0.0000536	451
180	0.0000536	451
210	0.0000536	451
240	0.0000587	493
270	0.0000676	565
300	0.0000831	674
330	0.0001014	779.15
360	0.0001174	896.506

Von misses Stress Analysis

The stress values depend on the pressure angle and the contact width from the center of contact. The stress analysis can be numerical calculated using the above derived formulas.

$$\sigma_y = -\frac{p_0}{\pi}\left(\frac{b_2 + 2y_2 + 2z_2}{b}\varphi - \frac{2\pi}{b} - 3y\varphi\right)$$

$$\sigma_z = -\frac{F0}{\pi}z(b\varphi - y\varphi)$$

$$\tau_{yz} = -\frac{\sqrt{\frac{1}{\pi(1-\mu 2)L}\frac{F\left(\frac{1}{E1}+\frac{1}{E2}\right)}{\left(\frac{1}{R1}+\frac{1}{R2}\right)}}}{\pi} z^2\varphi \quad (9)$$

Blow table shown in the contact stress of the cam and roller follower.

Table 4 Stress distribution on the cam and follower surface

Cam angle (θ)	Von misses stress (σx) Mpa	Von misses stress (σy) Mpa	Von misses stress (σz) Mpa
0	-183.93	-166.55	-633.37
30	-159.73	-135.48	-613.34
60	-138.2	-125.2	-530
90	-115.85	-105.2	-474
120	-101.08	-91	-387.4
150	-92.48	-83	-354.35
180	-92.48	-83	-354.35

The maximum pressure, the von misses stress and the shear stress is attained at the cam lobe surface when the cam rotational angle is 360 and the pressure angle is 30. The maximum contact pressure is 897Mpa at the cam lobe. The maximum von misses' stress is also at the cam lobe and is value is 705 Mpa and the maximum shear is 269.31Mpa.

Theoretical Analysis of Surface Wear

Most wear models assume linearity, and they often also assume that the wear is directly proportional to the local contact pressure. The most common wear model is named Archard's Wear Law,

- Delamation
- Abrasion
- Adhesion
- Oxidation etc.

Archard's wear law would thus serve as the appropriate wear model to describe the wear, so the above listed wear mechanisms can be described by archard's wear equation. The model is expressed mathematically as follows;

$$V = k \times \frac{F_n}{H} \times S \quad (10)$$

The wear volume per sliding can be expressed as follows;

$$Q = \frac{K \times F_n}{H} \quad (11)$$

Generally cam wear rate with respect to cam rotation angle and with respect to contact pressure can be analyzed as follows;

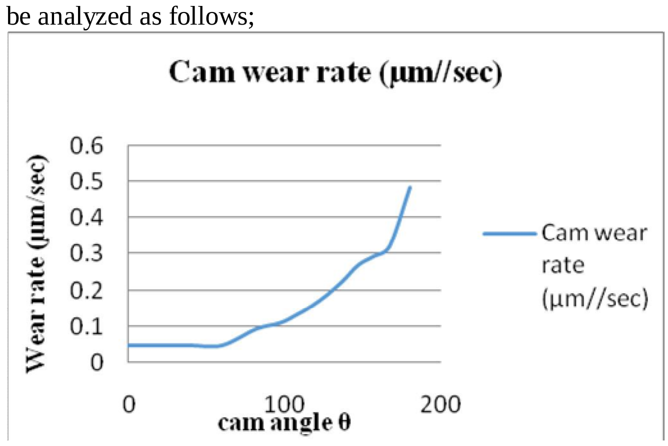

Fig. 7 Wear rate of cam profile

Then the above derived wear model is the wear of the softer material. The wear of the harder material (follower) is can be described as

$$V_2 = \left(\frac{H}{H_2}\right)^2 \times V \quad (12)$$

Table 5 Cam and follower wear rate

cam angle θ	Cam wear rate (μm/sec)	Follower wear rate (μm/sec)
0	0.0495	0.0308385
20	0.0495	0.0308385
40	0.0495	0.0308385
60	0.0495	0.0308385
82	0.09479	0.05905417
97	0.111	0.069153
107	0.132	0.082236
117	0.157	0.097811
127	0.188	0.117124
137	0.226	0.140798
147	0.2698	0.1680854
157	0.294	0.183162
167	0.3214	0.2002322
180	0.4823	0.3004729

5. Finite Element Analysis of Surface Wear

The contact pressure distribution on the follower surface is determined using ‘finite element non-linear contact pair analysis. The magnitude of the contact force varies with follower movement on the cam profile, and is predominant at the nose zone of cam because of the reduced contact area. The wear rate on the contact surface of the follower is calculated by using linear wear relation. The wear coefficient characterizes the significant changes on the topography of the surfaces.

5.1 Modeling of 3D Cam and Follower

In this section finite element approach is used for contact stress analysis in cam and follower system.

Modeling the three dimensional cam and follower using solid edge

To model the system the geometry cam and follower must be known that is the basic circle radius of cam, radius of cam lobe, radius of follower and maximum lift must be specified. These parameters are depicted below:

Table 6 Geometrical value of cam and follower

Elements name	value
1.Cam basic circle radius	24mm
2.cam lobe radius	13mm
3.roller radius	9mm
4.maximum lift	12mm

Create an instance of the cam and follower in the Assembly module to include it in our model

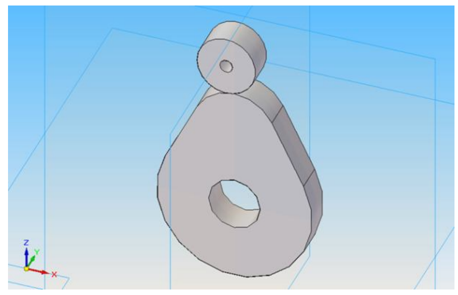

Fig. 8 3D assembly of cam and follower system

Creating the mesh assembly

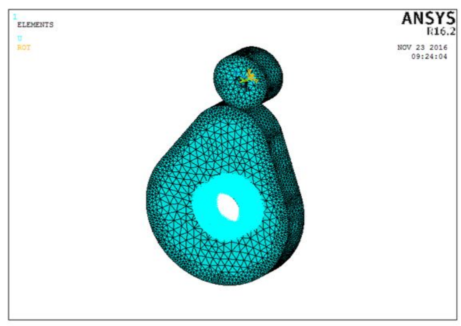

Fig. 9 Meshed assembly

The finite element representation of cam and follower system has three positions at the follower will in contact with the cam surfaces. These are the cam basic surface, the cam flank and the cam lobe. The results of these three conditions are depicted below:

Cam lobe results

The Contact pressure distribution for cam lobe surface is shown in below figure

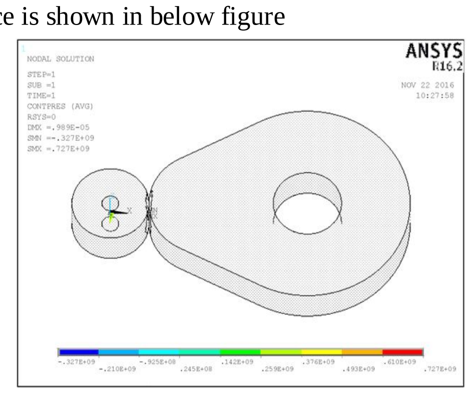

Fig. 10 Contact pressure distributions in lobe surface

The cam lobe surface contact pressure is Minimum 327Mpa and Maximum 727Mpa.

Von misses stress distribution of cam lobe surface

The von misses distribution for cam lobe surface is shown in below figure

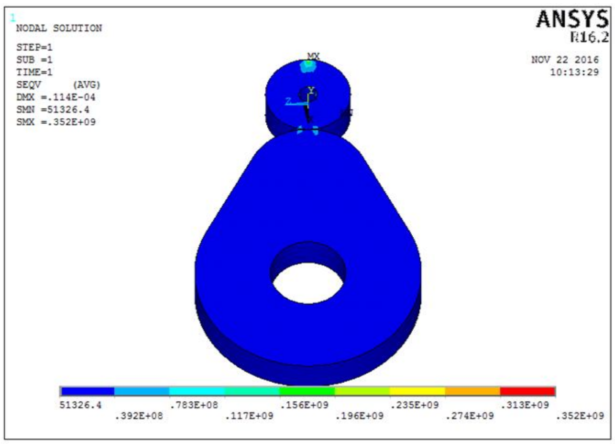

Fig. 11 Von misses stress distributions of lobe surface

The cam lobe surface von misses stress is Minimum 51326.4pa and Maximum 352Mpa.

6. Comparision of Theoretical and Ansys Results

In this section results from finite element method the results using for contact stress and the theoretical analysis with the application of hertz contact theory for stress analysis will be described and the results will be compared. The finite element representation of cam and follower system has three positions at the follower will in contact with the cam surfaces.

When we analyze the comparison between the theoretical and ansys results, both the theoretical and ansys results shows that the contact pressure increases with the increases of cam rotational angle for the rising action of cam. The comparison shows these values are in good agreement.

Comparison of Theoretical and FEA analysis contact pressure

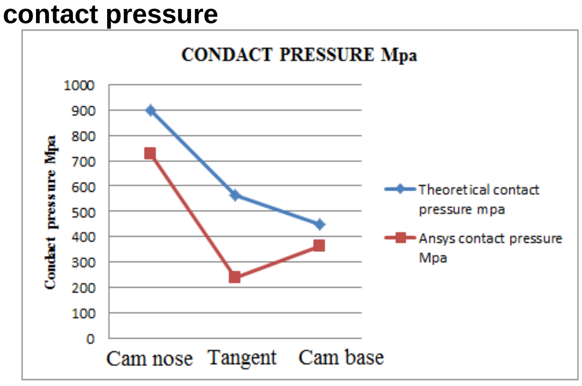

Fig. 12 Comparison of contact pressure distribution

Comparison of Theoretical and FEA analysis von misses stresses

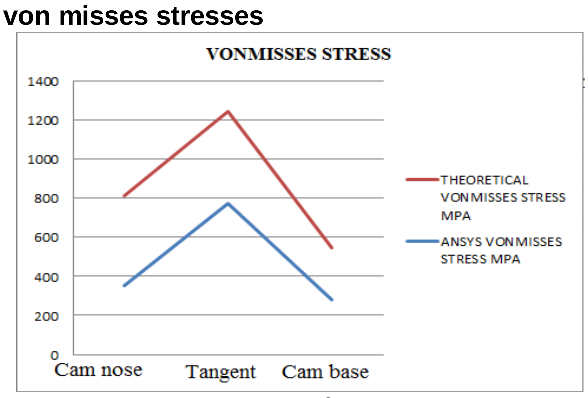

Fig. 13 Comparison of Von misses stress distributions

When we analyze the comparison between the theoretical and ansys results of the von misses stress, both the theoretical and results shows that the von misses stress increases with the increases of cam rotational angle and contact width for the rising action of cam.

Comparison of cam and follower wear

The wear of cam and follower can be also calculated using the results of Ansys analysis software shows the below table

Table 7 Comparison of Theoretical and Ansys wear rate in cam

Region	Theoretical wear µm/sec	ANSYS wear µm/sec
Cam nose	0.4823	0.411
Cam tangent	0.2942	0.1456
Cam base circle	0.0495	0.0343

If we analyze the comparison of wear calculated from the contact result of ansys and theoretical contact pressure results, both theoretical and results of wear is in good agreement the wear increases with the increase of cam rotation angle, and the wear is also increases linearly with the contact pressure.

The distribution of follower wear is depicted below it shows that in the roller follower wear rate increases linearly with the cam wear rate. The cam rotation angle had an effect on follower wear rate i.e. the roller follower wear rate increases with the increase of cam angle shows the below figure

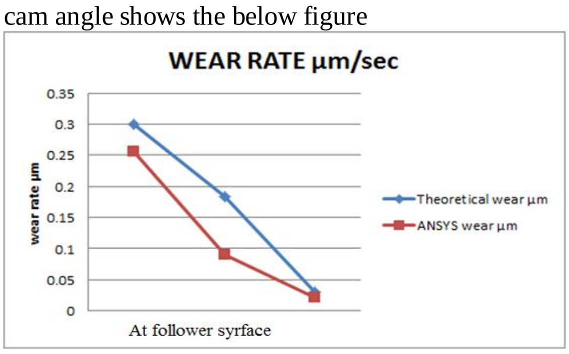

Fig. 14 Comparison of Roller follower wear distribution

7. Conclusion

A theoretical model has been developed for predicting the valve train tribological performance of cam and follower which includes the contact pressure; von misses stress and surface wear analysis on cam/follower contact. That a theoretical model for evaluating the surface wear from the follower and cam contact by taking into accounts the follower displacement has been presented. Furthermore, a multi-aspect comparison between the theoretical predictions and the ansys results has been undertaken. The main conclusions which can be obtained from these theoretical and ansys results and theoretical comparisons are summarized below;

The critical position of cam for wear is the cam lobe. This is due to the application of highly compressed spring that results high normal load on smaller contact area. The cam angle and pressure angle are important geometrical parameters during the design of cam and follower system. As it is expected, in this work wear increases with increasing of cam angle with pressure angle of zero degree and it will below on cam of smaller cam angle with the pressure angle of zero degree.

As a result, based on this finding if the pressure angle and the cam angle are the criteria as for wear of cam and follower mating then a Cam and follower mating with gray cast iron of desired hardness with relatively smaller pressure angle with maximum limit 30 degree is preferred for good function of engine valve train system.

Future scope of the work

In this thesis work contact pressure, von misses stress and wear is studied for different portions of cam at dry condition. Other influencing factors are not studied. So this work is restricted to the specified cases. However, this paper can be extended to other situation listed below.

- Numerical method investigations should be conducted on Effect of lubricants in cam and follower contact.
- The wear of cam and follower system should be conducted experimentally and the results should be compared with the theoretical and finite element analysis software i.e. ANSYS results

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