A Review on Finite Element Analysis of I.C. Engine Piston –Ring

Shubham Bhawsar[1], Prof K.K. Jain[2]
[1] *Research Scholar, department of mechanical Eng. SRIT, Jabalpur (M.P)*
[2]*Professor, department of mechanical Eng. SRIT, Jabalpur (M.P)*

Abstract- **Piston rings have been being used for whatever length of time that ignition motors themselves. Regardless of this, obliviousness or lacking information of piston rings is still every now and again clear today. No other segment is so basic when control misfortune and oil utilization are in question. With no other part in the motor is the partition amongst desires and used capital more noteworthy than when supplanting piston rings. Very regularly, trust in piston rings endures because of the misrepresented requests made on them. This literature review presents the synthesis of the main technical contributions already published in the IC engine field and mainly discuss the piston and piston ring dynamics in internal combustion engines and highlights the work done in modelling of piston ring for almost four decades. This review discloses that in order to appreciate the complete and complex dynamics of piston and ring, a three-dimensional approach is required; hence the author proposes a study to understand the complete behavior of the piston ring by making a three-dimensional finite element model of the complete engine and plans to optimize the design parameter and estimate by FEA methods of the model.**

Index Terms- **Piston, Piston-Ring, ANSYS, Rectangular Cross Section and Tapered Face Cross Section piston rings.**

I. INTRODUCTION

The first need for minimizing the fluid leakage between the piston and the cylinder bore occurred in many types of machinery, water pumps, combustion engines, air compressors, hydraulic motors, hydraulic pumps and others. In the early steam engines no piston rings were used. The temperatures and the steam pressures were not so high. Increasing power demands required higher temperatures, which caused stronger heat expansion of the piston material. Initial attempt to make an extremely narrow gap resulted in very low efficiency. The solution was found in isolating the sealing function and making a separate element – the piston ring – that could better conform to the contact surface of the cylinder bore or cylinder liner. The very first piston ring was made of rope and assembled into a steam engine in 1774 – thermal efficiency increased to 1.4 %. It had the sole task of sealing off the combustion chamber, thus preventing the combustion gases from trailing down into the crankcase. This development increased the effective pressure on the piston.

A piston ring is a split ring used in internal combustion engines to fulfill three main functions:

- seal the combustion chamber from transferring gasses into the crankcase,
- assure the heat flow from the piston to the cylinder and

Prevent the oil, not required for grease, from going from the crankcase to the burning chamber and to give a uniform oil film on the barrel bore surface.

The piston rings need to meet every one of the necessities of a dynamic seal for direct movement that works under requesting warm and compound conditions. To put it plainly, the accompanying necessities for piston rings can be recognized:

- low rubbing, for supporting a powerful proficiency rate,
- low wear of the ring, for ensuring a long operational lifetime,
- low wear of the chamber liner, for holding the coveted surface of the liner,
- emission concealment, by restricting the stream of motor oil to the ignition chamber,
- good fixing ability and low pass up for supporting the power effectiveness rate,
- good protection against thermo-mechanical weakness, compound assaults and hot disintegration and

- reliable operation and cost viability for a fundamentally prolonged stretch of time.

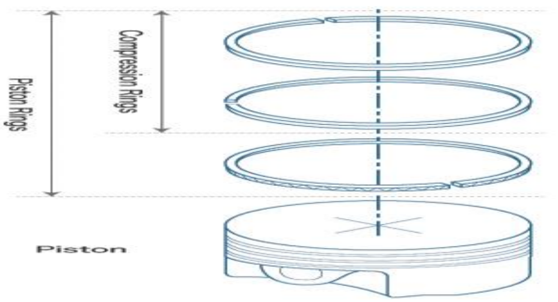

Figure 1.1 Typical ring pack for Internal Combustion Engine

1.1 Piston Ring Design

Piston rings are metallic seals which have the capacity of fixing the ignition chamber from the crankcase and assuring the stream of warmth from the piston to the barrel. Different capacities are to keep the oil not required for grease from going from the crankcase to the burning chamber and to give a uniform oil film on the barrel bore surface.To achieve this, the piston rings must be in contact with the cylinder wall and the piston groove side. Radial contact is achieved by means of the inherent elastic force of the ring, by means of the external spring integrated in the piston ring or by gas pressure acting on the back side of the piston ring. Piston rings are categorized into three basic types:

- compression rings,
- scraper rings and
- oil control rings.

The piston rings form a ring pack, which usually consists of 2-5 rings, including at least one compression ring. The quantity of rings in the ring pack relies upon the motor sort, however for the most part includes 2-4 pressure rings and 0-3 oil control rings (two-stroke start touched off motors don't have an oil control ring since they have grease blended in the fuel).

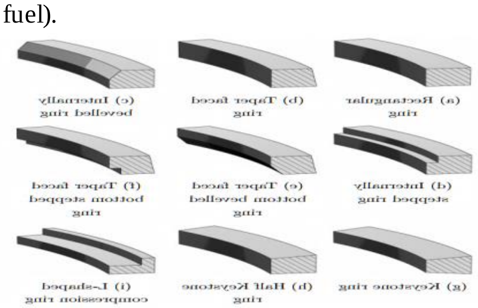

Figure 1.2 Compression ring cross sectional shape

1.1.1 Compression ring

The primary capacity of the compression ring is to make a seal between the cylinder and the liner divider, keeping the burning gasses from afterwards to the crankcase. The rings have a specific claim, i.e. they have a bigger free width than the chamber liner, which helps the ring in adjusting to the liner. The barrel gas weight follows up on the posterior of the ring, particularly on the best ring, squeezing it against the liner.

The most essential piston ring is rectangular molded. This ring plays out the fundamental fixing capacities under typical working conditions and because of its straightforwardness it is utilized for all calculations in this current ace's postulation.

1.1.2 Scraper ring

The scraper ring has the assignment of fixing and scratching off the oil from the liner divider. Subsequently for all intents and purposes the greater part of this kind of rings are with a stage recessed into the base external face - bill. This guarantees a to a great degree viable oil scratching, by expanding the unit weight and causing a positive wind. The volume made by the snout is advantageous in enabling a lot of oil to be put away there. This implies the ideal attributes of a ring with a ventured base external edge can be balanced by changing the span of the progression. Rings with a nose have a higher oil scratching impact than decrease confronted rings, yet this is normally combined with higher pass up.

1.1.3 Oil control ring

An appropriate oil film on the cylinder, cylinder rings and chamber divider is required keeping in mind the end goal to avoid harm and lessen grinding. The oil control rings are uniquely intended to suitably disseminate the oil on the chamber liner and to rub off surplus oil to be come back to the crankcase.

II. LITERATURE REVIEW

The various researchers have been done research in the field of optimization of piston rings considering various parameters.

The piston rings are in charge of a substantial part of the fuel utilization in overwhelming obligation diesel motors. In this work Markus Soderfjalla et al (2017) utilized a fast segment test fix for assessment of piston ring contact. Various distinctive piston rings and barrel liners are assessed in view of their grating execution. Shear diminishing of run of the mill multi review oil is researched by contrasting it with single review oil. Exploratory recreation of higher speeds by diminishing the consistency is assessed. A technique for sign of impacts on oil utilization, without burning, for various oil control rings is introduced. At long last, a numerical reenactment demonstrate for the oil control ring is approved by contrasting the erosion anticipated and the model to the exploratory outcomes.

The principle hub piston-stick piston rings are most in charge of the arrangement of mechanical misfortunes. It is fitting to diminish grating misfortunes in the piston-barrel bunch prompt an expansion in the general productivity of the motor and along these lines lessen the fuel utilization. One method for accomplishing these targets is change of microgeometry of the piston bearing surface which collaborates with the chamber divider. Emil Wróblewski et al (2017) displayed the consequences of recreation for the ventured microgeometry piston bearing surface.

Sorin-Cristian Vlădescu et al (2017) presents an exploratory examination into the stream conduct of grease in a responding contact reproducing a piston ring– chamber liner match. The point was to comprehend the impacts of cavitation, starvation and surface, and the association between these, so as to enhance car motor execution. A custom-fabricated test fix was utilized, in which an area of piston ring is stacked against a responding, laser-finished, melded silica cushion speaking to the liner. A fluorescence magnifying instrument focusses through the silica example onto the contact with a specific end goal to picture the dissemination of colored oil. Tests were performed utilizing a scope of surface geometries and introductions, under starved and completely overflowed oil conditions, with estimations being looked at against those from a non-finished reference.Under restricted oil supply conditions, the non-finished responding contact clears oil towards the inversion focuses (TDC and BDC), prompting starvation and expanded rubbing. This issue is reduced by the nearness of surface finishing, with each pocket exchanging oil from the delta to the outlet of the contact as it passes; the outcome being 33% lower erosion and oil disseminated uniformly finished the liner surface. Indeed, even under completely overflowed conditions, starvation is appeared to happen following every inversion, as the alter in sliding course causes the cavitated outlet to end up noticeably the oil-denied bay. This evidence of cavitation-inversion starvation, which happens for up to the initial 5% of the stroke length, contingent upon the ointment's thickness, compares to areas of high wear, measured in this examination and on real barrel liners announced in the writing. This procedure is additionally checked by the nearness of surface, with each pocket keeping oil into the cavitated locale before inversion.

Fluorescence information additionally gives bits of knowledge into different instruments with which diverse surfaces geometries control contact. Sections arranged parallel to sliding course increment grating as they seem to interface the high weight gulf with the low weight outlet, prompting oil film fall. Depressions situated transverse to sliding heading produce confined cavitation inside each pocket, which bolsters the hypothesis that surface draws grease into the contact through the 'channel suction' system. These findings can aid texture design by showing how pockets can be used in practice to simultaneously control oil consumption, and reduce friction and wear along the stroke. It should be noted that the lubricant transport mechanisms described above should also result from other types of depressions, such those produced by porous coatings Reducing the fuel consumption of a combustion engine has been an important design issue. Engine friction has to be reduced and the piston ring - cylinder liner contact is a major source of friction. The *J. Fang et al (2016)* analyses the friction and load carrying capacity of an inclined parabolic at piston ring. This relatively simple geometry permits an analytical solution of the pressure distribution, the load carrying capacity and the friction. The friction coefficient is given as a function of twist angle, _at width and total width. The analytical expressions allow many thousands of calculations per second.

The piston ring cylinder liner contact is a large contributor to mechanical friction losses in internal combustion engines. It is therefore important to have methods and tools available for investigations of these frictional losses. *Markus Söderfjäll et al (2016)* describes the design of a novel component test rig which is developed to be run at high speeds with unmodifiedproduction piston rings and cylinder liners from heavy duty diesel engines. A simplified floating liner method is used and the test equipment is developed to fill the gap in between a full floating liner engine and typical component bench test equipment.

The piston assembly is the most complex tribological system within the internal combustion engine. In order to fully exploit its optimization potential a high level of system understanding is required. Therefore, *C. Kirner et al (2016)* combines the experimentalstudies of two single cylinder engines with CFD-simulation of the piston ring pack. The introducedmeasurement and simulation techniques enable a holistic approach to the investigation of the tribological conditions ofthe piston assembly. The results shows the like the comparison of crank-angle resolved oil _lm thickness to the piston assembly friction measurement{ illustrate the implications of design parameters of the piston assembly on the functional parameters friction, oilconsumption, blow-by, wear and acoustics and thereby permit purposive system optimization.

To minimize the frictional losses and wear of piston rings in an automotive engine, thick low friction TiSiCN nanocomposite coatings have been developed *(Jianliang Lin et al 2016)*. The coatings were saved by sputtering titanium focuses in argon, nitrogen, hexamethyldisilazane (HMDSN), and acetylene (C2H2) utilizing plasma upgraded magnetron sputtering (PEMS). The substrates were AISI 304 stainless steel coupons and cylinder rings with bore widths of 137mmand 86mm. The elemental composition and microstructure of the coatingswere optimized by varying the HMDSN and C_2H_2 flow rates separately to achieve a combination of excellent adhesion, good mechanicalproperties, low coefficient of friction (COF) and wear rate.The streamlined TiSiCN coatings displayed a commonplace nanocomposite structure which demonstrated magnificent attachment and dry COF in the scope of 0.17 to 0.2 utilizing a ball-on-circle tribometer. The tribological execution of the covered cylinder rings was assessed utilizing Plint TE77 tests in SAE 10W-30 diesel motor oil. The TE77 tests showed a 10% reduction in the COF (0.058) of the optimizedcoating compared to the uncoated baseline (0.065) at test conditions of 20 Hz, 30 N, and 25 mm stroke length.

Finally, the coated rings were evaluated in a single cylinder gasoline engine using SAE 5W-20 engine oil and ina heavy duty diesel engine using 4.1% sooted SAE 10W-30 diesel engine oil. The gasoline engine test showedthat the uncoated piston rings contributed 25% to 34% of the frictional loss in two separate baseline enginetests. Interestingly, the covered rings added to 18% of the aggregate frictional misfortune in the motor test. The dieselengine durability test showed a 28% and 40% lower ring weight loss for the coated top and second rings,respectively, as compared to the uncoated baseline. In addition, the cylinder liner,whichwas not coated, showedan average 50% lower wear than that in the uncoated baseline engine test.

Pavlo Lyubarskyy, Dirk Bartel (2016) built up the 2D CFD-model of piston assembly to analyze the mass transport through the piston-liner crevices of a diesel engine. Calculations of piston ring dynamics are performed by means of the balance of forces solved in CFD A flexible plastic contact show is fused in the CFD-model to ascertain the harshness contact and limit grating in rings/liner/grooves interfaces. The hydrodynamic rubbing is figured by methods for CFD. An explanatory approach is actualized in 2D CFD-model to consider the mass-move through the ring holes permitting the estimation of between ring weights and blowby into the crankcase. The 2D CFD-model can be utilized to consider the impact of the different ring-pack outline parameters on the ring contact, blowby and oil transport.

Parthiban S et al (2015) studied the wear characteristics that govern on the piston ring pack inside the piston assembly of an engine Among a few techniques, most beneficial strategy is to give a covering layer on the cylinder ring pack. Since, ring seal is basic to the execution of the motor, it is must be an ideal seal between the ring pack and chamber divider. In this stage, existing material of the cylinder ring material were considered and contemplated, a model comparing to its measurements were readied and examination were done on them in static conditions. Likewise, Mathematical counts were performed in outlining the ring pack for displaying. The investigation on covering materials were made and reasonable materials were decided for covering.

The contact between a finished chamber liner and a cylinder ring is contemplated.*N. Biboulet and A.A.Lubrecht (2015)* proposed a simplified analytical 1D model of the pressure distribution and the load carrying capacity. Two main cases are distinguished: a ring with a small radius of curvature where the texture has a detrimental effect on the load carrying capacity, and a ring with a large radius of curvature where the texture generates a significant additional load carrying capacity.

Starved smooth contacts and groove pressure perturbations are modelled. Deep, wide and dense grooves have a detrimental effect on the load carrying capacity for rings with a small radius of curvature; whereas a phenomenon of 'optimal' groove to enhance the load carrying capacity appears for a large radius of curvature. The amplitude of the pressure perturbation is a function of the groove location, the groove depth and width. The groove shape (triangular/sinusoidal) plays only a secondary role.

The harm of piston rings is ascribed first to wear, at that point to oil and weariness. Their harm might be generously moderated by making a FGM-Functionally Graded Material composite with streamlined mechanical conduct. The point of O. Carvalho et al (2015) was to deliver an AlSi– CNTs practically reviewed material (FGM) that can be considered for motor pressure piston rings. The AlSi reviewed composites (strengthened with 0– 2 wt.% CNT FGM approach) was gotten with another gear that was intended to deliver FGMs by powder metallurgy (PM) preparing course. SEM investigation demonstrated that the delivered FGMs have a continuous change in wt.% of support and on mechanical properties. Aftereffects of yield quality, extreme rigidity, elastic strain, weariness restrain execution and wear misfortune are introduced and talked about. It is normal that the acquired AlSi–CNTs practically evaluated composite produced for piston rings may have a worldwide harmony of properties.

Isam Jasim Jaber and Ajeet Kumar Rai, (2014), composed piston and piston ring for a solitary barrel four stroke oil motor utilizing CATIA V5R20 programming. Finish configuration is foreign made to ANSYS 14.5 programming then investigation is performed. Three distinct materials have been chosen for basic and thermal investigation of piston. For piston ring two distinct materials are chosen and basic and thermal examination is performed utilizing ANSYS 14.5 programming.Results are shown and a comparison is made to find the most suited design.

The measurement of radial pressure distribution of piston rings is very important for minimizing the wastages of lubricating oils and hence the lower gas emissions; for improving the friction status to reduce the gasoline consumption and for the reasonable heat transfer efficiency for the desired accuracy levels. For accurate and efficient measurement of radial pressure distribution of piston rings, a new PC based prototype instrument based on a partial-thin-walled cylinder sensor is designed and developed by *Xingsong Wang and Xiaosong Chen, (2010)* The present paper describes the details of the measurement principle, hardware and software of this instrument. The measurement results thus obtained using the proposed instrument during experiments performed on a conical ring of diameter 110 mm and a drum ring of diameter 120 mm, are quite accurate, consistent and repeatable within the desired level of accuracy.

Piston ring dynamics play important roles on the lubricant characteristic of reciprocating engines which lead to the consequences of engine wear and vast amount of lubricating oil consumption. Due to the complexity of motion, a study of motions and effects of the piston ring is mostly conducted by *Krisada Wannatong et al (2008)* in a simulation program. This paper shows a theoretical work and a new simulation algorithm of the 3D piston ring motions. The reenactment idea is to decide the places of the cylinder ring, which are the arrangements of the Newton and Euler conditions. Surely understood models like blended oil demonstrate, acrimony contact model, and pass up/blow-reverse model were utilized as a part of this investigation. The new recreation calculation comprises of four procedures: development of count hubs, utilization of limited diverse strategy, assurance of the non-straight condition framework, utilization of parallel computational system.

T Tian (2001) talks about a few critical procedures that have extraordinary effect on the oil between the best two rings and the liner. The analysis is conducted on the basis of the calculation results on a heavy-duty (HD) diesel engine using theoretical models. Oil supply mechanisms to different liner regions are analysed, and emphasis is given to the oil transport to the top liner region that is found critical to friction, wear and oil consumption in HD diesel engines. Additionally, the paper discusses the oil supply to the second ring, its uncertainties and the effect on the prediction of the performance of the top two rings. Furthermore, the effects of dynamics of the piston and rings on friction, wear and oil transport are illu strated and the effects of bore distortion on oil transport are discussed.

For practical purposes, a formula to describe the second ring running surface pro®le is given based on simple geometrical constraint. A new truncation method is rendered for plateau surface roughness in order to effectively use the existing mixed lubrication models.

III. PISTON RING DISCRIPTION

3.1 Piston Ring Forces and Moments

The piston ring auxiliary movements can be isolated into piston ring movement the transverse way, piston ring turn, ring lift, and ring turn. These sorts of movement result from various burdens following up on the ring. Heaps of this kind are latency loads emerging from the piston speeding up and deceleration, oil film damping loads, loads attributable to the weight distinction over the ring, and rubbing loads from the sliding contact between the ring and barrel liner.

The gas weight above, underneath and behind the ring produces resultant powers on the ring area (Dowson, 1993). The dormancy powers following up on the piston rings, and additionally those following up on the other responding wrench system parts, change relatively to the square of the motor speed (Röhrle, 1995). The side stacking of the piston against the barrel divider is an aftereffect of the enunciated joint of the associating bar (Röhrle, 1995). The impact of the leeway between the chamber liner and the piston on the piston and piston ring movement and to the ring powers . The shearing of the greasing up film, the sliding grating powers and the contact weight between the ring and the liner cause ordinary and extraneous powers on the ring face.

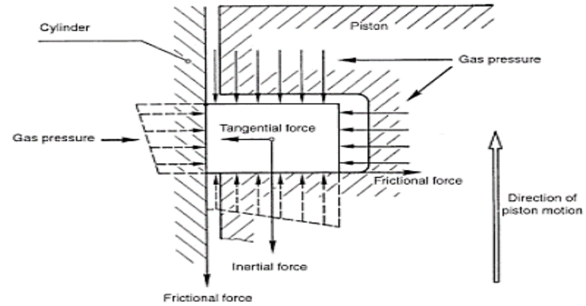

Figure 3.1 Forces acting on he Piston Ring (Handbook of Diesel Engines by Klaus Mollenhauer, Helmut Tschöke)

The gas weight behind the primary pressure ring differs as per the barrel weight. The gas weight behind the second pressure ring is as of now essentially lower than the weight behind the principal pressure ring. The gas weight behind the oil ring remains through the entire work cycle practically equivalent to the weight on the wrench chamber. With a gas weight following up on the piston ring, the contact weight and in this way the congruity is significantly expanded. Then again, the gas weights are of noteworthiness just for a little extent of the motor cycle (Chittenden et al, 1993).

3.2 Piston Ring Relationships

The ring is squeezed against the barrel divider under a contact weight p which is represented by the measurements and aggregate free hole of the ring and by the modulus of flexibility of the material utilized. The aggregate free hole is characterized as the separation, measured along the impartial pivot, between the finishes of a piston ring in its uncompressed state.

Estimation of the contact pressure is tremendously challenging. Consequently, the solution is to calculate it from the tangential force. It can be defined as the force which when applied tangentially to the tops of the ring, is adequate to compress the ring to the quantified closed gap. By solving the internal forces and moments, the following expressions are obtained (Bc. Jozef Dlugos)

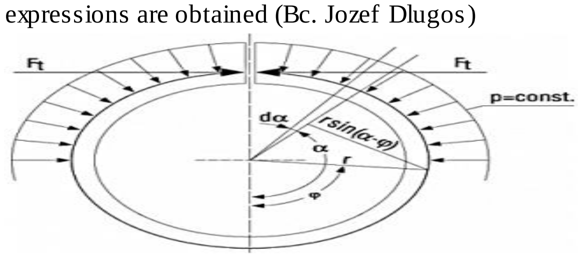

Figure 3.2 Forces applied on the piston ring surfaces.

$M = F_t r\,(1 + \cos\varphi)$ ……………. (1)

$M = phr^2\,(1 + \cos\varphi)$ ………….. (2)

where Mis the bending moment and his the axial width. By relating the bending moment of the constant contact pressure alongside of the tangential force, the subsequent relationship is recognized

$p = \frac{2F_t}{dh}$ …………….. (3)

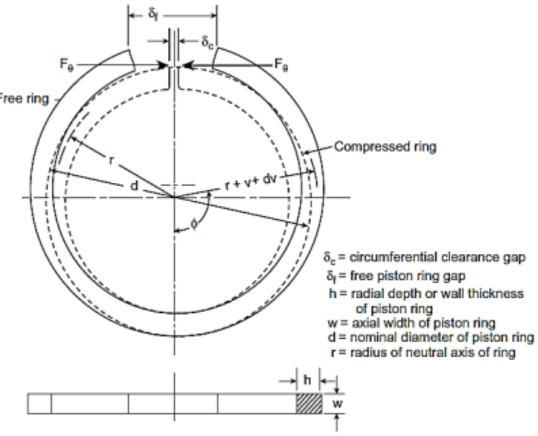

Figure3.3Nomenclature of piston ring

The nominal diameter of ring is represented by d.

The minimum contact pressure of compression rings on account of their inherent tension generally 0.059 MPa for petrol engine and 0.013 MPa for diesel engine. *(Handbook of Machine Design, McGraw-Hill Book Company, New York, 1996)*Figure shows the nomenclature of piston ring.

3.2 Piston ring material

The piston ring materials need to meet extreme requests – quality at a high temperature, low unrelated power diminish because of temperature or weakness, consumption protection, great warm conductivity (for good warmth transferability to the barrel divider) and furthermore great sliding attributes for operation in typical and dry grease conditions - keeping in mind the end goal to withstand the warm and mechanical burdens during the running conditions.

3.3 Finite Element Analysis

3.3.1 General

On behalf of Examination of the compression piston ring, the FEA method is the best. The finite element method (FEM) is a computational method adapted to get predictable resolutions of boundary value problems in engineering. The boundary value difficult can well explained like a mathematical problem in which exclusive or further dependent on variables essential meet the prospects of a differential equation in all places or directions in a famous domain of independent variables and fulfil specific situations on the boundary of the domain.

The finite element analysis is one of the numerical analysis methods that used to gain the resolution of partial differential equations. The iterative mathematical processes like as Galerkin’s weighted residual method and Raleigh-Ritz methods castoff to gain the finite element formulation of the partial differential equation.

ANSYS Transient Structural and Thermal are the valuable tool for examine problems connecting contact, huge distortions, nonlinear materials, high frequency reaction phenomena and problems needing explicit explanations.

The ANSYS support transient thermal analysis. Transient thermal analysis determines temperatures and other thermal quantities that vary over time. Designers regularly utilize temperatures that a transient warm examination ascertains as contribution to basic investigations for warm anxiety assessments. Many warmth exchange applications-warm treatment issues, spouts, motor pieces, funnelling frameworks, weight vessels, and so forth.- include transient warm investigations. This transient structural analysis is used to determine the dynamic response of a structure under the action of any general time-dependent loads. It can use to determine the time-varying displacements, strains, stresses, and forces in a structure as it responds to any transient loads

The figure 3.4 shows the structure of phases to achieve a simulation. Many steps have taken during the analysis which are:

A. Part Definitions: - Created sketched
B. Material Descriptions: - Based on previous research done by various authors.
C. Boundary Conditions Explanations
D. Meshing
E. Solution and Simulation Controls
F. Post-processing
G. Restarting

IV. CONCLUSION

A wide literature survey is carried out in the research area of piston- ring to identify about the simulation and experimental methods established to study its performance. There are stilllimited number of experimental methods in piston- ring analysis existing.

REFERENCES

[1] Bc. JOZEF Dlugos 2014, "Computational Modelling Of Piston Ring Dynamics", Brno University of Technology.

[2] C. Kirner, J. Halbhuber, B. Uhlig, A. Oliva, S. Graf and G. Wachtmeister, 2016 "Experimental and simulative research advances in the piston assembly of an internal combustion engine," Tribiology International

[3] C. Pettavino, N. Biboulet and A.A. Lubrecht, Load carrying capacity and friction of a parabolic-flat piston ring of finite width, TribiologyInternational

[4] Chittenden R. J. and Priest M. Analysis of the piston assembly, bore distortion and future developments. In: Taylor, C.M. (Ed.). Engine Tribology. Elsevier, 1993, Tribology series, 26, pp. 241–270. ISBN 0-444-89755-0.

[5] Dowson, D. Piston assemblies; background and lubrication analysis. In: Taylor, C.M. (ed.). Engine Tribology. Elsevier, 1993, Tribology series, 26, pp. 213–240. ISBN 0-444-89755-0.

[6] Emil Wróblewski, AntoniIskraa, MaciejBabiaka, 2017, "Geometrical structures of the stepped profile bearing surface of the piston", TRANSCOM 2017: International scientific conference on sustainable, modern and safe transport.

[7] IsamJasimJaber and Ajeet Kumar Rai, 2014, "Design and Analysis of I.C. Engine Piston and Piston-Ring Using Catia and Ansys Software", International Journal of Mechanical Engineering and Technology (IJMET), ISSN 0976 – 6340(Print), ISSN 0976 – 6359(Online), Volume 5, Issue 2, February (2014), pp. 64-73, © IAEME

[8] J. Fang, W. Ma, N. Biboulet and A.A. Lubrecht, "Load carrying capacity and friction of an inclined parabolic-flat piston ring", TribiologyInternational

[9] Jianliang Lin, RonghuaWei, Daniel Christopher Bitsis, Peter M. Lee, 2016, "Development and evaluation of low friction TiSiCNnano-composite coatings for piston ring applications", Surface & Coatings Technology 298 (2016) 121–131

[10] K. Sathish Kumar, 2016, "Design and Analysis of I.C. Engine Piston and Piston-Ring on Composite Material Using Creo and Ansys Software", Journal of Engineering and Science Vol. 01, Special Issue 01, July 2016

[11] KrisadaWannatong, SomchaiChanchaona, SurachaiSanitjai, 2008, "Simulation algorithm for piston ring dynamics", Simulation Modelling Practice and Theory 16 (2008) 127–146

[12] Markus Söderfjäll, Andreas Almqvist, Roland Larsson, 2016, "Component test for simulation of piston ring – Cylinder liner friction at realistic speeds", Tribology International 104(2016)57–63

[13] Markus Sooderfjall, Hubert M. Herbst , Roland Larsson , Andreas Almqvist , 2017, "Influence on friction from piston ring design, cylinder liner roughness and lubricant properties", Tribology International 116 (2017) 272–284

[14] N. Biboulet,A.A.Lubrecht, 2016, "Analytical solution for textured piston ring – Cylinder liner contacts (1D analysis)", Tribology International 96(2016)269–278.

[15] O. Carvalho , M. Buciumeanu ,S. Madeira, D. Soares , F.S. Silva , G. Miranda, 2015, "Optimization of AlSi–CNTs functionally graded material composites for engine piston rings", Materials and Design 80 (2015) 163–173

[16] PavloLyubarskyy and Dirk Bartel, 2D CFD-Model of the Piston Assembly in a Diesel Engine for the Analysis of Piston Ring Dynamics, Mass Transport and Friction, Tribiology International

[17] Parthiban S, Arshad Mohamed Gani P, Vasudevan R, Naveen Kumar C, 2015, " Design and Performance Analysis on Piston Ring" International Journal of Engineering Research and General Science Volume 3, Issue 5, September-October, 2015 ISSN 2091-2730

[18] Röhrle, M. D. Pistons for internal combustion engines – fundamentals of piston technology, MAHLE GmbH. VerlagModerne Industry. Landsberg/Lech, Germany. 1995. p. 70.

[19] Sorin-Cristian Vlădescua, Alessandra Cinieroa, KhizerTufail, Arup Gangopadhyay, Tom Reddyhoff, 2017, "Looking into a laser textured piston ring-liner contact", Tribology International 115 (2017) 140–153

[20] T Tian, 2001, “Dynamic behaviors of piston rings and their practical impact. Part 2: oil transport, friction and wear of ring/ liner interface and the effects of piston and ring dynamics”, ProcInstnMechEngrsVol 216 Downloaded from pij.sagepub.com at COLUMBIA UNIV on February 5, 2015 Part J: J Engineering Tribology

[21] Xingsong Wang, Xiaosong Chen, 2010, “Measuring radial pressure distributions of piston rings based on partial-thin-walled cylinder”, Measurement 43 (2010) 197–203