

Research Article

Innovative-Tribo-Design of Variable Valve Timing Mechanism: Need and Concept

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Abstract

The Variable Valve Systems (VVS) are emerging to exploit benefits towards improving gasoline-engine fuel economy and reducing emission. Such systems control the area, time and duration of cylinder opening. Literature review indicates that VVS are treated as an extension of existing engine valve by adding control elements in the existing system. However, extensions make valve systems complex, bulky and require additional cost. Therefore, their applications tend to be limited. This paper presents the design of variable valve systems using innovative-tribo-design concept that provides a systematic and scientific procedure. This concept provides future direction and enhances designers' creativity. The innovative-tribo-design approach is demonstrated to establish it as a comparator for upcoming variable valve systems (VVS).

Keywords: Design, tribology, engine valve, innovative design.

1. Introduction

The spark ignition engines have high specific power (power/weight ratio) and acceleration rate. However, they lack popularity due to low efficiency at partial load compared to diesel engine. The present paper describes three ways to deal with low part load efficiency and identifies variable valve system as viable mean to improve part load efficiency of gasoline engine. Further, dual role of variable valve system to save the pumping work (and improve efficiency), and efficiently deal with emission is discussed.

Many variable valve devices/mechanisms have been designed in various research labs in the past. But their applications tend to be limited because these devices are complex, bulky and incur additional cost. Therefore there is a need of a systematic design methodology for designing engine valve system that performs all required functions without increase in cost or any undesirable effect. The proposed methodology is named as Innovative Tribo-Design and is presented in this paper.

Innovative-Tribo-Design consists of three words: Innovation (current market demand), design (systematic methodology) and tribology (required to reduce friction, wear, pollution and enhance durability). Innovation leads product/process to a better technical alternative at reduced cost (financial, social, environment) to society. An index ideality is adopted to quantify innovation.

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In design of a product/process the importance of functional approach that opens up gates of creative thinking is emphasized. Concept of functional independence is adopted to identify right design function. Importance of uncouple design is exemplified. A list of guidelines is provided to avoid the tribological failure and enhance the overall efficiency. The innovative-tribo-design concept can be applied for the design of bearings [Hirani, 2009, Hirani *et al*, 2000, Hirani *et al*, 1999, Hirani *et al*, 1998, Muzakkir *et al*, 2011, Hirani, 2005, Hirani *et al*, 2001, Muzakkir *et al*, 2013, Hirani 2004, Muzakkir *et al*, 2015, Hirani, Verma, 2009, Hirani, Suh, 2005, Hirani *et al*, 2001, Rao *et al*, 2000, Hirani *et al*, 2000, Hirani *et al*, 2002, Burla *et al*, 2004, Hirani, Samanta, 2007, Lijesh, Hirani, 2015, Lijesh, Hirani, 2014, Shankar *et al*, 2006, Lijesh, Hirani, 2015, Muzakkir *et al*, 2014, Lijesh, Hirani, 2015], seals [Hirani and Goilkar, 2011, Goilkar and Hirani, 2010, Hirani and Goilkar, 2009, Goilkar and Hirani, 2009, Goilkar and Hirani, 2009], brakes [Sarkar and Hirani, 2015, Sarkar and Hirani, 2015, Sarkar and Hirani, 2013, Sarkar and Hirani, 2013, Sarkar and Hirani, 2013, Sukhwani *et al*, 2009, Sukhwan and Hirani, 2008, Sukhwani *et al*, 2008, Sukhwani *et al*, 2008, Hirani and Manjunath, 2007, Sukhwani *et al*, 2007] and gears [Shah and Hirani, 2014, Hirani, 2009].

2. Need of a variable valve system

The amount of power produced by an four strokes gasoline engine is directly related to the rate at which it can burn gasoline, therefore the engine-power is

governed by volume of fresh-air drawn into the cylinders. The general philosophy adopted in the design of four strokes gasoline engine is to design it for optimum performance under partial loads. The optimum performance under full load is achieved by other means like down sizing of the engine, providing rich mixture for combustion and using variable intake valve timings [Muzakkir and Hirani, 2015]. But each of these solution strategies suffers from one or the other drawbacks and as such do not provide a complete solution.

The valve settings required for optimum performance of a gasoline engine is dependent upon the operational speed and load. A variable valve timings system that would permit the optimum performance of the four strokes gasoline engine under the changing requirements of speed and power is identified to be the best possible solution.

The apprehensions about atmospheric pollution have been rising since 1970. As per EURO-IV standards, allowable limits for HC and NOx emissions are only 3% of the values of 1970. Conventional engine with constant valve timings supported by catalytic converter cannot handle such stringent emission requirements. However, a promising possibility is the combination of fully-variable inlet and exhaust systems with a catalytic converter. To sum it up, an engine needs controllable opening and closing of cylinder ports.

The present paper introduces the concept of innovative-tribo-design. The aim is to design an innovative valve-assembly that is easy to control valve functions, but is robust against environmental conditions (temperature, wear, etc.). The design requirements for valve systems are considered from a scratch. Various valve configurations are analyzed to demonstrate the concept of innovative-tribo-design and establish this methodology as a comparator for upcoming variable valve systems (VVS). Finally a concept of VVS is suggested that includes minimum number of moving parts, consumes minimum power loss, and provides full flexibility to actuate the valve. The proposed valve system has lesser inertia, lower noise, and higher sealing capacity.

3. Innovative Tribo Design

Innovation is useful to the society. It may be combination of two existing inventions, mechanism saving human efforts, application of new technology in old invention, or serendipity. Innovation is technically a new and useful solution to a problem faced by society. It requires creativity. Creativity is basically related to unlocking imagination. Sometimes it is termed as breaking psychological inertia. Open mind is receptive to ideas from any and all sources. Therefore innovation can be defined as a process by which an invention or idea is brought into successful practice and is utilized by the economy.

Innovation can be quantified by increment in the ratio of benefits to cost ratio. In theory of inventive

problem solving, this benefit to cost ratio is termed as ideality and is defined as:

$$I_{\text{ideality}} = \frac{\sum \text{Useful Functions}}{\sum \text{Harmful Functions} + \sum \text{cost}} \quad (1)$$

Useful functions are desired functions from a product, system or process. Harmful functions include undesirable functions such as: weight, friction, misalignment, noise, vibration, wear, etc. As every harmful function costs the society, it is necessary to account it.

Equation (1) indicates a functional approach to the make a product, system or process innovation. It is a key concept in opening the doors of creativity. Often problems are stated in terms of geometrical shapes, or physical entities, which provide biased solutions. However, functional thinking provides a room for creative thinking to accomplish useful functions in a neutral environment. For example, if one thinks on improving part-load-efficiency of a four-stroke-port-fired-spark-ignition, he/she is committing a mistake by even thinking about a physical entity, spark ignition engine. Options of using engines such as diesel engine, direct ignition engine and/or gas turbine, will never even cross his mind unless he starts thinking out of the box. Similarly, to design a variable valve actuation one might think how to improve the classical camshaft-poppet valve system to make it suitable for variable valve -timings, -lift and -duration. This type of thinking is a classical engineering thinking and restricts creativity, and also innovation. However, pondering over control on cylinder opening and control on cylinder closing forces a designer to search out of the box, generate more creative solutions and select the best among the feasible proposed designs.

3.1 Approaches to Improve Ideality

Improving ideality (Eq. 1) is the prime objective of the designers. Increasing useful functions, reducing cost and other harmful functions always brings out successively better product/process/material. Equation (1) provides a wide design scope. It can be used for an existing design or applied for a new design. The concept of innovative-tribo-design enhances ideality to a greater level and makes products/processes novel. Outcome of this approach is substantially distinct from already known solutions. This approach not only improves the useful functions but also cuts down cost and harmful functions. This approach seems to be impractical, however TRIZ suggests making it practical by overcome one or more contradictions. Contradiction matrix, utilizing forty inventive guidelines, is often used to resolve the contradictions. For example, it is an accepted/ a proven fact that increasing velocity increases wear rate. However, higher speed but lesser wear-out is always preferred. So there occurs a contradiction. If one tries to enhance useful function (increasing velocity),

harmful functional (wear rate) is also correspondingly increased. To solve this contradiction TRIZ suggests four guidelines:

- (1) Preliminary action: Protective layer covering the rubbing surfaces,
- (2) Reverse action: useful to reduce erosive wear.
- (3) Mechanical Substitution: By using hydraulic, pneumatic, electric, magnetic or electromagnetic field to separate two surfaces, and
- (4) Strong oxidants introduction: By making/inducing oxide lubricant layer immediately before virgin soft surface is exposed to wear prone environment.

3.2 Deciding Functional Requirements and Constraints

It is always important to start designing by identifying a right problem. Problems are often recognized by voice of customers and house-of-quality. Many times new directions to identify problem emerge from creative mind watching the way people react or even adjust the available product/process. For example one may feel the need for: (1) Intelligent parking system for cars, (2) Headlight which turn with car steering angle, (3) Self eye drop dispenser for old people, or (4) Automatic book scanner. Once the problem is identified, one needs to decide on an approach to attack the problem. If one chooses to develop a completely new product/process for certain specified functional requirements, when the old one is not yet exhausted/matured (Fig. 1) in its development, then acceptance by industry/society will be very harsh and long.

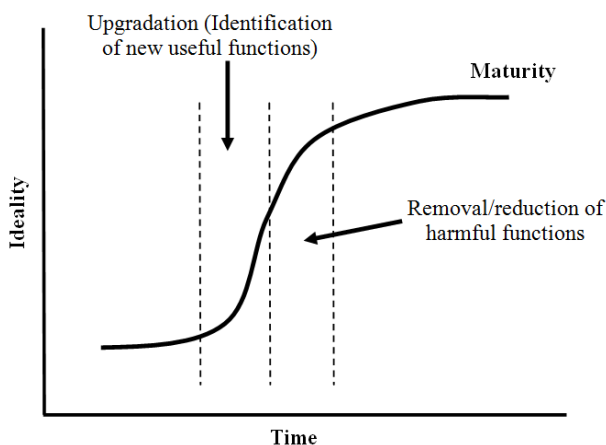


Fig. 1: Improvement in Ideality with Time

As per Altshuller’s patent survey only 20 percent of patents fall in the novel approach category. Remaining eighty percent patents are shared between upgradation and optimization approaches. Optimization approach, which is very popular in the industries, requires a domain specific knowledge and it is more analysis oriented. Depending on the availability of time, resources, and market demands; one needs to decide one the aforementioned three

ideality improving approaches. Decision on the functional requirements and constraints can be worked out based on the selected approach. For example if one decides to work on novel approach he/she will develop a number of solutions using creative design methods (such as substance field analysis, forty inventive principles, lateral thinking, etc.). Such solutions need to be checked for minimum cost and harmful functions, and maximization of useful functions. Choosing second (upgradation) approach keeps constraints on the cost, harmful functions, and old useful functions; while requires addition of new functions. Once the approach to improve ideality has been identified, one needs to explore proper selection of functions and corresponding solutions. The concepts of functional independence and uncoupled design described in axiomatic design are powerful means to improve ideality.

In axiomatic design approach there are two fundamental axioms that govern the design process. The first axiom, named Independent Axiom, states that the independence of functional requirements (FRs) must always be maintained. This independent axiom can be explained in two stages. In the first stage, selected functions need to be independent from each other. To understand function independence, let us consider two cases:

- The temperature rise ($\Delta T=f_1$) and flow rate ($Q=f_2$) as two objective functions for bearing optimization. The temperature rise (ΔT) is function of power loss (W) and flow rate (Q), which means $f_1 = \text{func}(W, f_2)$. Therefore, the objective function maximizes and minimizes flow rate. This leads to an introduction of artificial contradiction.
- Hirani [2004] considered $W(=f_1)$ and $Q (=f_2)$ as two objective functions for bearing optimization. Therefore Hirani’s [2004] objective functions satisfy function independence.

Second stage of independent axioms is one DP for one FR. To exemplify this concept let us consider a designer who is working for a company which produces only port-fired-gasoline-engines and he/she is given the task to improve part-load-efficiency of such engine. The designer is free to design any engine that operates on four-stroke-cycle and uses port-fired-gasoline. In such a case, the designer needs to maximize efficiency at idle condition f_1 , low load f_2 , medium load f_3 , and full load f_4 , which are functions of speed and torque. The functional requirements can be set as: FR_1 (Maximize efficiency at idle condition), FR_2 (Maximize efficiency at low load condition), FR_3 (Maximize efficiency at medium load condition) and FR_4 (Maximize efficiency at full load condition). Here, all four functional requirements are independent. The requirements for four physical parameters (they may be components, geometric parameters, or control strategies) that maintain the independence of FR_1, FR_2, FR_3 and FR_4 are now considered as solution (say Solution A) by

assigning four cylinders DP₁, DP₂, DP₃ and DP₄ to satisfy FR₁, FR₂, FR₃ and FR₄ respectively. Here DP₁ is smaller in size compared to DP₂. Similarly DP₂ is smaller than DP₃. This solution indicates that the engine operates on: DP₁ cylinder for idle operation, DP₂ cylinder for low load condition, DP₃ cylinder for medium load condition and DP₄ cylinder for full load condition. At first sight this solution appears to be an ideal solution, as there is no contradiction and every function has a separate solution, which can be maximized individually. However, the concept of ideality (Eq. 1) indicates high overall cost, material utilization, and engine weight that reduce the product ideality. Therefore, one needs to think of a different solution.

Independence of functions from each other not the physical parts is the requirement of independent axiom. Therefore one can think of solution B, which assigns only one cylinder (of capacity equivalent to that of DP₄ of solution A) for all four FRs. This cylinder has three additional geometric parameters which change the volume of cylinder. In other words to satisfy: FR₁, volume of cylinder is made to DP₁, FR₂, volume of cylinder is made to DP₂, FR₃, volume of cylinder is made to DP₃, FR₄, volume of cylinder is made to DP₄. The variable volume of cylinder in solution B may be referred as variable stroke cylinder, variable compression ratio cylinder or a cylinder with variable EGR. The variable compression ratio approach can be implemented by tilting the Monohead relative to the crankcase. Ideality of solution B is better than ideality of solution A. Let us note here that both the solutions satisfy the independent axiom.

In general, large diameter cylinders are used where greater emphasis is on the reliability, durability (minimum cylinder wear), and fuel-economy. In automotive engines power to weight ratio is very important. In automotive applications, large single cylinder is not only detrimental in the view of knocking, weight, vibration, noise, and crankshaft balancing; but also is difficult to fit in a small vehicle demanding large power. To reduce these harmful (undesired) effects, the solution B needs modification. Let us think of solution C that provides four cylinders of same volume capacity for four FRs. Designing same capacity cylinders reduces the manufacturing cost and helps in engine balancing.

In solution C, FRs and DPs relation can be expressed as:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \tag{2}$$

(2)

Equation (2) states dependence of FRs on DPs. To satisfy FR₁, DP₁ is sufficient, whereas FR₂ requires DP₁ and DP₂. FR₄ depends on all four DPs. This type of design is termed as decoupled design. To illustrate the

concept of uncoupled and coupled design, let us consider two functions f₁ and f₂ that need to be minimized. If both the functions are independent, then these functions can be minimized individually. However, if functions are coupled, and they have contradictions, then minimization will always be a compromise. Figure 2, indicates that lesser the dependence of functions, better the optimum solution.

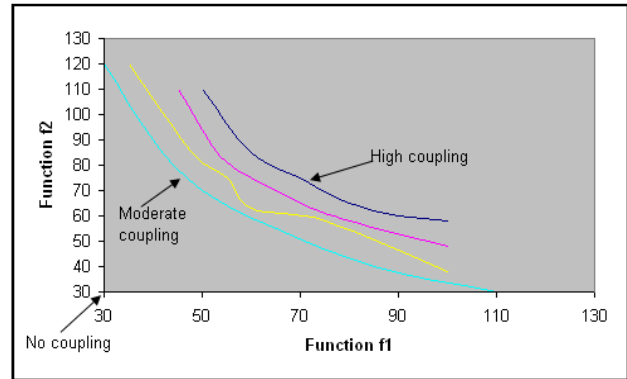


Fig. 2: Coupling vs. uncoupling

Further uncoupling is very essential for future development of the concerned product/process. A coupled design may work, but improvement due to change in technology, customers' views, economics, failure analysis, safety and health issues, or environmental protection will be required in future. Because of coupling, even small essential improvement may require whole-redesign of system, as improvement in one sub-system might create harmful effects in other sub-systems. Repeated redesign of whole system will be costly and time consuming. Therefore a good design needs to have minimum coupling. To reduce coupling, off-diagonal terms in design matrix of Eq. 2 should be as low as possible. So there is a further need to improve solution. However, careful examination of FRs indicates that only one FR is active at a time. There come the concepts of separation in time of TRIZ and multi-functionality. Here DP₁ can be made suitable for FR₁ at time t₁, suitable for FR₂ at time t₂, appropriate for FR₃ at time t₃, and fit for FR₄ at time t₄. Such a multi-functionality is obtained by variable spark timing, variable amount of fuel injection, and variable valve actuation system. If DP₂ and DP₃ also have such multi-functionality, then solution C is an innovative design solution. In automotive industry solution C is referred as Cylinder Deactivation. Such process of cylinder deactivation may improve fuel economy from 7 to 14%.

3.3 Quantifying Ideality

Once the designer is convinced about proper design strategy (Approach 1/2/3), independence of functional requirements, and uncoupled design, he/she can generate a number of solutions. There are numeral creative design methods such as: brainstorming, synectics, forty invention guidelines of TRIZ, 76

standard solutions of TRIZ, etc. These methods try to increase the flow of ideas and widen the area in which a search for solutions is made. In short, creative design methods help to generate a number of systems that satisfy the functional requirements. Larger the number of required functions, the larger is the number of concepts generated. Obviously, not all concepts will lead to a high ideality. Therefore there is a need to quantify the ideality that helps to evaluate different concepts.

Equation (1) indicates a better product will have high value of useful functions and low value of harmful functions and lower cost. Generally units of different useful/harmful function are different so there is a need to look for a common scale which can be utilized for all functions and cost. For this purpose, four methods can be proposed:

1. Elimination method
2. Utility method
3. Method based on Information Content
4. Rank based multiobjective genetic algorithm [Hirani, 2004]

In elimination method, design concepts are short-listed based on the minimum essential requirements. For example, essential FRs for an engine valve are (1) open the port, (2) regulate flow area, (3) minimize back flow, (4) seal the port, and (5) minimize variability due to temperature, wear and misalignment. Now if one considers a rotary valve, a single valve body may be used to inhale fresh air and exhale combustion products, but four apex seals are required to avoid back flow. The successful design of seal, is itself a complex and a modified design concept is required. This elimination method provides a go and no-go procedure. For quantification, one needs a better method.

Utility method is one of the most common techniques used for evaluating the concepts. It is very simple to understand and implement. For example to quantify fuel consumption (negative function) based on 10 point scale, ten points can be given to design concept that consumes maximum fuel and one point can be allotted to sound concept that consumes minimum fuel. Similarly if function is to improve service life, then one point can allotted to the concept that bears minimum service life, while maximum points (ten points) can be given to the concept which predicts longest service life.

As not all the design features are of equal importance, therefore this method provides weighting factors for each design feature. To reduce the subjectivity, often a digit logic method is used, where all properties are compared among each other, but two properties are taken into consideration at a time. Among the two, the more important property gets value of 1 and the other gets a value of zero. To exemplify this method, let us consider an example of ring spinning textile machine [Basu et al, 2001]. Components of this machine go through unlubricated

sliding friction at low load but high relative speed (20,000 rpm). For design of better interface, five FRs were identified (1) increase hardness, (2) reduce surface roughness (3) reduce cost (4) improve adhesion to substrate and (5) reduce increase in dimension on surface treatment/coating. Basu et al [2001] compared design requirements in the following way:

Table 1: Identifying weighting factors [Basu et al. 2001]

Design property	Hardness	Roughness	Cost	Adhesion	Dimension	Weighting factor
Hardness	-	1	1	0	1	0.3
Roughness	0	-	0.5	0	0.5	0.1
Cost	0	0.5	-	0.5	0.5	0.15
Adhesion	1	1	0.5	-	1	0.35
Dimension	0	0.5	0.5	0	-	0.1

Five methods were identified to fulfill the required functions (1) Plasma sprayed Al₂O₃ (polished), (2) carburizing (3) nitriding (4) boronizing and (5) plasma sprayed Cr₂O₃ (polished). Basu et al [2001] showed (as shown in Table 1) that boronizing was a better option compared to other surface improvement methods.

Table 2: Coating selection [Basu et al. 2001]

Surface improvement method	Hardness	Roughness	Cost	Adhesion	Dimension	Weighted total
Weighting factor	0.3	0.1	0.15	0.35	0.1	
P S Al ₂ O ₃	9	2	5	5	3	5.7
Carburizing	4	7	7	8	8	6.55
Nitriding	4	7	6	8	8	6.4
Boronizing	8	7	5	9	7	7.7
P S Cr ₂ O ₃	10	1	4	5	3	5.75

Major drawback of this utility method is subjectivity. One designer can provide four points to one concept and other designer may provide seven points to the same concept. Therefore there are always chances of misinterpretations.

To avoid this subjectivity, Information Axiom, based on the probability can be used. As per this axiom the design concepts can be quantified in terms of the probability of achieving the design goals (Maximizing useful functions, minimizing harmful functions). Superiority of concept is judged based on information content, which is expressed for negative function as:

$$I_i = -\log_e P_i = -\log_e \frac{\text{Allowable range}}{\text{Offered range by concept}} \quad (3)$$

As per Equation (3), if allowable range of noise level is 30db and design concept A is generating 35db, while design concept B is generating 29 db, then information index for concept B is zero, while information content for concept A is 0.154. Similarly if \$100 are permitted for a product, then design A provides product in \$105 and design B provides in \$125, then $I_A = 0.048$, and $I_B = 0.223$. However, in the case of useful function reverse of Equation (3) will be used, such as:

$$I_i = \log_e \frac{\text{useful function offered by concept}}{\text{Minimum requirement}} \quad (4)$$

Now if 70% is minimum requirement for mechanical efficiency, then design A with 75% efficiency and design B with 90% efficiency, will get $I_A = 0.069$, and $I_B = 0.251$. This evaluation method is certainly better than utility method in reducing the subjectivity. However, it is very difficult to get offered range by the concept, without detailed design. Therefore it will be advisable to use utility method at the start of design. As design converges to lesser number of solutions, then method based on the concept of information content can subsequently be used.

Rank based genetic algorithm [Hirani, 2004] is a versatile tool to evaluate the various designs. This method explores a set of equally efficient, or non-inferior, alternative design solutions, known as Pareto Optimal Set. A design concept x_i for minimization of two negative functions (W and Q) is treated as non-inferior if the following conditions are fulfilled:

$$W_i \leq W_j \text{ and } Q_i < Q_j \\ \text{or} \\ W_i < W_j, \text{ and } Q_i \leq Q_j$$

Major advantages of this method are:

1. It is based on Pareto optimal concept and does not require weight factors to show importance of one function over another as used in Utility method.
2. It does not require normalization of concept range with allowable range, as used in Axiomatic design.
3. Further, it provides whole range of non-inferior solutions (a set of equally efficient). This is very useful particularly when there is no unanimous decision on importance of one function over another. For example in United States, pollution control on CO₂ is flexible while it is stringent in Europe and Asian countries.

However, this rank based method is computation intensive and requires sound understanding of system and its modeling. Therefore this method is recommended at final stage of design.

3.4 Convergence based on Tribological Principles

Concepts and illustrations covered in previous pages were related to innovative-design. There is another stream, named as Tribology that needs to be merged with innovative design. Tribology is the science and technology of interacting surfaces in relative motion. The principles of tribology essentially require minimizing wear and friction between relatively moving components. However some tribo-elements require controlled friction, such as: brake, clutch, wheels, shoes, etc. Wear is a failure mechanism, and usually associated with the loss of material due to contacting bodies in relative motion. Durability can be enhanced by avoiding or delaying failures occurring in service, by better incorporation of tribological principles into innovative-design. As there is a continuous demand of reliability of useful functions, such as SULEV standards require an increase in durability from 80,000 to 240,000 km, there is a need to bring the tribology at the conceptual design level. Knowledge of friction, wear and lubrication can be used to generate tribological compatible solution

Design of machine components using tribological knowledge reduces the chances of excessive friction and frequent wear failures. Further, it help in generating a number of design solutions which turn out to be better. To illustrate this, the author wants to quote some examples:

- (1) A company X, decided to design air-circulators for paint shops. Length of two meters and diameter of sixty centimeters was designed for rotor of air-circulator. Company X wanted to design suitable bearings that consume minimum power, and sustain rotor load. When one of the authors studied the air-circulator from innovative tribo-design point of view, he found rotor length could be reduced from 200 cm to 140 cm by relocating the drive-motor. Reduction in length of rotor itself solved the problem.
- (2) A company Y increased speed of diesel engine without considering its effect of lubrication system. As a result crankshaft and its six bearings failed in no time.
- (3) A structural design of hydrodynamic bearing subjected to dynamic load, such as engine load, results in larger bearing dimensions compared to dimensions of bearing subjected to static load of same magnitude. In reality it happens in reverse. Bearing dimension under engine load is smaller than dimension of bearing designed under static load.
- (4) Let us consider following examples of cam-follower design, where lack of tribological knowledge caused early failure:
 - a. Cam-nose radius of 8 mm vs. 15.28 mm: As per common structural design, cam with larger nose radius, that reduces Hertzian stress, was designed. However, better results were shown by smaller

cam-nose radius. In actuality, reduction in cam-nose radius increases the relative velocity and provides thicker film that operates satisfactorily whereas large nose radius reduces relative velocity, provides thinner film and fails prematurely.

- b. Direct acting overhead cam. Usage of direct acting cam mechanism is favored as it reduces the number of linkages. However due to unavailability of suitable lubricant, there were a number of cam failures. Now with help of tribological knowledge failures are decreased.

Therefore, a designer should consider tribology from the very start of the design process. Unfortunately, friction and wear are statistical in nature and variation in results is significant. It is because tribology between two mating surfaces depends on several variables: material properties, nominal contact stress, relative sliding velocity, ambient temperature, reactivity of environment, humidity, geometric parameters, distance traversed, etc. There is no established wear equation available that accounts the design parameters and predicts reliable wear rate. Wear data, published in various books and papers do not provide sufficient details that can be used by designer. Quoting Ludema's words Overall, it is probably accurate to say that there is little incentive for a designer to use any of the wear-equations available in the literature. A scan of many wear models shows considerable incongruity. Equation have either too many undefined variables or too few variables to adequately describe the system. So where does the designer go when he/she knows that waste of resources resulting from high friction and wear is as much as one-third of all useable resources. The potential savings offered by improved tribological knowledge will correspondingly be great.

As per author's understanding designer should keep following tribological key points at conceptual design level:

1. **Minimize number of tribo-pairs:** It is always better to keep choosing design solutions (DP) that incorporate minimum number of sliding pairs as one of evaluation criterion. To elaborate this let us consider Fig. 3 that indicates two components, bridge and base plate, of a car's safety belt on left hand side figure, will integrated base-plate and bridge on the right hand side figure.

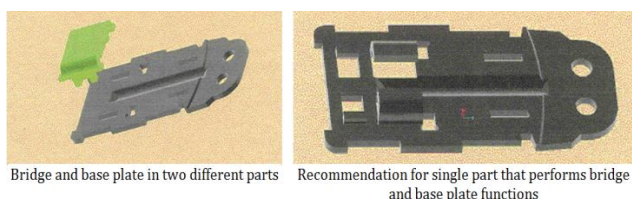


Fig. 3: Minimizing Tribo-pair

During test run, around ten percent failures occurred due to unlocking of bridge from base plate. This

resulted due to slight wear of bridge that had reduced the friction between bridge and base plate. Author suggested integration of bridge with base plate using minimization of tribo-pair strategy. However the suggested design was little difficult to manufacture, yet it was manufactured. The overall cost of integrated bridge-base plate turned out to be lesser than original two-component design and failure due to unlocking of bridge from base plate was eliminated. Similarly failures due to bolted connections are enormous.

2. **Design for Minimum wear:** If it is difficult to avoid tribo-pair (due to significantly high manufacturing cost, essential requirement of relative motion, excessive stress level on other components, etc.), then one needs to think about design for minimum wear. Wear can be defined as a change in the surface contour, such as a groove formed in the flat surface or a flat spot produced on a curved surface. Zero wear is a change in the surface contour of less than or of the same order as the surface finish. Concept of zero wear is important from the durability point of view, and defined for a specified time. For example, in boundary lubrication there will be continuous contact in tribo-pair, therefore their life of tribo-pair is defined in number of operating hours. However, in journal bearing material contact occurs at the start and stop of bearing, therefore life is defined by number of start/stop activities.

Wear can be minimized by choosing proper geometry, material pair and lubrication mechanism. Surface roughness has significant effect on friction and wear of tribo-pair. Minimum peaks and ability to retain lubricant for long time are two essential requirements to keep wear and friction with prescribed limits. Tribo-material may be single bulk material, coating on structural material, or multilayer. Layer, covering the rubbing surface, is frequently used in protecting its substrate from wear. The tribological function is assigned to the layer and the structural strength is provided by the substrate material. Further, lubrication mechanism can be solid, boundary, elasto-hydrodynamic, hydrodynamic or aerodynamic. Generally degree of wear decreases from solid lubrication to hydrodynamic lubrication. Elasto-hydrodynamic lubrication, where deflection within elastic limit helps to support large imposed load, is one of recent tribo-design concept. This concept can be exploited to achieve minimum friction, wear and lubrication.

3. **Trimming of secondary functions:** Secondary functions are generally required to help primary functions. These functions are often dependent on the physical entity/parameter selected to fulfill the primary functions. To exemplify, let us consider the valve guide, shown in Fig. 4.

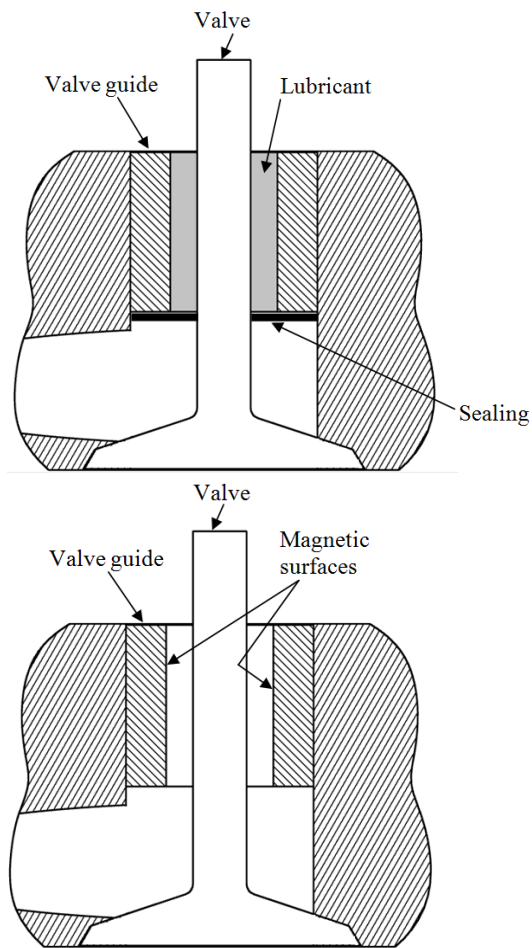


Fig. 4: Valve guide

This valve guide is required to support and align the reciprocating movement of poppet valve. Relative motion between the valve and valve-guide generates friction. To reduce this, one needs lubricant. To prevent lubricant going in the combustion chamber, one needs sealing. If lubrication can be trimmed, then there is no need of lubricant-seal. In such a case magnetic repulsion can be exploited to guide the valve.

4. **Self service/help:** Many times it is difficult to minimize the number of tribo-pairs, use zero-wear concept, and avoid secondary functions, to yield a competitive product. There the concept of self service provides a rescue operation. Due to wear and friction, the system range changes with time. Such a problem was showed by agency EPA in 1990, where about 60% of the unburned hydrocarbon emissions from vehicles were caused by gasoline vehicles with a faulty exhaust gas after-treatment system. Due to these findings the EPA demanded that all engine control systems should be equipped with a self-diagnostic system that indicates a malfunction to the driver. Self service concept means the problem resolves on its own. Sealing and cleaning between poppet valve and its seat are based on the concept of self service. Figure 4 shows the interface geometry of poppet valve and seat. Sealing between the valve and

seat improves with increase in pressure at poppet disk face. Similarly Fig. 5 shows self-adjusting feature of piston ring.

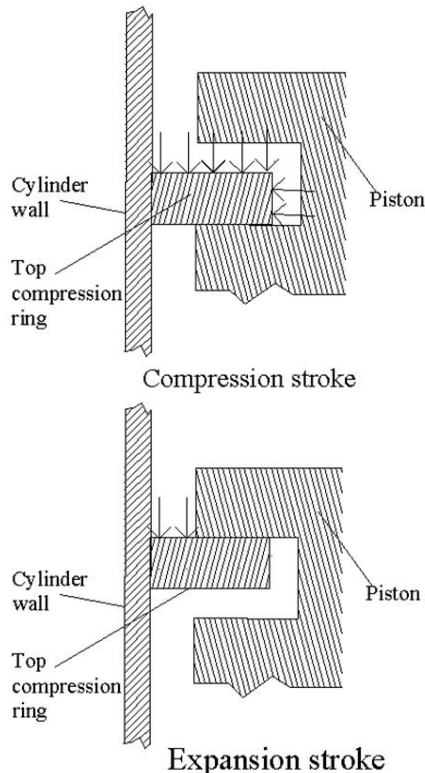


Fig. 5: Self adjusting featuring of piston ring

This can be termed as self sealing. Similarly geometry of seat and valve is made in such a way that two surfaces crush any interfering porous and brittle combustion product and remove it from the interface. This can be called as self-cleaning action. Self service concept always improves the value of ideality.

5. **Eliminatory tribological analysis:** It is necessary to know whether tribological contact is conformal or nonconformal. Stress levels are very high in nonconformal tribo-pair and design needs to be oriented towards resistance to wear, while conformal surfaces are designed to minimize the friction. Further, friction and wear are localized surface effects and properties of tribo-surfaces influence the overall tribological behavior. Therefore there is a need to consider tribo-materials along with structural materials. The primary function of a tribo-material is to control or modify friction or wear behavior in an engineering application. A hard-hard pair is preferred for design for wear resistance, while hard-soft pair is favored for minimization of friction. The effective tribo-surfaces are very shallow, but sufficient to affect the wear resistance and frictional behavior. Increase in the thickness of soft friction-reduction layer reduces the structural strength, while thicker wear-reduction hard layer reduces the toughness of machine component. Therefore, thickness of these tribological layers is a trade off

between bulk (structural) and surface (tribological) properties. As far as possible selected tribological materials need to be anti-corrosive in nature. Slight corrosion may initiate whole chain of tribological failures. Eliminary analysis generally uses empirical and curve fit equations, and common sense to predict the geometries and materials for tribo-pair. Figure 6, shows a bearing failure, which was analyzed using eliminary equations. Two four row brass cage type bearings failed catastrophically within 250 to 400 hours of their operation.

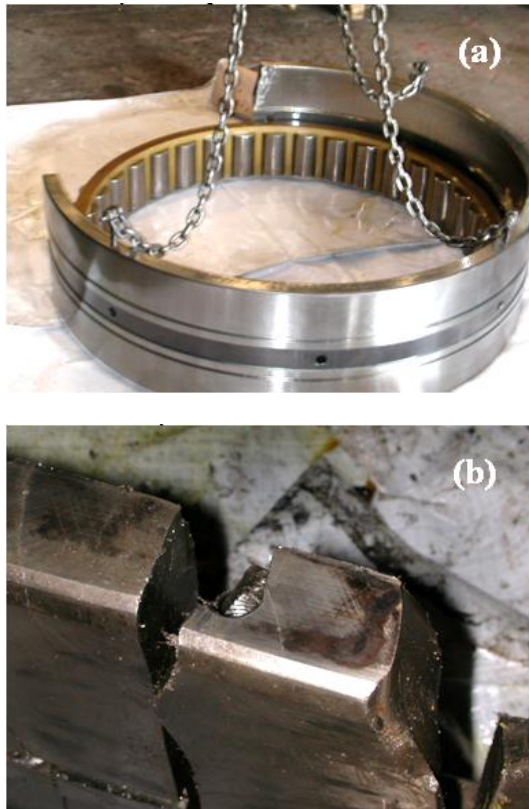


Fig. 6: Failed Roller bearing [Hirani, 2009]

Bearings were designed for 40,000 hours operation. Mist lubrication, with oil viscosity of 470 cSt at 40°C and 31 cSt at 100°C, was used. Four threaded holes of 9.5 mm in dia and 45mm length were used to handle the outer race. As figure 6(a) indicates one fourth of outer race was damaged. Mostly in rolling element bearing only one fourth of race is loaded. Therefore elementary analysis indicated either there was problem of overload (twice of the designed load) or some assembly problem. Tolerances between chock and outer race were examined and found as per design. However, because of misinformation, wrong assembly hole (designed for material handling) was subjected to maximum load (as indicated in Fig. 6(b)). Presence of hole directly in concentrated load reduces axial length and thickness of outer race. The effective load turned out to be twice the design-load and bearing failed under such a severe load condition.

6. Detailed tribological analysis: Once the geometry and materials for tribo-pair is tentatively decided, detailed tribological analysis and testing can be performed. However, tribological solutions are computationally intensive, and the testing (on actual assembly or simulation test rig) is expensive. This step is generally adopted just before final decision of product/process design and can be avoided at the conceptual level. Detailed tribological analysis is more useful for predicting and testifying the tribological failures.

Conclusions

The concept of innovative-tribo-design is presented. This concept is applied for the design of the variable valve syatem for an four stroke gasoline engine. The main advantage of this concept is that it enhances the ideality of the system to a greater level and makes products/processes novel. In summary, value of new or old product/process can be enhanced by targeting high ideality, choosing appropriate design strategy, identifying independent functions, generating a number of design concepts based on functional, uncoupling and tribological approaches.

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