Chapter

Role of Bearings in New Generation Automotive Vehicles: Powertrain

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Abstract

Modern Automobile powertrain's technology is transforming to enable "connected, autonomous, shared and electric" (CASE). Modern automobiles are targeting to achieve the maximum vehicle uptime, utilization, and better total cost of ownership (TCO). Bearing is a vital component (sub-system) to achieve modern automobile's performance targets. Bearings plays important role of performance enhancement of all the rotating parts in systems by carrying the load and facilitating transfer of torque. Bearings achieve its performance via correct selection of materials, manufacturing technologies, design optimized geometries, sealing, lubrication in addition to application specific features. In modern automobile passenger comfort is key consideration and role of bearing is critical to achieve lower system noise. This chapter focuses on building awareness of the bearing technical requirements for different aggregates and means to achieve the requirements for modern automobiles. Summary of 11,300 patent's titles and customer voice analysis suggest the bearing development focus areas direction which are covered in this chapter. This chapter also introduces bearing technology research focus areas like reliability improvement, power-dense solutions, integrated functions, friction optimization, sealing/lubrication solutions, adoption of sensors, and also special application-specific eMotors bearings. Modern electronic technologies integrated with bearings are performing the critical role of powertrain health monitoring in the vehicle. However, bearings are having furthermore potential to contribute and enhance the performance of modern automobiles in near future.

Keywords: electric vehicles, bearings, power-dense, sensorization, NVH, capacities, integrated functions, friction, electric insulations

1. Introduction

Modern automobiles have made a significant contribution to the growth of society and humankind. Automobile vehicles and power train technology refined over the century of focused hard work by automobile engineering and scientist. Modern internal combustion engine propelled automobiles have satisfied multiple needs humankind in everyday life. It is difficult to imagine a world without automobiles in the present time [1]. The contribution of bearing to enhance the performance of automobiles is also immense. Bearings play's a critical role in the enhancement of any rotating systems performance by bearing loads and facilitating the load transfer

with minimum friction in addition to other functions. All rotating components of automobile systems require bearings to do its functions appropriately. Bearings improve the performance of the automobiles by supporting heavy loads and reducing friction. Major automobile sub-systems where bearings are implemented are internal combustion engines, transmissions, wheels, steering, pumps, and other electrical systems.

However, the popularity of automobiles, population density in the urban areas as well as rapidly growing urbanization has negatively impacted the environment. It raised health-related concerns to humans as well as other habitats. Internal combustion engines played the critical role of being prime mover for automobiles however, it is also a major source of pollution in urban areas due to the burning of fossil fuels and its by-products like CO2, NOx, etc. In recent times focus on emission control from regularity bodies, country specific laws are increasing which is pushing researchers to look for solutions beyond internal combustion engines. In recent times electric powertrains, hybrid powertrains have already proven to be the strong alternatives to conventional engines.

1.1 Mega trends in automotive industry

Present time, the global automobile industry is focusing on clean transportation solutions including hybrid and battery electric drives. Automobiles are typically considered person-driven, personal transportation internal combustion engine (fossil fuel) propelled and independently operated transportation medium. In present times automobiles (passenger vehicles) are majorly part of personal transportation, however, incoming times the way automobiles are being utilized in practice is transforming toward shared mobility, autonomous vehicles.

The automobile industry is experiencing a major technology shift. Connected, Autonomous, Shared, and Electrified (CASE) are major technology trends in the automobile utilization and technology development (**Figure 1**).

Shared mobility is more of productive utilization of vehicle and related technology which connects vehicle or operator via internet-based communication for sharing the vehicle. Basically, vehicle ownership and utilization are extended for more productive utilization vehicle. Modern information technology, internet, and availability of electronic hardware making it feasible to ensure vehicle to vehicle, vehicle to device communication, and improve vehicle utilization to improve the uptime of vehicles. Modern automobiles are expected to utilize to its maximum potential, so it is becoming imperative to monitor the health of the system in real-time.

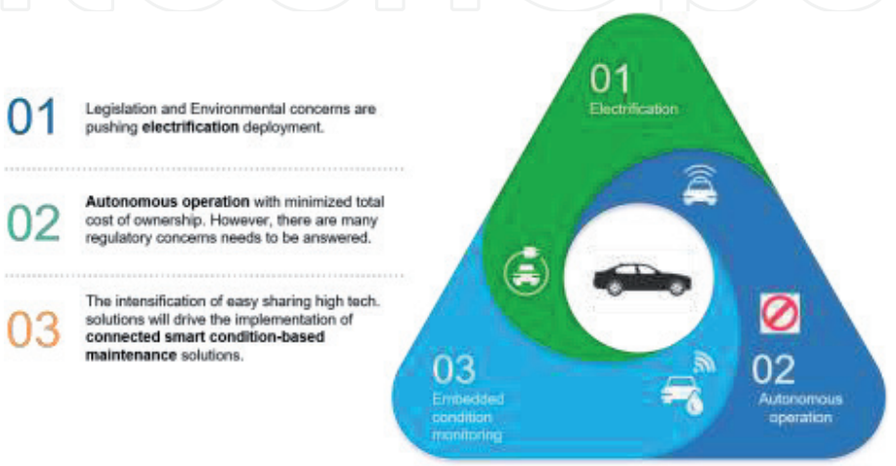

Figure 1.
Mega trends in automobile industry.

The electrification of the powertrain is another megatrend in the automobile industry. The electric vehicle powertrain is a major shift from fossil fuel-based prime mover (engine) to battery operated electric motors as a prime mover. Electrified vehicles are more efficient, less polluting making it a more transportation friendly solution. Electrification of powertrains is a major technology shift in which the propulsion of vehicles needs a lesser number of rotating parts as well as it simplifies the complete powertrain. Electric powertrains operate at lower cost as well.

In the present time, commuting to work in dense traffic is putting additional stress on vehicle operators and waste of precious productive time. Autonomous operation is the solution to these new challenges. Automobiles are using more electronics hardware than ever before due to these added functionalities. Driver assisted operation as well as complete autonomous drive powertrains are implemented in practice in modern automobiles. Real-time health monitoring of vehicle is important for the trouble-free operation as well as the safety of passengers in modern era vehicles.

As the automobile powertrain technologies are changing it is also percolating to critical components/subsystems like bearing. Modern vehicle bearings are far refined and technologically superior compare to traditional automobiles bearings. They are having multiple additional functionalities over the primary bearing functions. This chapter is about understanding the role of bearings in modern automobiles vehicles to achieve the mega technology shift in the automobile industry. The subsequent text introduces bearing technology research focus areas like reliability improvement, power-dense solutions, integrated functions, friction optimization, sealing/lubrication solutions [2], adoption of sensors, and also special application-specific eMotors bearings.

1.2 Modern automobiles powertrains and its significance

Modern automobile powertrains are working on the same engineering principles however, they are having far superior performance compare former powertrains. Modern powertrains are an integrated mechanical, electrical and electronics system to achieve the objective of lesser emission, better fuel efficiency, and higher overall efficiency. The modern powertrain can be classified into two major categories: Hybrid powertrain and battery electric powertrain.

Hybrid powertrains are having dual power sources like internal combustion engine and motor + battery arranged in multiple layouts like parallel, series, balanced, etc.

Figure 2 is a typical layout of a hybrid powertrain. It can be observed in the figure that the complete powertrain is having all the systems of a conventional powertrain including an internal combustion engine, transmissions and additionally it is also having a battery and motor to support the vehicle propulsion.

In a hybrid powertrain number of bearings are more compare to the conventional powertrain. The bearings are used in the engine, transmission, motors, and transfer case. The hybrid powertrains are having more rotating parts however, this powertrain runs efficiently as all special events in operations like peak power requirements are fulfilled by the battery powered electric motor.

Full battery-electric vehicle powertrains are simpler in construction and having lesser rotating components. Battery electric vehicle powertrains are also having multiple configurations like traction motor + transmission, independent in-wheel motors for each wheel, etc.

Figure 3 is a typical layout of a battery-electric powertrain, in which it is having a floor-mounted battery pack and traction motor drive for driving the wheels. Compare to conventional ICE vehicles this layout is simple and efficient. A lesser

Figure 2.
Typical hybrid powertrain layout [3].

Figure 3.
Typical full battery electric powertrain layout [4].

number of rotating parts means there are lesser possibilities of parts damage due to wear and tear and hence the system life is higher. This is one of the reasons Battery Electric vehicles are claimed to have higher life as well as OEMs offers longer warranty period. However, electric vehicles are having other challenges like higher speed, higher operating temperatures of parts, and risk of fire due electric system. It is important to mention here that batteries used in electric vehicles need proper cooling to operate at prescribed temperature limit to have extending time for battery discharge as well as minimizing other risks.

Refer **Figure 4**, which is indicating the battery packs construction in battery electric vehicles and its stacking, connection to electric motors.

Figure 4.
Typical battery pack in battery-electric powertrain [5].

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1.3 Different types of powertrains

In the previous section, two main types of the modern powertrain are discussed i.e. hybrid power train and full battery-electric powertrains.

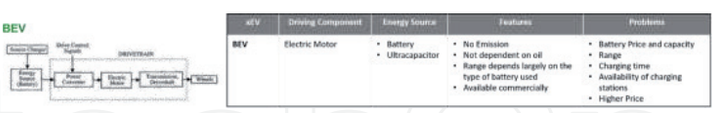
In this section, a comparison of different types of powertrains is presented (refer **Figures 5**–7).

Multiple parameters influence the selection of the powertrains types to implement in the vehicle such as vehicle operating range, power requirements, charging time, cost, availability of access to charging infrastructure, etc.

Battery electric vehicles powertrains (refer **Figure 5**) are comparatively simples in the structure. These vehicles operate very efficiently. However, they need significant time for the recharging so the vehicle will be down until it recharges. It is expensive to increase vehicle travel distance range mainly due to battery prices.

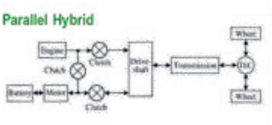
A hybrid power train (refer **Figure 6**) utilizes the current powertrain configuration and adds the battery/emotors to enhance the performance of the powertrain as well as extend the operating range by improving the fuel efficiency of the internal combustions' engine. It does not require an exclusive charging infrastructure as it primarily runs on fossil fuels. However, this powertrain does have emission-related concerns and having more number of rotating parts makes the powertrain complex due to effective management of dual power sources is essential optimum performance.

Practically, environmental impact due to fuel should be considered from well to tailpipe or from the source of raw material to conversion into power for vehicle propulsion. Considering this criterion battery vehicles are not completely emission-free vehicles. In a true sense, fuel cell vehicles (refer **Figure 7**) are practically green vehicles as they are not emitting any emission to the environment. Fuel cell powertrain uses hydrogen as prime energy source and utilizes chemical reactions process to charge the battery. Post electric energy conversion hydrogen atoms react with oxygen and forms water (H_2O) which gets emitted from the tailpipe. Battery electric vehicles and fuel cell vehicles are having similar configurations except in addition to battery storage the fuel cell vehicles also require hydrogen fuel storage.



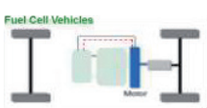
xEV	Driving Component	Energy Source	Features	Problems
BEV	Electric Motor	• Battery • Ultracapacitor	• No Emission • Not dependent on oil • Range depends largely on the type of battery used • Available commercially	• Battery Price and capacity • Range • Charging time • Availability of charging stations • Higher Price

Figure 5.
Battery electric vehicle powertrain.



xEV	Driving Component	Energy Source	Features	Problems
HEV	• Electric Motor • ICE	• Battery • Ultracapacitor • ICE	• Very little Emission • Long Range • Can ger power from both electric supply and fuel • Complex structure having both electrical and mechanical drivetrains • Available commercially	• Management of the energy sources • Battery and engine size optimization

Figure 6.
Hybrid electric powertrains (HEV).



xEV	Driving Component	Energy Source	Features	Problems
FCEV	• Electric Motor	• Fuel Cell	• Very little or no Emission • High efficiency • Not dependent on supply of electricity • High price • Available commercially	• Cost of fuel • Feasible way to produce Fuel • Availability of fueling facilities

Figure 7.
Fuel cell vehicle powertrain.

All the modern powertrains are available commercially, however, its penetration is driven by multiple commercial factors including acquisition cost, operation cost, and ease of re-charging (refueling). All these modern powertrain configurations uses multiple types of bearings in the powertrain including deep groove ball bearings, needle roller bearings, special ceramic rolling element bearings with many other features to provide intended functions in the vehicles which are discussed in the following sections.

2. Role of bearings in modern powertrains

In modern powertrain, bearings are utilized not only for primary functions i.e. supporting the load and reducing the friction but also bearings are used with multiple other integrated functions like signal transmitting device on the motor, rotor positioning sensing bearings, etc.

In conventional powertrain bearings, functions are limited to its primary functions to support operating load on the shaft and facilitate the torque transfer smoothly.

Additional functions like lower the noise, the vibration of the system, and providing stiffness to the shaft system are few of the expected functions of bearing in the powertrain.

However, modern powertrains are having different requirements from the bearing considering constrains like lower weight, space as well as demanding operating conditions includes higher temperatures, speeds, inability to lubrication as well as longer service intervals, or no service for the design life of the system. The role of bearing is changing in modern automobiles. This demanding operating requirements putting immense pressure on bearing performance and achieving the desired specifications of the bearings. The role of bearing is moving from shaft support component to system solution to achieve multiple performance parameters in the intended aggregates. Bearing plays the role of catapult for the system health monitoring utilizing the vibration signature on bearing for identifying, predicting, and proactively preventing the potential breakdown of the system. The modern electronics hardware and miniaturization of the sensors facilitate integration pf the same with bearing to achieve many other intended functionalities.

Battery electric powertrains run at higher rotational speed and having a higher operating temperature. Being an electric system ensuring the lubrication to rotating parts is one of the major challenges. Hence, maintenance-free silent operation is one of the critical technical requirements for the bearings. The bearing design must fulfill the criteria of high-speed operation, lower NVH characteristics, high-performance lubrication, and robust sealing to retain the lubrication inside the bearing as well as protecting the bearing raceways from foreign contaminations.

Modern powertrains, particularly motors operates at a higher rate of acceleration as well as decelerations and to facilitate the same bearing design should be capable to handle the acceleration requirements. Inappropriately design of bearings can experience the functional as well as reliability issues in the system which may leads to system breakdown or reduced life the powertrain or also invite unwanted services of the system.

Bearing load carrying capacity is required to be higher considering the higher power of the prime movers and availability of less space due to lower weight expected from the system. The design of bearing from geometry, material selection, and manufacturing process plays a critical role to achieve higher load carrying

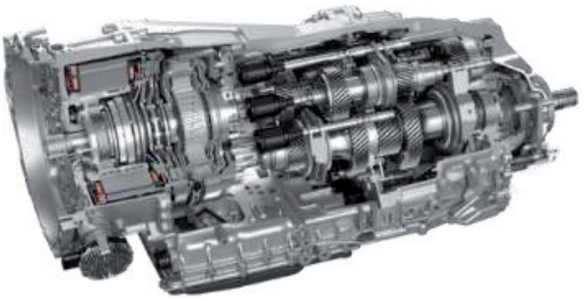


Figure 8.
Conventional ICE automatic transmission [6].

Figure 9.
Traction motor EV powertrain.

capacities in smaller envelope dimensions. The reduced the size of bearings facilitate lower overall system weight.

Bearings are playing a mission-critical functions in modern automotive powertrains. A deeper understanding of applications and expected functionalities play a crucial role to design of appropriate bearing for the modern automobile systems.

Figure 8 illustrates the internal combustion engine vehicles' conventional transmission. It can be observed that bearings in this transmission are having comparatively different technical requirements. The bearings are well lubricated, having comparatively lower speeds of operation.

Figure 9 is one of the EV power train configuration of modern electric vehicle transmission. Compare to conventional IC Engine vehicles the transmission layout is simpler in modern electric automotive vehicles. However, technical specifications and performance requirements of bearings are demanding.

3. Aggregates bearings and its requirements

Application and intended function in the aggregate is having an influence on the selection of bearings as well as on the performance of bearing. It is important to understand the bearing working environment, technical requirements, and application details for optimizing the performance [7]. Different aggregate applications are having different technical requirements that need to be fulfilled by bearing for optimum performance of the system. In this section, different aggregate and technical requirements of bearing in these aggregates are discussed,

3.1 Transmission system bearings

Automobile transmission facilitates speed and torque variation as per vehicle requirements and support engine to run in optimum performance range. The transmission system is having gears, shafts, shift system, and bearings arranged in the housing which perform speed and torque variation function together in coordination with the control system.

Transmission bearings are having multiple requirements to achieve the desired functions, some of them are mentioned below,

3.1.1 Axial and radial load carrying capacity

Transmission bearings experience combined axial and radial loads during the operation based on types of gears as well as shaft arrangement. The magnitude of the load depending upon the bearing position, gear arrangement, and torque transmission. The transmission bearings must be capable of handling these varying speeds and loads.

3.1.2 Lower space and weight

Vehicle powertrains are becoming compact due to the availability of space and emphasize on the reduction of the overall weight of vehicles. Power dense bearings that are capable to carry higher loads in a smaller size are the key selection criteria of bearings for modern transmission. Power density for the bearing is achieved with the usage of better material cleanliness from commonly used bearing materials like 100Cr6, 52100 with stringent specification of nonmetallic inclusions, oxygen content etc., optimized geometry, and precise manufacturing of bearings. It is worth mentioning here that each bearing manufacturer are having its own material specifications customized based on common bearing material chemistry. Most common bearing materials are SAE 52100, DIN 100Cr6, SUJ1, SUJ2 and many more.

3.1.3 Optimized friction

System efficiency is largely influenced by friction. Bearing contributes to the transmission system largely. Generally, Sealed bearings are having more friction compared to open bearings. Transmission bearings selection must have consideration of the friction.

3.1.4 Lower NVH

Modern automobiles particularly battery electric vehicles operate quietly. In the case of ICE, the engine noise suppresses some of the bearing noise, however, in modern automobiles bearings, noise is one of the major concerns. It is expected bearings with lower noise are implemented in the transmission system. In addition to noise, vibration and harshness are also to be given due consideration for the transmission bearings.

Automobile manufacturers specify the system level NVH requirements and typically bearing noise requirements are derived from system level requirements. However, very few manufacturers are having clearly defined NVH specifications for bearing. It is common practice in bearing industry to specify the bearing vibration level and measure at the end of the bearing assembly line. Each bearing manufacturer is having its specification for noise quality level of bearing. Low dB, Gen C, Q44 and other bearing manufacturer internal nomenclature of bearings quality

classes have been developed and specified accordingly [8]. Low-frequency noise is barely audible while high-frequency vibration does not audible to human ear. Hence noise problems at low frequency are categorized as "vibration problems" and at high frequency vibration are as "noise problems". As a rule of thumb, the arbitrary border separating vibration problems from noise problems is 1000 Hz. In other words, below 1000 Hz is vibration and above 1000 Hz is considered as sound or noise [8].

3.1.5 Assembly and disassembly friendliness: easy to mount and adjust (preload/pressing, etc.)

Modern automobile transmissions are expected to be assembly and disassembly friendly considering the automation of the manufacturing process. Complex adjustment during bearing assemblies also calls for a complex assembly process, higher assembly time which increases the overall manufacturing process complexity as well as capacities.

It is expected the bearings implemented in the transmission systems are assembly as well as disassembly friendly. Most suitable bearings need to have a minimum or no adjustment during the assembly.

3.1.6 Compatibility with lubricants

Lower viscosity lubricants with multiple other additives and chemicals are used as lubricants of the transmission for the reasons like reducing the churning losses in the system etc. However, lubricants in the system having influence on the bearing selection and bearing must be suitable to operate and compatible with lubricants in the transmission. Additionally, the sealed bearing application is also common in modern transmissions, so compatible seal material should be selected to avoid damage or performance issues.

3.1.7 Higher tolerance to demanding operating conditions (varying load and speed, temperatures, contaminations)

Bearing field issues analysis over the years suggests that external contamination, poor lubrication, and abusive operating conditions are major reasons for premature bearing failure. However, in modern powertrains, it is expected that bearing manufacturers should consider these conditions and develop bearing suitable to operate or having better capabilities to handle these operating conditions.

3.2 Engine system bearings

A hybrid powertrain utilizes dual power sources and one of the prominent power sources is the internal combustion engine. The importance of engine is prominent even though electric battery-powered vehicles are penetrating its presence. Engine is one of the great innovations of our time and will be around for many reasons. It is expected that more than half of the vehicles will be transformed into electric, but still majority will be hybrid vehicles. Engine bearings are having some typical requirements and some of them are mentioned below,

3.2.1 High-temperature operation

The engine converts chemical energy into thermal/mechanical energy via the fuel-burning process. The engine operates at elevated temperatures due

to fuel burning. Engine bearings must have dimensional stability at elevated temperature in addition to other performance parameters. Bearing mounting and operating clearances are largely affected due to different materials and their expansion rates.

3.2.2 Varying loads and speeds

Engine loads and speeds are varying during the operation. Bearing kinetic should be considered for varying speeds and loads. Rolling bearings use on crankshaft and camshaft is increased in recent time. However, at the connecting rod end, needle bearings or journal bearing are commonly used in an engine for multiple reasons including varying load and speeds.

3.2.3 Demanding operating conditions like contamination

Crankshaft bearings are positioned bottom of the crankcase in the engine. The engine piston is reciprocating (sliding motion), so the wear of the engine part is not uncommon. However, wear particles are mixed in the oil contaminate the oil. Engine oil is the primary source of lubrication to bearings. The contaminated oil is having a negative influence on bearing operation and due consideration should be given to have good performance of bearing in this condition. Special heat treatment can be considered on the bearings rolling elements and raceways in such demanding operating conditions. Optimum ball pass frequencies selection is also important to ensure the hunting of rolling elements is not affecting the raceways or rolling element.

3.2.4 Mounting and dismounting of bearings

Engine bearing mounting and dismounting is one of the important considerations, not only from a service, assembly perspective but also from the operational performance perspective. Appropriate fits must be applied to the bearing to ensure bearing is loaded and operates in favorable clearance zone. Wrong selection of fits can lead to catastrophic damages to bearing with prolonged use.

3.3 eMotors bearings

Battery electric vehicles are using motors as prime mover of the vehicle. Hybrid powertrain vehicles are also uses motors to propel the vehicle. Traction motors used in vehicles are having many special technical requirements that are different from conventional motors.

Some typical requirements are discussed in the following session,

3.3.1 Bearing arrangement

Traction motors bearing arrangement plays an important role in bearing selection. In most of the traction motors application two bearing arrangement (drive and non-drive end) is preferred. However, integration of transmission and motors is also common practice in electric powertrain due to which three inline bearings arrangement is also implemented.

The bearing arrangement adds complexity to the overall bearing system and the need for the appropriate distribution of bearing loads. Comparatively, two bearing arrangement is simple compare to three bearings arrangements.

3.3.2 Handling higher and varying speed/load

The traction motors that drive vehicles are required to run at very high speeds – up to 30,000 rpm, or almost three times the speed of the typical industrial motor. This high-speed operation places enormous strain on the bearings in the system. High-speed operation of bearing calls for special raceway geometry as well as separator designs to handle the additional centrifugal forces.

3.3.3 The higher temperature in operation

In the conventional system, lubrication oil dissipates the heat from the system and ensure the specific operating temperature. However, in electric motors heat dissipation is done via a cooling fan. Additionally, bearings are running at high speed, so the heat generation rate is higher hence the operating temperature. Motor bearing with seals and grease must have the ability to retain the lubricant inside the bearing at elevated temperature.

3.3.4 NVH and lower friction

Motor bearings are expected to operate at lower noise and lower vibrations. This is one of the key requirements for the motor bearings considering the high speed of operation, varying loads, and acceleration.

3.3.5 Maintenance free and sealing performance

Motor bearings are expected to be maintenance free so the grease selection, seal selection plays a major role in bearings performance and life.

3.3.6 Handling acceleration and deceleration during operation

Electric motors are very responsive to vehicle operating conditions. Motors accelerate as well as decelerate faster compare to ICE. The bearings must be designed to handling this rapid acceleration as well as deceleration. Rolling element separators, raceways geometry should be designed appropriately. Rapid acceleration and deceleration generate sliding motion in the bearing which can lead to damage to bearing raceways or other surfaces. In extreme acceleration and deceleration conditions, may result in catastrophic bearing damage or malfunction of bearing.

3.3.7 Tolerance to electric current leakage

Present bearings are made up of bearing steel material which is good conductor of electric current. In electric motor current passed though the bearing for any reason is detrimental to bearing function. However, motor feature that can affect conventional steel bearings is the high-frequency voltage switching of the inverter that produces current leakage, particularly at high motor speeds. This current leakage can pass through the bearing and causes, surface damage like surface pitting also called fluting. The initial stage of surface damage generates bearing noise, but the advance stage of surface damage can be catastrophic.

3.4 FEAD bearings

Front End Accessories Drive (FEAD) system is a combination of multiple subsystem drives in the vehicle for the purpose like air condition compressor drive

or alternator drive etc. The system requires basic requirements like axial and radial loads, static load carrying capacity, dynamic load-carrying capacity, speed, or rpm. However, the FEAD system requirement range beyond basic load-carrying capacities. Modern automobiles are expected to provide more comfort, steering pumps and air conditioner compressors have been added to the FEAD system in addition to alternator or BSG system. Modern automobiles are using comparatively more electronics parts/system operates using electricity which are rising the battery charging capacity. The charging capacity of alternators has increased its size, accordingly, leading to a rise in the amount of torque to be transferred to alternators. The increased torque transfer demands from higher load capacities for the FEAD system bearings.

Below are few technical requirements of FEAD system bearings.

3.4.1 Higher speed capabilities

FEAD systems are running at higher speeds like alternators are running in excess of 20000 rpm, the bearing must-have capability to handle the system increased speed. Additionally, the tendency of the engine running at a slower idle speed is also implying bearing selection due to extended time slower speed operations.

3.4.2 Handling acceleration and deceleration during operation

Acceleration and deceleration handling requirements coming from higher system speed, variation in loads.

3.4.3 Lower friction

Lower friction is a common requirement for all the modern automobile system bearings that are also applicable for FEAD system bearings.

3.4.4 Lower space and weight

Higher emphasis on the compact and lower weight of the system demands for lower size of the bearing with a higher load-carrying capacity.

3.4.5 Higher temperature operation

Higher operating temperature due to proximity to the engine as well as higher operating speed requires bearings seals, lubrication as well as dimensional stability at the higher operating temperature. The alternator bearings are expected to work at 180 to 200 Deg C temperature.

3.4.6 Maintenance-free operations (better sealing performance)

Maintenance-free operation is predominantly driven from no lubrication to bearing for life and sealing performance. The seals should be capable of running for the life of the vehicle and retain the lubricant inside the bearing.

3.5 Wheel bearings

The wheel bearings enable low-resistance rotations of the wheels by transferring axial and radial forces and support for wheel hub, wheel, and brake disc or brake drum. In modern automobiles, the wheel bearings are equipped with sensors that

send rotational speed signals to driver assistance systems like ABS, ESP, etc. [9]. The wheel bearings perform multiple functions, some of them are listed below.

3.5.1 Precise wheel guidance

Wheel bearing provides support to wheels, so rotation accuracy of bearing facilitates the guidance to the wheel. It is an important function for vehicle stability and control during operation.

3.5.2 Low weight, high bearing stiffness/rigidity (stability)

Wheel bearings are expected to have a lower weight. However, higher stiffness or rigidity requirement is an important consideration for wheel guidance and vehicle stability. As modern automobiles are having higher road speeds achieving safety of vehicle wheel bearings plays an important role.

3.5.3 Reduction in unsprung masses, which contributes to better driving dynamics

Unbalanced wheel bearing adds the unsprung mass to the system which affects the vehicle driving dynamics. As the speed of the vehicle increases the unsprung mass becomes more detrimental from the driving dynamics perspectives.

3.5.4 Absorption of external forces

Wheel bearings are subjected to many unknown forces due to constant changing road conditions and speeds, corners, and other conditions. The wheel bearings must be capable of absorbing the external loads without affecting the performance.

3.5.5 Long service life, lower maintenance and sustainability (environment and disposal), corrosion resistance

In operation, the wheel bearing is subjected to many unusual conditions like contact with mud, dirt, undulations, etc. However, in modern automobiles wheel bearing is expected to sustain all the working conditions without or with minimal need for maintenance. In addition to bearing design, lubricant and seal performance is an important parameter for long service life.

3.5.6 Thermal stability

Bearing should be stable in all aspects with all operating temperature ranges and perform as per the intended level. Temperatures can affect the preload of the bearing which can be detrimental for bearing performance.

3.5.7 Simple assembly/disassembly

As mentioned in the transmission system section, modern manufacturing considerations like automatic assembly, less complex mounting to reduce the complexity in the assembly process as well as at service time (**Figures 10** and **11**).

3.6 Steering system bearing

The steering system controls the direction of the vehicle, so the steering system bearings are having typical requirements to receive the feedback as well as facilitate

the execution the operators' intended command to operate the vehicle with minimum lag in the system.

3.6.1 Low frictional torque

Steering system bearing must have lower frictional torque for the system to be responsive.

Higher frictional torque adds operator fatigue as well as a slow response from the steering system which can influence the effective functioning of the vehicle control system.

3.6.2 Relatively high rigidity

Steering system bearing must have higher rigidity to enhance the system integrity as well as to achieve the system responsiveness and removing any sluggishness in the system.

3.6.3 Lower wear rate

All the bearings should have a lower wear rate, however, the steering system bearing it is critical requirements. The higher wear rate of bearings calls for frequent system adjustments or malfunctioning of the system operation.

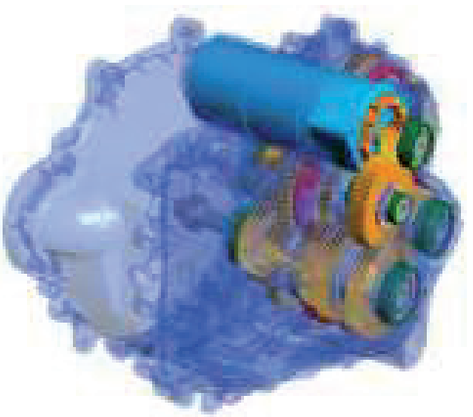


Figure 10.
Electric vehicle transmission.

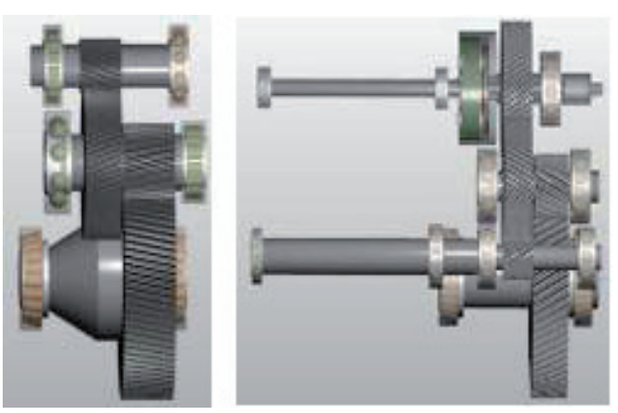


Figure 11.
Electric vehicle transmission.

3.7 Suspensions system bearings

Suspension system bearing relates to comfort and vehicle stability. Suspension system bearing have some unique requirements are mentioned below considering other requirements are common with other bearings as well.

3.7.1 Low-friction and distortion-free movement of the shock absorber spring during steering and deflection, enabling the spring

Suspension system bearings are connecting vehicle chassis with suspension/shock absorbers, so movement in response to road conditions should smooth.

3.7.2 Operate without self-aligning torque

Suspension bearing requires a self-aligning function considering the movement. It is expected that bearing should self-align without requirements of any additional external force for smooth operation.

3.7.3 Locate the shock-absorber spring and form a support surface for full deflection of the shock absorber

Suspension bearings support and locate to shock absorbers so it should function to provide the full deflection of the shock absorber.

3.7.4 Help isolate the body from road noise

Suspension bearing connects the suspension system with the vehicle body so any noise or undulation coming from the system results in noise. The bearing should be capable to isolate such noise from the vehicle body. A non-metallic bearing body is one of the ways to achieve this function.

In general, bearings play a significant role in vital aggregates to achieve the intended objective of modern automobiles. A deeper understanding of technical requirements and intended functions help bearing engineering to provide the most appropriate solutions which optimizes vehicle performance.

Figure 12 summarizes the requirements of bearings in modern automobiles and available options to achieve the same.

Refer to the discussions of the last section it can be observed that bearings requirements are driving trouble-free operations, longer service life, the lower

Figure 12.
Bearing requirements and means to achieve in bearings.

total cost of ownership, compact construction, lower friction, noise, better sealing performance as well as integrated functions.

Bearing engineers achieve these requirements in the right proportionately blending and integrating engineering know-how of different bearing materials, manufacturing processes like heat treatment, surface finishes, and geometries. Long service life functions are achieved with lubricants, better sealing in addition to optimized geometries and design parameters. Integrated functions and application-specific solutions make bearing versatile with few additional features to be used for multiple applications.

4. Bearing technology development focus areas

4.1 Identification of bearing technology focus areas

Modern automobiles are improved by challenging the status quo as well as by adopting the technology changes to current level of performance. The modern automobiles are also empowering and enforcing bearings innovations and technological limits to further enhance the performance of the vehicles.

Patent filing data provide great insights about the innovation areas in the industry. In order to understand the bearing technology development focus areas patent analysis is performed on last 10 years of global patents filing in bearing area, modern automobiles. **Figure 13** is a word cloud plot of 11,300 patents titles in bearing, modern automobiles areas filed in different global patent offices. The word cloud analysis provides quick insights into the analysis areas based on the frequency of keywords in the analysis data. It does not provide in-depth analysis; however, it is a good way of understanding the focus areas in technology development and the direction industry's research is leading.

Rolling bearing and bearing assembly is an obvious appearing word in the patent title hence not considered for further analysis discussion (**Figure 13**).

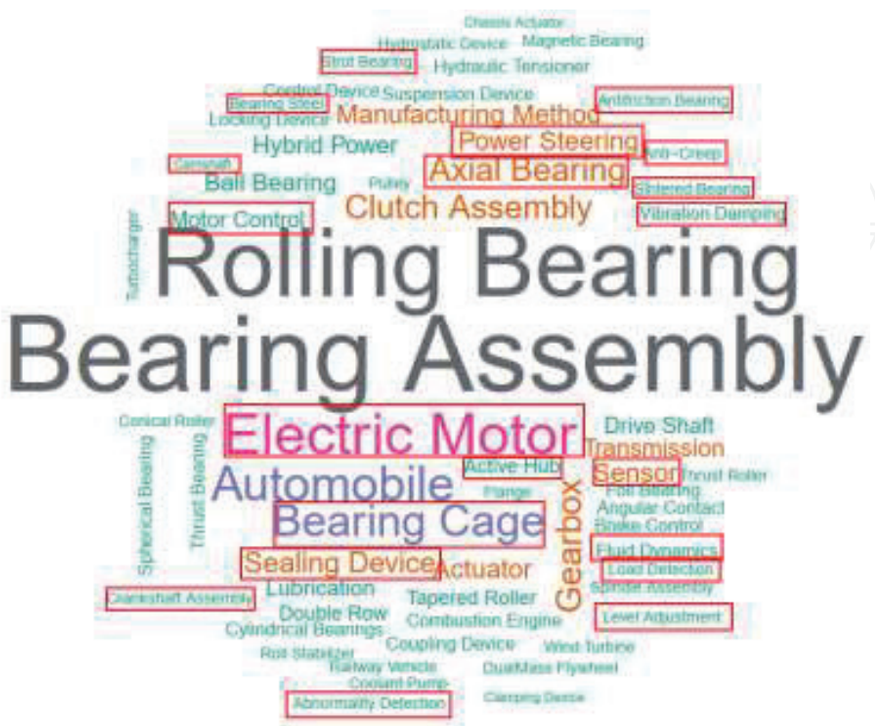


Figure 13.
Bearing technology focus word cloud plot of patent analysis.

Word cloud analysis pointing more research is being focused on electric motor bearings, bearing cage, sealing, anti-friction, fluid dynamics, lubrication (areas generally connected with the higher speed of operation), bearing steel, sintered bearing (areas indicating the material related research), motor control, sensors, active hub, load detection, level adjustment, abnormality detection (areas indicates the focus on bearing plus integrated functions like sensorization), camshaft, crankshaft, magnetic bearing, sealing devices, axial bearings (indicates areas of special bearing development, application-specific solutions development), special bearings in the current family of bearings also is the areas of technological research. Patent filing analysis is good indicator of the technology areas and direction.

Interactions with the automobile industry players are also summarized for connecting the technology focus areas with customer mandate or request for solutions. These areas can also be considered customer challenges, pain areas, or directions for the modern automobile development.

Modern automobile powertrain and system customer's voice is captured in two fundamental buckets i.e. must-have requirements (highly desirable) and good to have (differentiating) requirements.

High-speed bearings, high operating temperature, current insulations or conduction, lower friction bearings, power-dense solutions, and lower noise, vibration, and harshness (NVH) solutions are highly desired by automotive customers. However, long life, maintenance-free, better reliability, integrated functions, condition monitoring, sensor bearings, lower weight bearings are considered as differentiating features.

Patent analysis and modern automobile customer's voices are having a high level of similitude to interpret that bearing technology development customer requirements are indicating future development trends for the bearing. The above analysis also indicates that bearings are playing a vital role in automobiles and will also play a vital role in modern automobiles in the future.

4.2 Bearing technology development focus areas and ways of achievements

In the previous section, it is mentioned that haptic requirements from bearings are fulfilled with blending the bearing constituents in different proportions. In this section, some of the key influencers are discussed which facilitate the bearing technology development as well as achieving the modern automobiles bearing requirements.

Figure 15 is a summary of different constituents of bearings is its influence on bearing requirement achievement.

Typically, bearing materials are the backbones to achieve the bearings' fundamental functions. Different grades of materials can be implemented based on the intended requirements of the application. Bearing materials also facilitate next processes like heat treatment, machining, and many other parameters.

Heat treatment of bearing is very important to achieve the next level requirements of bearing. Standard heat treatment also called through hardening is commonly used to all-purpose bearings. However, if the bearings are required to operate in the demanding operating conditions, appropriate special heat treatment can be considered to enhance the bearing utility to application.

Bearing geometry plays a role in bearing friction, NVH, and different load handing areas. Bearings geometries need to be applied based on expected application requirements. Accuracy and functional requirement need to be well balanced to achieve economics.

Large number lubricants are available based on application requirements. The right selection of lubricants and seals increases the bearing utility in the application.

Many times, multiple application requirements can be achieved by applying suitable sealing/lubricant on the fundamentally same bearings (**Figures 14** and **15**).

The left side of **Figure 15**, summarizes the special or application-specific functional requirement fulfilling means of bearings. Customization of bearings is addressing the exact application needs however, customized solutions make bearing special and expensive.

4.3 Major bearing technology development areas for modern automobiles

4.3.1 Reliability improvement solutions

Reliability improvement of bearing relates to bearing performance and service life in the actual application. Reliability improvement of bearing means increasing the mean time between failure of bearing.

Bearing reliability can be improved by implementing special consideration to demanding operating conditions with special heat treatment, better materials, lesser intervention from the operator by unitized bearings, increasing wear resistance, implementing the better lubricants, tighter manufacturing tolerances.

Bearing life can be increased by multifold by right selection of heat treatment like compare to through hardening heat treatment, case hardening heat treatment (CN) can give 2 to 5 times more life to bearing in contaminated working environment. In addition to base material bearings can be coated to increase resistance of

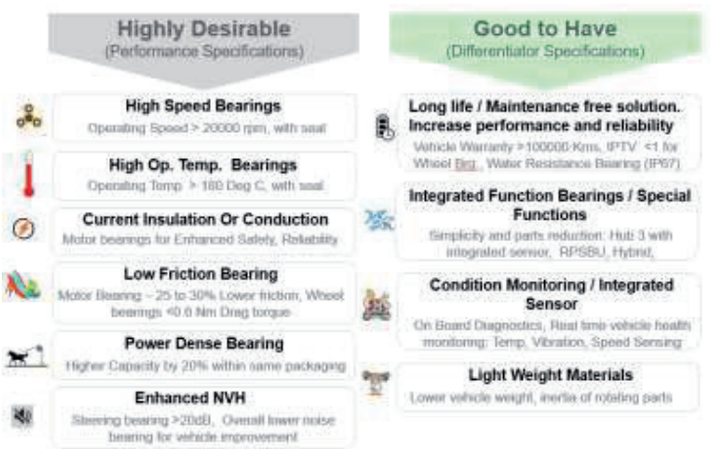


Figure 14.
Modern automobile "Voice of Customers" for bearings requirements.

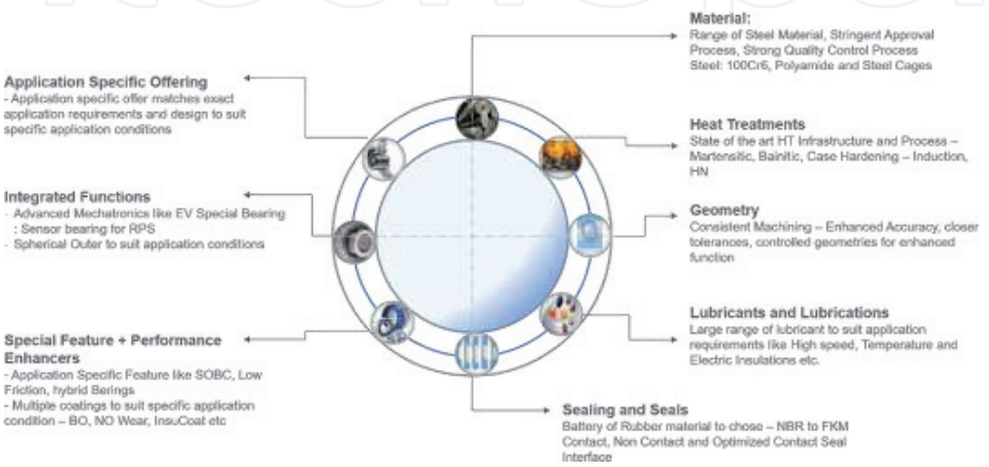


Figure 15.
Means of achieving intended bearing functions for modern automobiles.

bearing in specific working condition. Carbide based coatings are popular in some application, alumina material coatings are used for electrical insulations.

4.3.2 Power dense solutions

Power dense solutions related to more load carrying capacity per unit bearing size. As mentioned in the last sections, the bearings are catalysts to achieve a lower weight of the aggregate. Weight is the enemy for vehicle performance particularly in electric vehicles as it directly influences range as well as battery capacity. Lower size of bearings accumulates lesser space as well is makes the aggregate system compact. An additional advantage of power-dense bearing it utilizes lesser material, so it is also another means of achieving environmentally friendly solutions.

Current bearing material development and steel cleanliness is increase material mechanical properties. Additionally, manufacturing technologies increased control over the tolerances are enabling the power dense solution. Typically, 20 to 30% higher load carrying capacity can be improved within same envelope of bearings with right selection of material, geometries and manufacturing process including heat treatment.

4.3.3 Integrated functions

In recent times, frugal engineering is typically connected with terms like "more for less". In this text, integrated functions can relate to frugal engineering and can be termed as "more functions per bearing". Bearings can be attached with sensors and utilize for the position, speed as well as direction signals. Bearings are integrated with multiple functions like in new generation wheel bearings brake and wheel mountings are combined with bearings. Integrated bearing functions support compactness, reliability improvement, however, in some cases also adds complexity.

4.3.4 Friction optimization

Friction optimization solutions are intended to achieve better efficiency, lower losses in the bearing. Type of bearing and depending upon the application requirements bearing friction level can be achieved with the manufacturing process and tighter specification controls. Generally, bearing friction is a function of multiple factors like internal geometry, type of seals, material, lubricant, and the rolling element grade. Kinetics of bearing also plays a role in achieving the optimum friction of bearing. Adjustment in assembly, preload requirements, and assembly process influence final friction behavior of bearing in the application.

Lower friction of bearings directly contributes to wear performance as well as the efficiency of the system.

Figure 16 depicts the typical wheel bearing friction rate. Conventionally, vehicle manufacturers were assembling different parts together including bearings into wheel hubs. However, this arrangement is not effective considering the performance parameters. Hub 1 bearing is integration of two bearing into one, so it provides 10 to 15% better friction rate, Hub 2 is further improvement having integration of out race of bearing into housing and it provided 10 to 15% friction reduction compare Hub 1. Currently most of the modern automobiles are using Hub3 which are complete integration of bearing and wheel mounting.

This arrangement provides 50 to 60% friction reduction compare to conventional arrangements and additional 10 to 12% improvement compare to hub 2 arrangement.

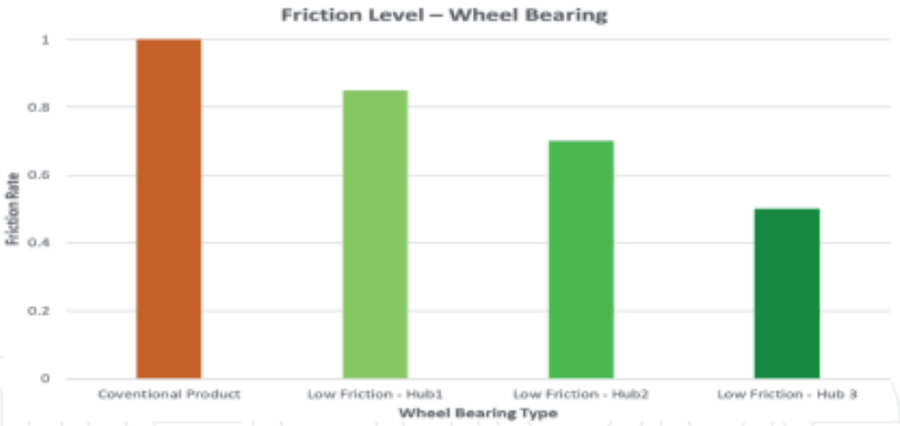


Figure 16.
Typical wheel bearing friction rate.

4.3.5 Sealing and lubrication solutions

Modern automobiles are targeting maintenance-free or maintenance less and fit for life reliable systems. Bearing sealing and lubrication solutions play a vital role in the achieving maintenance and reliability target of the system. Type of sealing (seal material, geometry, type of contacts, etc.) and lubrication selection for the bearing directly affect the bearing performance in operating conditions like temperature, speed, and friction. Good sealing on the bearings also increases bearing resistance to operating condition likes keeping the contaminations out of bearing raceways. Sealed bearings are not only maintenance-friendly but also environmentally friendly too.

Figure 17 depict the importance of capping (sealing) type in the bearing. Non-contact type of capping is good when bearing need to contain the lubricant like grease into the bearing with fair protection against exclusions, however, contact types of seals gives excellent protection against exclusions as well as retention of lubricants. Low contact capping compromise based on application requirements. However, all these capping is having impact on power loss or additional friction in the system. Non-contact type of capping gives lowest power lost among the all the capping types. Contact type capping is having highest power loss compare to both the non-contact and contact type capping. Typically, low contact type seals are having 30 to 40% higher power lost compare to non-contact type. Contact type capping is having 35 to 45% higher power lost compare to low contact type capping and about 70 to 80% higher power loss compare to non-contact type capping.

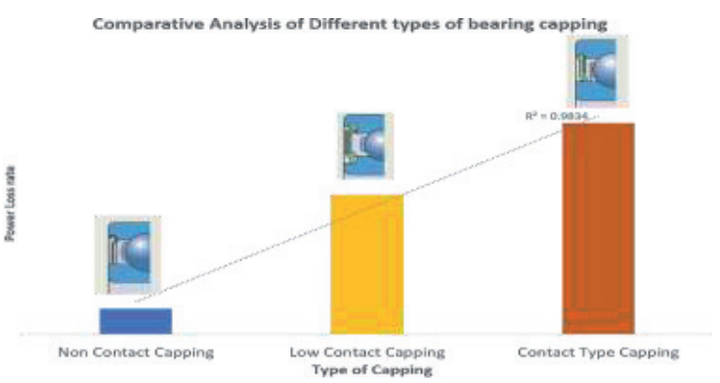


Figure 17.
Comparison of different type of capping and power loss.

Figure 18.
Modern automotive eMotor challenges.

4.3.6 "Sensorization" solutions

Modern automotive uses of electronics are increasing for vehicle control as well as operator comfort purposes. Vehicle control systems primarily need feedback from various systems which required sensor. Sensors are typically mounted on or around the critical rotating parts, hence sensors integrated bearings are a natural good choice for reliable signals. It is already proven that in rotating system's generate unique vibration signatures on the support bearing. These unique vibration signals can be processed electronically for multiple vehicle systems health monitoring via sensors. Sensor bearings provides better location as well as the accuracy of the signal for different feedbacks like speed, load, temperatures, etc. for effective vehicle monitoring. The miniaturization of sensor technology is an opportunity for the integration of bearings and sensors for modern automobile sensing needs.

4.3.7 Special electric motor bearings

Above bearing technology focus areas are covering major areas of eMotor bearings as well. However, some special requirements like current leakage and performance of bearing need special mention in this section (**Figure 18**).

High-frequency current passing through the bearing is detrimental for the bearing performance and there is a high probability of current leakage in eMotor bearings. If the current passed through the bearing generally results in "fluting" or micro pitting on the bearing races and start generating noise. The continued running of the bearing in this condition may encounter catastrophic damage. Bearing with special electric insulation coating, special materials for the rolling element (e.g. Ceramic) are developed and also under development for mass vehicle adoption by lowering cost. In addition to electric current insulations, technology development is also focused on electrical conduction solutions so the leakage current can be bypassed from the rolling area.

5. Conclusion

Modern Automobiles technology is transforming to enable "connected, autmonomous, shared and electric (CASE). Modern automobile powertrain development is focused on higher efficiency, maintenance free (higher reliability), compactness, light weight and autonomous control using mechatronics capabilities. New generation powertrains utilize lighter materials, lesser number of components and

integrated fuctions to achieve these objectives. Battery electric powertrains, hybrid power trains and hydrogen fueled fuel cell technologies are becoming popular in modern automobiles. Bearings are one of critical component (sub-system) to achieve modern powertrain's demanding technical requirements. It is imperative to bearing engineers to understand critical technical requirements of modern automobiles aggregates functions and bearing performance expection. Understanding aggregate performance and expected bearing technical requirements facilitate optimized solution development. Bearing plays crucial role in enhancing efficiency, integrating the functions, facilitate the compactness to achieve the lightweight powertrain. Bearing technology development focus area concentrating to addressing the modern powertrain's requirements. Bearing technology research and development areas focused on reliability improvement, power dense solutions, integrated functions, friction optimization, sealing/lubrication solutions, adoption of sensors and special application specific eMotors bearings. In addition to primary functions of bearing with the help of modern electronic technologies bearings are performing critical role of overall system health monitoring in the vehicle.

Bearing research is typically aligned to applications requirements and trends of the machine's technology. Modern automobiles are focusing more of passenger comfort with focus on autonomous driving, connected vehicles and electrification of vehicle. These technological requirements pushing bearing research more on sensorization, lower noise, vibration and harshness in addition to reliability improvement, maintenance free operation and application specific solutions. Bearing noise is one of the key concerns in modern powertrain specifically in electric drive trains. Bearing technologist are focusing on this aspect more than ever before. The bearing noise is directly connected to passenger comfort as well as overall system health. Bearing noise is also indication of system health as the issues with any part in the chain directly reflect to bearing vibrations. Leading bearing manufacturers are focusing on the sensor bearing technology as this feedback from vehicle critical parts is key to autonomation of modern automobile vehicles. Chronologically bearing research focus is more on application specific solutions, sensorization, maintenance operations. At system level bearings research is also focused on the "connected vehicle technologies" using on-board diagnostic using vibration signature identification capabilities at the bearing.

However, bearings are having furthermore potential to contribute and enhance role in modern automobiles in future. Future bearing technologies will focus more on the "bearing as a service" than typical product. Bearing as a service includes ability to collect the data, process the data and transfer the data for better understanding of vehicle dynamic behaviors. In modern automobiles bearing role will be second to electronics. The miniaturization of electronics complements to bearings utility exploitations and expansion to bearing space for additional functionalities. In modern automobiles the role bearings are as important and vital as the electronics considering potentials bearings provide for further integration and research.

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