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Commentary

Current and Future Trends in Tribological Research

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Abstract: The paper provides a commentary on the theme of "Current and Future Trends in Tribological Research: Fundamentals and Applications", which is a special feature issue commemorating the 10th anniversary of the journal, Lubricants. A historical discourse is provided regarding various aspects of tribology as a multi-disciplinary subject that interacts in an inter-disciplinary manner with many other subjects: multi-body dynamics, thermofluids and heat transfer, contact mechanics, surface science, chemistry, rheology, data science, and biology, to name but a few. Such interactions lead to many important topics including propulsion with different sources of energy, mitigating emissions, palliation of friction, enhancing durability and sustainability, optimization through detailed analysis, and the use of artificial intelligence. Additionally, issues concerning kinetics at various physical scales (from macroscale to microscale onto mesoscale and nanoscale) affecting the kinematics of contacts are discussed. The broad range of considered applications includes vehicular powertrains, rotor bearings, electrical machines, mammalian endo-articular joints, nanobiological attachment/detachment, and locomotion. Current state-of-the-art tribological research is highlighted within a multi-physics, multi-scale framework, an approach not hitherto reported in the open literature.

Keywords: tribology; contact mechanics; tribodynamics; electrotribodynamics; textured surfaces; coated surfaces; biotribology; nanotribology; biomimetics; artificial intelligence

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1. Introduction

With the increasing emphasis on product sustainability, reducing emissions, and using alternative sources of energy to hydrocarbons, tribology, like many other disciplines, is set to undergo significant and rapid changes. In the realm of vehicle propulsion power, there is already a shift away from pure hydrocarbon fuels to hybrid or fully electric systems for all modes of transport [1–7]. These trends have been supplemented by the growing interest in harnessing the power of natural gas and, more recently, hydrogen as cleaner sources of energy [8–12]. In the area of electrical power generation, there have already been developments in off-shore and on-shore wind turbine farms [13–16] and the acquisition of solar power from nationally as well as domestically installed solar panels [17–19]. Of course, there are other alternative sources of energy such as nuclear and wave power, but the arguments for some are shrouded in political and societal controversaries. Impending and ongoing changes have brought opportunities to combat some critical issues such as harmful emissions and global warming. However, the uptake of some of these technologies introduces a state of transience through the lack of necessary support infrastructure. There are new and unexplored issues in tribological research, where established methods fail to address the emerging problems. Nevertheless, much research will remain the same, firmly supported by long-established fundamentals and principles [20–24]. Tribology has a broad spectrum of applications, interacting closely with other major disciplines, such as dynamics, contact mechanics, surface engineering, combustion, chemistry, and rheology, in a multi-scale manner [25,26]. As a multi-disciplinary subject with inter-disciplinary interactions, tribology encompasses a broad area of research. This paper aims to advance, propose, and focus on some of the important aspects of tribology.

2. Tribodynamics

The manifestation of friction and wear in real applications, particularly in machinery, is mainly due to the existence of motion between contiguous surfaces. Hence, the dynamics of the components to which the surfaces belong is an important issue in determining the tribological state of their contacts. However, there is a reciprocal relationship as well, where the tribological state and behavior of contacts can affect their dynamics, for example, by inducing noise, vibration, and harshness (NVH) issues. Within the realm of vehicle engineering, there have been many tribodynamic (integrated tribology and dynamics) studies of internal combustion (IC) engines, including NVH issues [27–32]. Some of these studies have focused on various IC engine sub-systems, mainly on the palliation of friction (aiming to improve fuel efficiency and durability, and to reduce emissions) and NVH refinement. These are two aspects that often conflict because increased friction reduces NVH at the expense of decreased energy efficiency. The tribodynamic studies of IC engine sub-systems have included piston–cylinder conjunctions [33–40] owing to their lion's share of frictional power losses. In an attempt to improve fuel efficiency and thus reduce fuel consumption and emissions of hydrocarbons, various fuel additives have become commonplace, including a percentage of ethanol as a fuel additive. However, tribological issues of concern, such as wear of surfaces/coatings and removal of protective tribofilms as the result of combustion by-products, have emerged [41,42]. The same issues are likely to present themselves with dual-fuel hydrogen or pure hydrogen combustion engines, which normally run at higher surface temperatures [43]. An increased lubricant temperature can reduce its viscosity and thus its load carrying capacity, promoting direct boundary interactions [44]. Thermal damage to contacting surfaces can also occur, as well as lubricant dilution with water as a by-product of hydrogen combustion. These will be important considerations in future research into alternative/mixed fuel IC engines [9,45,46].

Another IC engine sub-system is the valve train. Tribodynamics of cam-follower pairs in engine applications and in many other mechanisms (e.g., in the food processing, textiles, and knitting industries) is subject to high contact loads. In IC engines, there have been many valve train analyses, including the use of multi-body dynamics to accurately model the constrained mechanism motions [47–53]. The trend has been to include component flexibility (e.g., the elastic valve stem or camshaft [50]). Contact/impact dynamics of mating pairs (e.g., cam and follower, and valve and valve seat) have also been included in analyses [54,55]. Therefore, integrated elasto-multi-body dynamics studies have been carried out, including contact mechanics analysis and lubrication. Some analyses have been extended to the case of generated sub-surface stresses [55], which are often responsible for the inelastic deformation of surfaces [56–61] such as in fatigue spalling and pitting at highly loaded contacts of cam–follower pairs. Generated friction and heat are other inclusions in some valvetrain tribodynamic analyses [50,62].

The aforementioned are just a few representative areas of engine tribodynamic analysis, for which there have been many studies. Other main areas of tribological research in IC engines have been crankshaft support bearings, connecting rod bearing (big-end bearing) and wrist-pin bearing (small-end bearing), all increasingly using soft tin-based or copper overlays and thin wear-resistant protective coatings such as indium or bismuth [63–69]. Investigation into the use of polymer coatings in journal bearings with potential application to IC engines has also been conducted [70–73].

Other conjunctions in powertrain systems include transmissions and differentials. The non-linear rattling dynamics of lubricated meshing teeth pairs depends on the applied load. Various forms of rattling behavior result from the dynamic transmission error (DTE) of meshing pairs [74,75], subjected to various regimes of lubrication. These comprise lightly loaded idle rattle (hydrodynamic conditions) [76–80] and highly loaded creep and drive rattle categories (with elastohydrodynamic contact conjunctions) in transmissions [81–84], timing gears [85], and the intermittent stop–start impacting motion of chain drives [86]. Transmission rattle is a very good example of interactions between system dynamics and contact mechanics/tribology (i.e., tribodynamics) in vehicular powertrains.

Constant velocity joints (CVJs) can play a significant role in vehicular NVH. For instance, launch shudder, particularly encountered in electric vehicles (EVs), is linked to half-shaft CVJ excitation and is mainly attributed to frictional characteristics [87]. However, the tribology of CVJs is not well researched, and in many dynamic analyses, it is often customary to use a constant friction coefficient for the CVJ contacts [88–90]. This is despite the fact that such contacts are often lubricated with grease and are subjected to complex kinematics, which result in variable friction. In addition, the regime of lubrication during operation can vary from pure EHL to mixed and boundary interactions, even within a single cycle. Recent studies have shown that the accurate prediction of the coefficient of friction and the appropriate representation of the mechanics of contact of CVJs have significant effects on the predicted dynamics, particularly in high-performance racing applications [91]. The accurate analysis of kinetics of CVJ contacts has a significant effect on predicting the observed failures in such contacts [92]. An example of the multi-physics tribodynamics approach is the study of hot judder of automotive clutches shown in Figure 1. The developed model combines multi-body dynamics with measured friction data by tribometry, as well as with a thermal network contact model.

The future trend toward alternative sources of vehicular propulsion is expected to deviate from the current IC engine systems. However, predicting the early demise of IC engines is rather presumptuous and mostly politically driven rather than scientifically based. The reasons are manifold, including the high power density of hydrocarbon-based fuels, which cannot be easily matched by other alternative sources of energy, and the already established and inexpensive methods of processing and distribution for hydrocarbon fuels compared with the alternatives. Other issues concern hybrid technologies that still use IC engines, mainly in the form of down-sized range extenders (i.e., small engines with few cylinders). These are used as supplementary power for electric powertrains due to the range limitations imposed by battery capacity. Dual-fuel hydrogen–diesel, hydrogen–CNG (compressed natural gas), and pure hydrogen-fueled engine configurations are likely to be the future source of vehicular propulsion for long-haul trucks and lorries, as well as for some marine, mining, agricultural, and construction applications. Therefore, putting aside political expediency, IC engine-based powertrains should be around for many years to come, with the ever-improving take-up of optimized new technologies, which include cylinder deactivation (CDA), variable valve timing (VVT), stop–start, turbo- or supercharging or both, and gearshift monitor. All these technologies are employed to reduce fuel consumption and emissions. Their tribological impacts have been ascertained by in-depth analyses [93–96]. Therefore, improvements in IC technologies have already been made and are increasingly implemented. These trends bode well for the future development of combustion engines that use alternative fuels, as well as for hybrid powertrains.

Although tribodynamics has been explored to a good extent in the context of propulsion and, in particular, vehicular powertrains [97,98], there are other equally important areas where it can play a significant role. These include the tribodynamics of space mechanisms [99,100], biological joints [101,102], and robotics [103], as a few examples. In addition, any non-linear dynamic behavior of a system where the origin of the non-linearity either partially or fully relies on the existing tribological contact(s) can only be ascertained by appropriate tribodynamics models [104–106]. Future advances are expected in these areas of tribodynamic research.

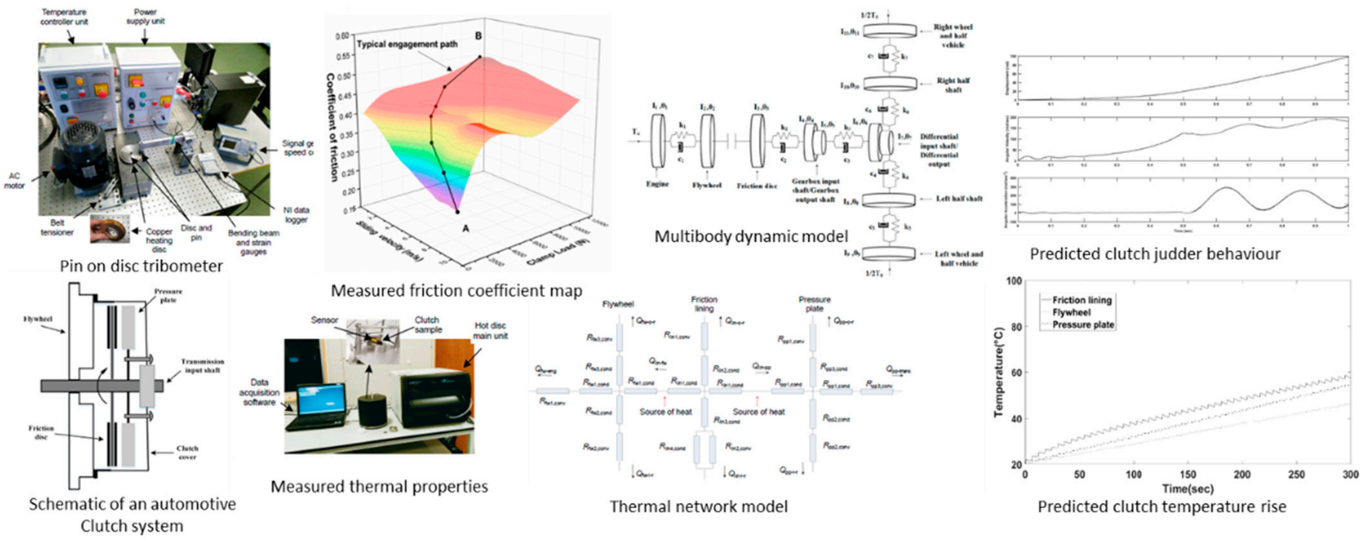

Figure 1. Elements of a multi-physics tribodynamics model of automotive clutch systems [97,98].

3. Electro-Tribodynamics of Modern Propulsion Systems

In the quest to decarbonize energy sources for the purpose of propulsion, electrification has been proposed as the primary candidate. Indeed, there are already many modes of transport that rely on electric power. Variable frequency electrical generators and motors have been developed with the main aim of reducing greenhouse gas emissions in the transport sector, which currently contributes to nearly a quarter of all harmful UK emissions [107,108]. Manufacturing industries also increasingly rely on variable high-frequency drive electric motors. It is estimated that in the UK's commercial and industrial sectors, electric motors account for 30% and 70% of energy consumption, respectively [109].

Popular permanent-magnet synchronous traction motors with variable frequency drive control systems provide high power density, efficiency, and low-cost operation. However, these drives can cause electric currents to pass through the contacts of mating surfaces. These currents cause various forms of surface damage, sometimes manifested as small craters, resembling those created by the electro-discharge machining (EDM) process. Other forms of damage include frosting, fluting, and pitting of bearing races. They can all lead to premature failure of tribological contacts [110–117]. Detailed electrotribodynamics of bearings has shown the interplay between bearing mechanical vibration frequencies and those of electrical power supply (Figure 2), leading to the fluting and frosting patterns on bearing races [118]. The reduction in fatigue life is through microstructural degradation [119]. It is thought that electrically accelerated fatigue is the result of localized electroplasticity [120,121]. Therefore, understanding the root cause of electrically induced bearing damage is an important first step in failure diagnosis and monitoring, which reduces critical failures and machine downtimes. Combined electro-tribodynamics investigations should be carried out as a form of multi-physics multi-scale analysis [122–125].

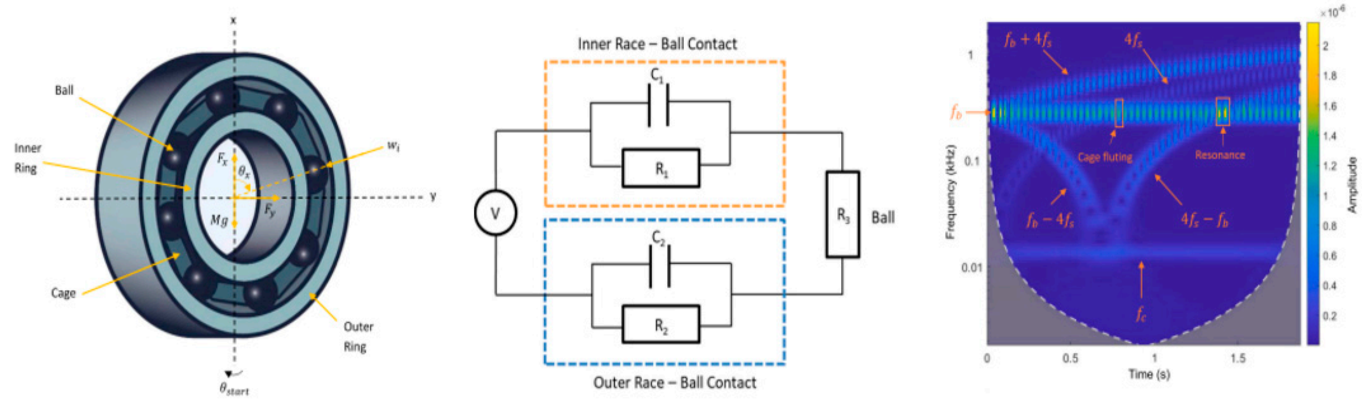

Figure 2. Combined tribodynamics and electrical contact analysis for prediction of electrical contact phenomena such as fluting in the bearing: schematics of rolling element bearing (**left**), the developed electrical circuit model (**middle**), and results (**right**) [118].

4. Tribology of Engineered Surfaces

Contacting surfaces are progressively engineered to suit specific applications. This is in order to reduce friction, wear, or fatigue, in line with the intended application. A large area of research and development includes controlling the surface topography and surface texturing and the introduction of coatings. More detailed methods of analysis have been developed to deal with rough surfaces under hydrodynamic, elastohydrodynamic, mixed, and boundary regimes of lubrication. In the case of vehicular powertrain sub-systems, studies of hydrodynamics of rough surfaces have been mostly directed to the piston–cylinder system because of its dominant share of the frictional losses of IC engines.

With improved instrumentation, the effects of surface topography, surface texturing, and applied coatings on the tribological performances of various contact conjunctions have been ascertained. There has been a plethora of such studies in the case of vehicular powertrains. In particular, there have been many fundamental experimental and numerical studies of layered solids (coatings) [56,126–131], some concerning cam–follower and gear meshing contacts with hard wear-resistant coatings to guard against contact fatigue under highly loaded contact conditions [132–140]. Therefore, contact mechanics analysis, specifically the evaluation of sub-surface stresses, is essential for determining the onset of fatigue spalling [54–59]. Nevertheless, refinement of current analyses is required to deal with muti-layered structures with graded elasticity, such as advanced coatings made of a mix of hard and soft bonded layers.

In recent years, there has been a trend toward the integration of surface engineering and tribology. This is mainly to enhance lubrication in various applications or under operating conditions that promote direct boundary interactions, resulting in increased friction and wear. In powertrain systems, any conditions leading to motion reversal (e.g., piston reversals at the top and bottom dead centers [141,142] and inlet reversals prior to and after the cam nose contact with the follower [143,144]) lead to a momentary cessation of lubricant entrainment into the contact. Therefore, boundary or mixed regimes of lubrication occur. A way of mitigating this is to create micro-reservoirs of lubricant entrapped in the contact, for example, by creating micro-wedges by fabricating surface textures in the form of dimples, grooves, etc. These are fabricated by a host of different methods, including mechanical indentation [145,146], chemical etching and electrochemical machining [147,148], and the use of laser-based techniques [149–151].

Surface texturing can be used in a wide range of tribological applications, from automotive engines [151–154] and bearings [155–157] to biomedical implants [158,159], and nanoelectromechanical and microelectromechanical systems (NEMS/MEMS) [160–162]. The appropriate texturing of surfaces can reduce friction (Figure 3), improve wear resistance, and enhance lubrication. It can also improve the surfaces' ability to retain and distribute lubricants, leading to improved performance and longer service life [150,163,164].

There are still a number of challenges, such as the optimal design of texture features including the shape, size, and distribution, and bespoke design for specific applications and operating conditions, although some pioneering work in this regard has already been reported [165–170]. Emerging robust developments with computationally efficient methods for designing surface textures include artificial neural networks (ANNs) [171]. Developing manufacturing methods that can be applied to many surfaces and for complex geometries at the industrial scale is still a major challenge. Additive manufacturing techniques can be explored for this purpose. New surface texturing techniques can create more complex and tailored surface attributes in the form of 3D hierarchical nanostructures or microstructures. The integration of texturing with other tribological technologies, such as advanced coatings and lubricant formulations, can lead to synergistic enhanced lubrication. Recent research in this regard includes combining surface texturing with self-lubricating coatings [172]. Surface texturing can also be employed in new research domains such as wearable devices [173], soft robotics [174], and renewable energy systems.

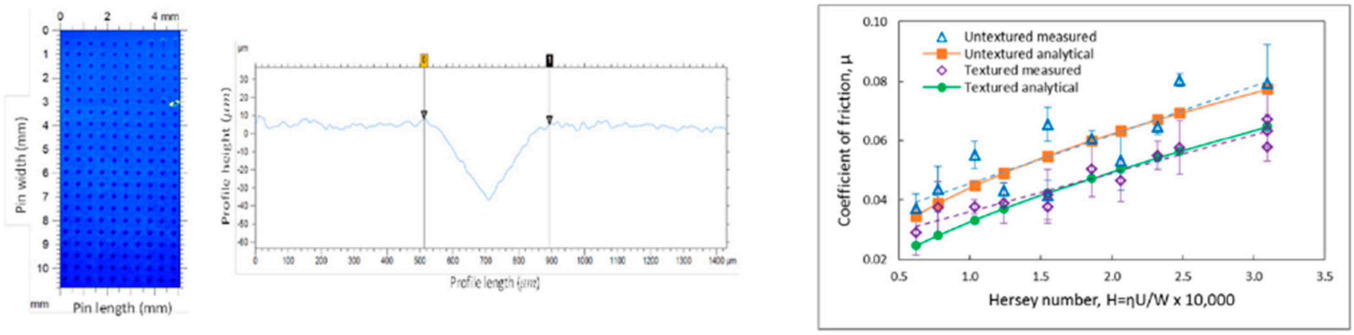

Figure 3. Combined numerical and experimental studies have shown a dramatic reduction in friction through use of tailored textured surfaces: an example of created microscale texture features (**left**) and experimental and numerical results (**right**) [146].

5. Artificial Intelligence in Tribology

Tribology will witness vast disciplinary expansion as more scientists, engineers, and laymen encounter it. Not all will be well versed in tribological interactions or indeed have appropriate predictive and design tools at their disposal. Therefore, the future is expected to bring increasing utilization of expert systems and artificial intelligence tools in tribological research. Despite the recent hype related to the development and use of artificial intelligence (AI) and machine learning (ML), their use dates back to the late 1980s. For example, in 1989, Li and Wu [175] proposed a pattern recognition and classification technique for the online detection of localized defects in bearings. Integrated sensing (e.g., vision) with parameters (e.g., moment invariants of an image) and the use of predicates (unique features to identify certain objects or patterns), together with a knowledge-based driven expert system, can discriminate between an assortment of objects. This approach has been commonplace in robotics and pattern recognition [176–178]. Others have used artificial neural networks (ANNs) for diagnosing localized defects in rolling element bearings [179–181].

AI-based techniques have been developed for automatic wear particle classification [182] or assessment of the useful lubricant life span [183]. Some early applications of AI in tribology can be found [184]. Later, Sinanoglu et al. [185] showed a feed forward three-layered ANN can provide better prediction of generated pressures in journal bearings under load disturbance than conventional modeling techniques. The development and use of AI techniques for tribological applications have been reviewed in [186–188].

The dominant area of research in early applications of AI in tribological research was online condition monitoring. This still remains a key area [189,190]. AI can be advantageous where no readily available fundamental physics-based governing relationships describing certain tribological phenomena exist. Problems become complex when all the required input data cannot be obtained directly or when there is measurement uncertainty.

One such area is lubricant formulation, including various additives and their individual interactions, as well as their interactions with the bounding contacting surfaces. A lubricant–surface combination as a bespoke system would be an ideal solution in many machines and mechanisms but requires considerable testing and evaluation [191]. In this regard, Bhaumik et al. [192] used ANN in combination with genetic algorithms (GA) to formulate a new lubricant with multiple friction modifiers (FMs). Recently, Campillio et al. [193] used AI for developing new lubricant dispersants. It is expected that AI can be used to formulate lubricants with particular molecular dispositions and rheologies to suit given applications. Rosenkranz et al. [194] discussed in detail how AI can be used for the design of material composition, which is of significance in tribology.

Using AI tools, Marian et al. [195] predicted the EHL film thickness with a good degree of accuracy. Singh et al. [196] used an ML-based surrogate model for predicting the maximum contact temperature in TEHL line contacts. More recently, Mousavirad et al. [171] have used transfer learning techniques in ANNs for the geometrical design of textured surfaces (Figure 4). These approaches have the potential of bringing AI tools to non-expert users for complex lubricated contact predictions that otherwise would require time-consuming and computationally intensive studies.

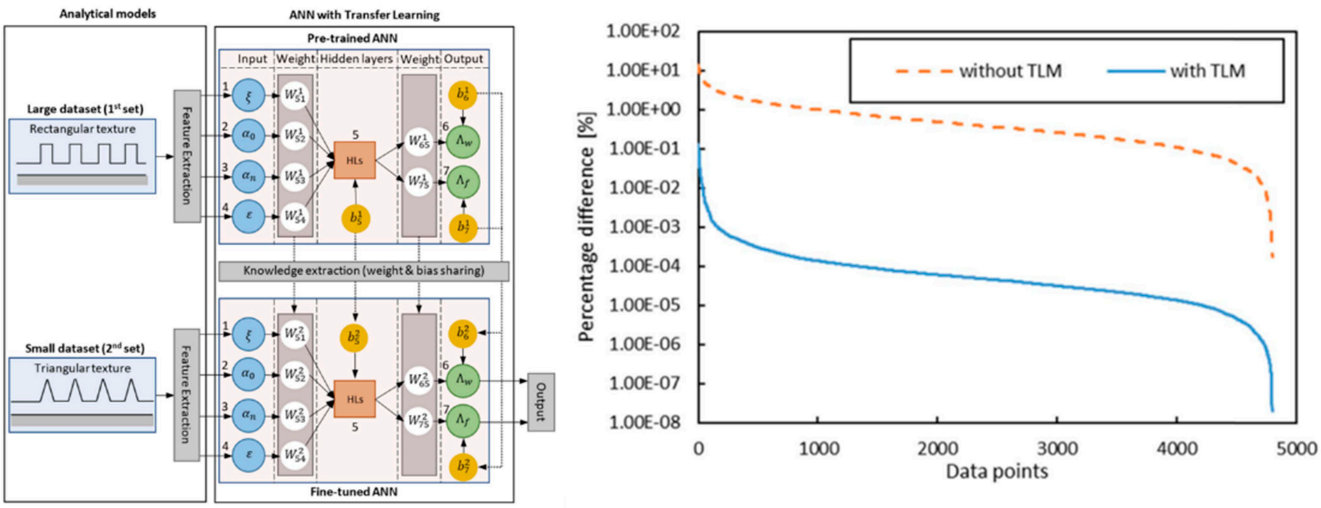

Figure 4. Among many potential applications of AI is its use in the design and optimization of textured surfaces: use of transfer learning methods in ANNs (**left**) in design of surface texture features with low friction (**right**) [171].

6. Biotribology and Biomimetics

With the growing aging world population, particularly in developed countries, an expanding area of research is biotribology. Tribology earnestly entered the domain of biological applications in the middle of the 20th century. The earliest research undertaken was in endo-articular joint arthroplasty, particularly hip joints. However, the mechanism of lubrication of synovial joints was not well understood. Several explanations were forwarded. Some favored boundary lubrication [197], some preferred hydrodynamics [198], and others proposed a weeping-type mechanism [199]. A landmark symposium was organized by Dowson and Neale on behalf of the Institution of Mechanical Engineers (IMechE) and the surgeons Charnley and Scales for the British Orthopaedic Association (BOA). Dowson [200] demonstrated that the main mechanism of lubrication was elastohydrodynamics with the squeeze film effect. Shortly afterward, Dowson, who was at this point the Chairman of the IMechE Tribology group, coined the term biotribology [201] and provided evidence of the complementary mechanisms of lubricant entrapment and enrichment [201–203]. A major problem was the failure of hip prostheses after a relatively short period. The femoral head was made of steel running against a polytetrafluoroethylene (PTFE) polymer acetabular member. The wear of PTFE was rapid, leading to the eventual need for revision surgery within a few years. At the time, Dowson was working on novel durable polymers for the Ministry of Defence, one of which, ultra-high molecular weight polyethylene (UHMWPE), was adopted by Charnley [204–206] for his new metal-on-polymer hip joint prosthesis with the diameter of the femoral head (known as the Charnley joint) determined by Dowson for optimum tribological performance. The Charnley joint remains the gold standard with durability averaging more than 20 years. It probably represents one of the greatest achievements in tribological research in the 20th century.

There have been many combinations of femoral head and acetabular cup materials for hip replacement arthroplasty. Dowson [207] presented his definitive review of endo-articular joint arthroplasty at the start of the new millennium. He also provided an in-depth introduction to hip joint replacements in Chapter 14 of [21]. Arthroplasty of the hip has been followed by the knee as well as by some other joints [208,209]. The study of hip and knee joint lubrication has led to the development of microelastohydrodynamics theory, entailing pressure perturbations and the enhanced load carrying capacity of contacts. The link between the microelastohydrodynamics of the rough cartilage surface [210,211] and the hydrodynamic lift of textured surfaces is a good example of biomimetic observation [151,212]. Another important outcome from the biotribology of joints has been the advent of biomimetics in tribology. This has led to many new areas of biotribological research. Dowson refers to these in [213] and in Chapter 14 of [21]. There is no doubt that biotribology will occupy a significant position in the future of tribological research.

With the exceptional performance of synovial fluids (nature's preferred lubricant), which is the result of millions of years of evolutionary processes, special attention has been paid to the physics of such lubricants. Synovial fluids and bovine serum possess many different types of molecules that are associated with each other in a complex fashion [214]. It must be noted that these lubricants are evolved not in isolation but along with the surfaces that they interact with and in particular the cartilage [215]. Therefore, it seems that Nature has treated tribological contacts as lubricant–surface systems.

The focus has been on understanding surfaces that act like cartilage and can mimic its behavior. Recent developments in hydrogels, which are essentially polymerized small molecules with large hydrophilic groups producing cross-links when they absorb water, have opened ap an avenue for the potential treatment of joint problems such as osteoarthritis [216]. The applications of hydrogels to drug delivery and release, mesenchymal stem cell entrapment, and cartilage regeneration have already been explored [216]. However, the structure and tribological performance of hydrogels is not yet well understood. The polymer network structure and absorption of water are key elements in the determination of tribological performance and the resulting coefficient of friction [217].

There are other areas in the biomedical and healthcare arenas where tribology can play a significant role. For instance, the materials used for dental restoration need to be resistant to wear and corrosion along with other obvious requirements such as biocompatibility. As highlighted in [218], ceramics have the advantage of improving wear resistance. However, they can be quite abrasive to the opposing interacting teeth. Any further dental tribological research and development requires consideration of practical clinical needs to establish guidelines and cross-communication between tribologists and clinicians [219].

Finally, an aspect that has achieved growing understanding is the role of tribology in the design and development of medical devices. The reduction in friction between endoscopic tools and esophagus or colon tissues [220] and tribological issues associated with cardiovascular devices [221] are a few examples.

7. Nanotribology

The trend in lightweight systems and downsized products includes the personalization of many small devices. This has led to downsizing and, in some cases, miniaturization as in microelectromechanical systems (MEMS) or nanoelectromechanical systems (NEMS). The diminutive devices use bearings, gears [222–224], pistons, joints, and other forms of contact [225,226] as also found in many traditional machines and mechanisms. Their contacts are minute and their separations almost in the vanishing scale. The advantages of small devices are negligible inertial dynamics, leading to smoother running operations. However, the kinetics of diminutive contacts deviate from those in the microscale (which are mostly governed by viscous forces). There is dominance of inter-molecular and surface forces, such as van der Waals, electrostatics, and a host of others. Diminutive contact conjunctions should run dry as predicted by Feynman [227] almost half a century ahead of nanoscale developments. This is due to the prohibitively high viscosity of any lubricant/fluid in such contacts. Consequently, adhesion plays a major role. For example, with rough-cut microgear teeth, as the speed of rotation falls below a normally high value of the order of tens of thousands of RPM, dry adhesion occurs [224]. However, in many cases, moisture can ingress into the vanishingly small contact conjunctions. In some cases, the tiny contacts are supplied with a basic lubricant, such as octamethylcyclotetrasiloxane (OMCTS). With light loads, the effects of inter-molecular forces become dominant in wet contacts. It has been shown that for non-polar lubricants such as OMCTS the effects of structural solvation and van der Waals forces are dominant in gaps of the order of a few to several molecular diameters of the intervening fluid [228–230]. This does not preclude a modest contribution to the load carrying capacity due to viscous action (hydrodynamics). When the film thickness is ultra-thin, pressure generated by the van der Waals inter-molecular forces and solvation should be considered.

The solvation effect was first noted by Chan and Horn [231]. They reported that for molecularly smooth contacts of mica surfaces and with the removal of the inlet meniscus force, the continuous supply of lubricant to the contact is drained from its outlet in a discrete fashion. This is in contravention of the continuity of flow conditions, which is the basis of the Navier–Stokes and Reynolds equations. Therefore, nanoscale lightly loaded contacts do not comply with continuum mechanics theories. In particular, solvation or structural force dominates whenever an ultra-thin film of the order of several molecular diameters of the intervening fluid is confined by solid barriers under very light loads. This causes layering of the fluid film and discrete molecular-level ejections at the contact outlet [232]. The key message of these findings is that the lubrication and mechanisms of friction and adhesion differ from those at the microscale.

With biomimetics making strong inroads into tribological research, the fundamental understanding of inter-molecular forces in nanoscale will become even more important in the future. This new area is open to further development, such as exploiting adhesion at nanoscale. For example, the remarkable small tokay gecko of mass 0.25–0.3 Kg can generate large adhesive forces, tens of times larger than its own weight, using more than 14,000 per mm^2 setae, each with 100–1000 spatulae in contact with surfaces. The gecko moves at speed up vertical walls or upside down and can carry loads several times its body weight [233–235]. The nanoscale kinetics comprise van der Waals and meniscus/capillary forces. To exploit the many mechanisms underlying the adhesion and locomotion used by small creatures and insects, a better understanding of nanotribological conditions is required, although progress has already been made [236–240]. Clearly, nanotribology plays an important role in multi-physics, multi-scale analyses (from microscales to mesoscales to nanoscales) [241,242].

Among many nanotribological studies, the use of nanoparticles in the formulation of future lubricants creates multi-faceted working fluids for applications such as electric vehicles, where thermal properties of the lubricant are of prime concern (Figure 5).

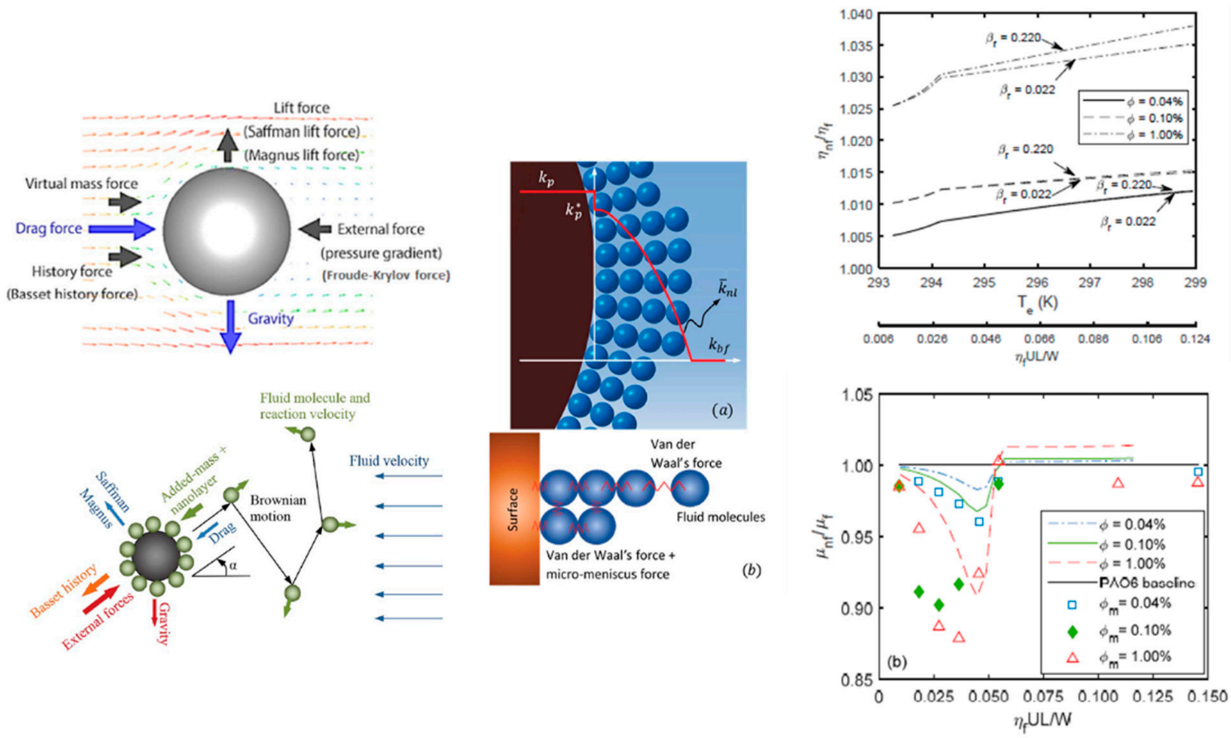

Figure 5. Forces exerted upon nanoparticles in a fluidic medium (**left**), the interaction of fluid molecules with the suspended nanoparticles (**middle**), and the effect upon lubricant viscosity and frictional properties of nanofluid (**right**) [243–245].

8. Computational and Multi-Scale Tribology

In recent years, fluid–structure interaction (FSI) computational tools have been widely developed. The first use of FSI in tribology was the seminal work of Dowson and Higginson [246] on providing a numerical solution to the elastohydrodynamic lubrication problem. Their method included the effect of generated fluid pressures upon the localized elastic deformation of contacting solid surfaces.

Tribological phenomena such as friction and wear have a multi-scale nature [191]. The rise in computational power has enabled the development of molecular dynamics (MD) models for studying phenomena from nanoscale through to macroscale (component level) [247]. Non-equilibrium molecular dynamics (NEMD) have been used in tribology to study the behavior of lubricant additives [248].

MD simulations are confined to very small spatial and temporal domains: a few atoms or molecules. Linking the findings at such scales to microscale contact behavior remains an unresolved issue. Nevertheless, MD simulations of lubricant molecules' interactions with atoms of solid contacting surfaces can provide realistic boundary conditions for larger-scale continuum mechanics.

A limitation of extensive computational models, such as those based on MD, CFD, or FEA or their combinations, is their unsuitability for timely industrial applications, where a plethora of contacts may exist. For industrial applications, analytical or semi-analytical design tools are favored. Insights from multi-scale analytical models can provide guidance for developing more detailed and targeted numerical analyses [43,106,249–251]. Multi-scale methods also require input data from various physical scales. Enhanced appropriate experimental approaches should be designed for this purpose (Figure 6) [252].

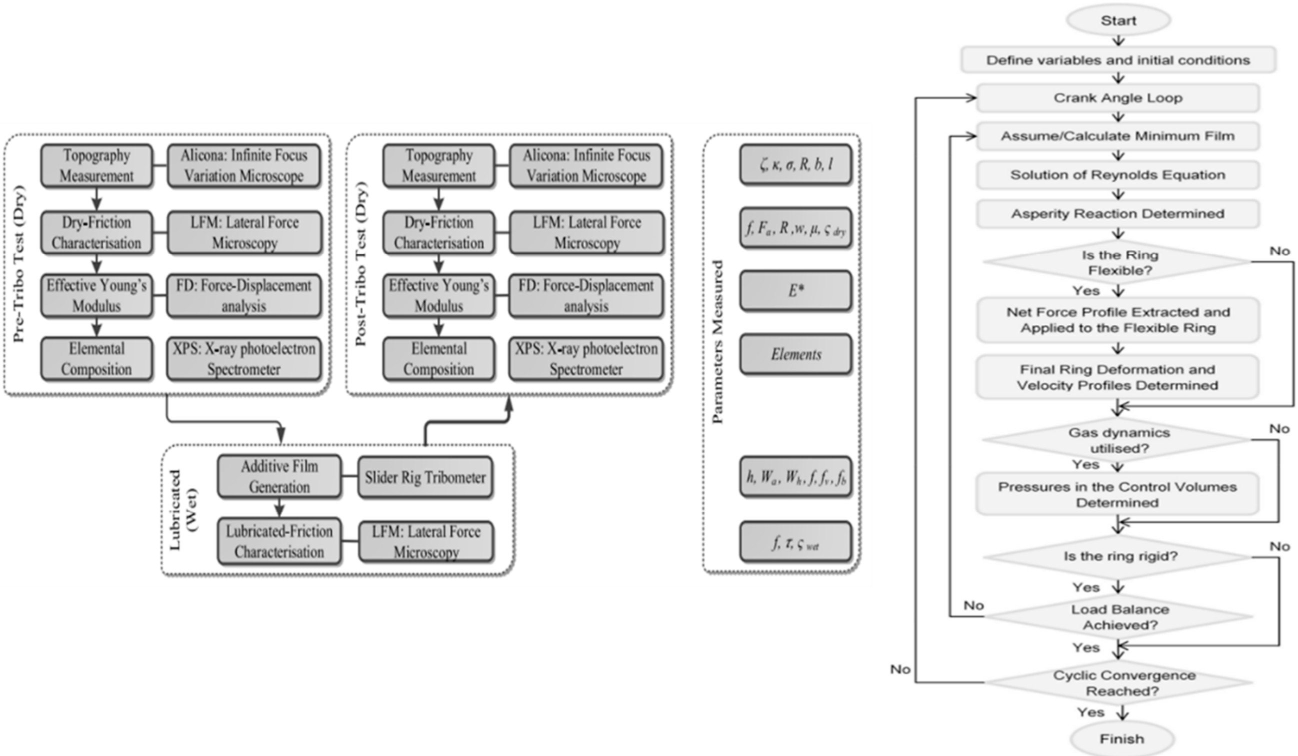

Figure 6. Multi-scale experimental approaches (**left**) require embedded multi-scale and often multi-physics numerical models (**right**) for cross-validation, providing further insight into the impact of multi-scale interactions [250–253].

9. Tribology in Space and Other Extreme Environments

There are additional tribological requirements for equipment and machinery intended for space operation. These include provisions to encounter the extreme conditions experienced in space, in orbit around other planets, or on their surfaces. The equipment must withstand the harsh transient conditions experienced during the launch and subsequent landing of space vehicles and also the temperature variation from cryogenic levels to hundreds of degrees Celsius. The very low pressures or vacuo and electromagnetic radiation can cause evaporation and degradation of liquid lubricants. Therefore, solid lubricants are usually preferred whenever possible. Research into the use of solid lubricants such as MoS2 and WS2 or polymers, as well as the characterization of their behavior under various tribological conditions, has been carried out [254–256]. The use of novel lubricants, such as ionic fluids, has been explored for space applications [257,258].

10. Measurements, Monitoring, and Tribo-Sensing

The monitoring and measurement of tribological contacts can provide very useful information regarding the nature of interactions and the underlying physics. Measurements are also critical in providing data for the validation of models. Early works on experimental evaluation have included the measurement of lubricant film thickness, generated contact pressures, temperature, and friction. One of the first techniques developed was the use of optical interferometry [259,260]. A seminal paper by Gohar and Cameron [261] used optical interferometry for the observation and measurement of film thickness in elastohydrodynamic lubricated point contacts. Optical interferometric studies of finite line contacts ensued [262–264]. These studies have significantly improved the understanding of concentrated lubricated contacts and led to the establishment and validation of fundamental predictive methods for all forms EHL contacts [265–270]. These methods were developed to encompass optical spectroscopic measurements of ultra-thin films in nanotribological contacts [271–275]. They have also been used for the validation of nanotribological contact analysis of molecular-level lubricant films under transient conditions [232]. Further advances in nano- and molecular-level tribology are expected in the future.

Measuring the elastohydrodynamic pressures from minute concentrated contacts of rolling element bearings has always been a challenge. The pioneering work of Bridgman [276], developing pressure-sensitive bulk manganin with low temperature sensitivity, provided an opportunity for the development of miniature pressure transducers. These were deposited using flash evaporation to study EHL contacts [277,278]. The initial devices were rather crude and unable to resolve the high elastohydrodynamic pressure spikes at the contact exit. Refined manganin microtransducers with active element dimensions of $5 \times 10\ \mu m^2$ and thickness between 100 and 300 Å were developed through RF sputtering of bulk manganin powder under high vacuum at Imperial College [279]. They were used for elastohydrodynamic line contact conditions in roller bearings or in a disc machine and for the circular point contact of a ball and a flat glass race [280–284]. These initial precise measurements provided excellent insight into concentrated elastohydrodynamic contacts. They also provided a means of validating a detailed analysis under impacting conditions [233,285]. The involved and resource-extensive deposition methods limited this form of tribo-sensing, resulting in a dearth of further work. However, improved deposition techniques have opened up many research opportunities in active tribology applications.

Measuring friction is an important issue because of the continuing desire to reduce frictional power losses and harmful emissions and enhance fuel efficiency. Measurement methods for piston–cylinder friction and film thickness have involved the use of various sensors, including proximity and capacitive devices [286–290], laser-induced fluorescence techniques [291–295], and ultrasonic sensors [296–300]. Floating liners (Figure 7) are flexibly attached to stationary cylinder bores via preloaded piezoelectric load cells and dragged by the moving piston, enabling direct in situ measurement of friction [301–306]. The data thus obtained have been instrumental in understanding the different regimes of lubrication in the various parts of an engine cycle (i.e., compression, power, exhaust, and intake in the four-stroke process). The results generally show hydrodynamics/elastohydrodynamics, depending on the engine type, apart from the transition from the compression stroke to the power stroke, where the regime of lubrication is mixed or boundary. Floating liner measurements have proved to be very useful for the validation and refinement of analytical and numerical tribodynamic tools [142,307–310].

Active tribo-sensing (monitoring and intervening with contact conditions) requires integrated monitoring and active actuation. An example of active tribo-sensing is the use of surface charge variation for condition monitoring and wear assessment [311]. Recently, electronic textiles (e-textiles), utilizing conductive nanotubes (CNTs) or silver (Ag) and polytetrafluoroethylene yarn, have been developed to act as touch sensors, enabling human–machine interactions [312,313]. Powering sensors usually requires an energy source such as batteries, which add to the system weight and inertia and have a limited life span. Active on-the-spot tribo-sensing generates power that can be used for localized small embedded sensors such as triboelectric nanogenerators (TENGs). Friction generated from the rubbing motion in some contacts can induce a triboelectric effect that can power the TENGs themselves. These can be used as energy harvesting devices with superior power-to-volume and power-to-weight ratios compared with traditional devices [314]. TENGS are ideal for harvesting energy at low frequencies [315]. A number of issues to overcome with TENGs comprise their high output impedance and the wear of their polymeric materials. In addition, the existence of small wear particles can reduce their power output [314,316]. Controlling environmental parameters such as humidity, temperature, and atmospheric pressure can also significantly alter their power output [316]. Modifying materials at nanoscale to use in TENGs for better performance is an emerging area of research [317,318].

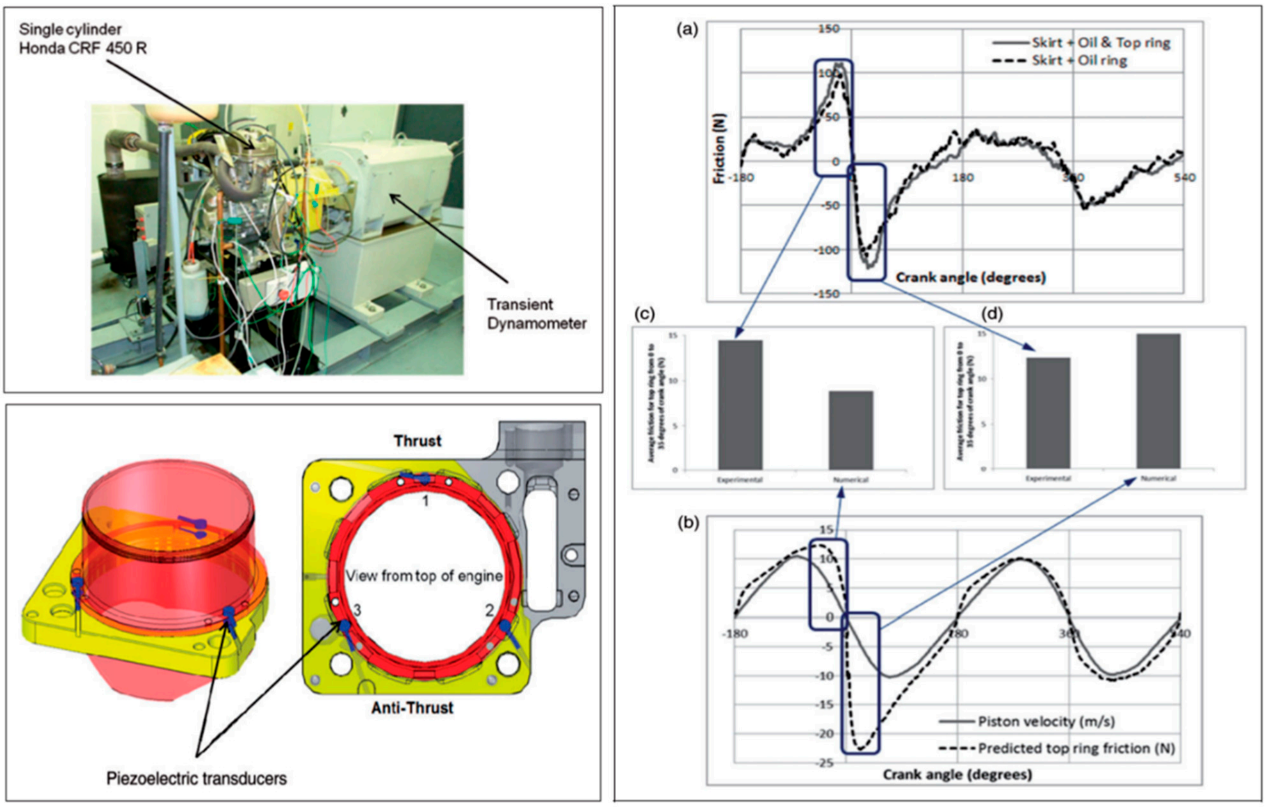

Figure 7. Floating liners are used for in situ measurement of in-cylinder friction in IC engines and are also used for validation of numerical models: engine test configuration and developed floating liner (**left**) and measurements used for model validation (**right**) [142].

11. Closure

The paper discusses the multi-disciplinary nature of tribology and the broad spectrum of its applications in Nature, engineering, and physical sciences. Tribology interacts with many other disciplines such as dynamics, vibration, thermodynamics, contact mechanics, surface engineering, rheology, and biology, thereby extending its reach and impact to integrate with topics such as additive manufacturing, artificial intelligence and biomimetics.

A key feature of tribology is its relevance to multi-scale applications, a point which is emphasized in the current discourse. Tribology is critical to the palliation of friction and to the mitigation of emissions to counter impending climate disaster. It also plays a growing role in human health (biotribology).

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