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Tribotronics—Towards active tribology

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Abstract

A constant trend towards more compact mechanical systems with higher power densities and increased thermo-mechanical loads emphasises the importance of the development of new design approaches and novel tribological systems. Ignoring this may cause a significant slow down in technological and industrial development. Tribotronics or active tribology based on adaptive performance is thought of as being critical in the implementation of smart machine concepts. Recognition of the importance of tribotronics, or active control of system loss outputs, such as those through friction and wear will have significant beneficial economic consequences as a result of the associated accelerated rate of technological progress. These smart tribotronic systems can be embedded in a great variety of machines and mechanisms. If this integration is made at the design stage, products that are more flexible, efficient and reliable can be produced. The concept of tribotronics is presented and discussed in this paper. Some illustrative examples that show the feasibility of an "active" approach are given. In addition, various possibilities already reported in literature are discussed.

Keywords: New design approach; Novel tribological systems; Embedded systems

1. Tribology field overview

Our modern society depends to a great extent on the functionality, reliability and efficiency of all the machinery that we see around us and use every day. All these machines involve numerous mechanical contacts between various surfaces. A contact between two surfaces that are in motion relative to each other will result in friction and wear. Friction leads to energy loss and thus adversely affects machine efficiency. Wear is responsible for shortened machine service life, machine failure and enormous losses due to interrupted production. To minimise the impact of friction and wear on machine performance lubrication is usually employed. Efficient and effective design of such rubbing and commonly lubricated contacts is enabled by tribology.

Forty years have already passed since the publication of the famous Jost report in which the term tribology was introduced and defined as "the science and technology of interacting surfaces in relative motion and of the practices related hereto" [1]. During these years, tribological practices have successfully been integrated into design procedures for various machines and mechanisms. This has allowed significant economic savings to be obtained through improvements in machine performance and reliability. These savings are not only on costs related to maintenance but also due to reduced consumption of energy and materials.

Achieving lower consumption as well as a decrease in polluting emissions are favourable for protection of the environment. There is now a continuously growing emphasis on environmental issues in contemporary machine design and tribology plays a key role in its implementation. To cope with environmental concerns a lubricant should now also be considered as a construction or design element.

Realisation of tribology-based machine design helps in developing more compact and low-weight machinery. For example, hydraulic motors are much smaller today than they were 30 years ago. Fig. 1 shows a comparison between hydraulic motors having the same operating characteristics but manufactured in different years. As can be seen, a five-fold reduction in weight was achieved without adverse effects on performance. Compact machines in turn require

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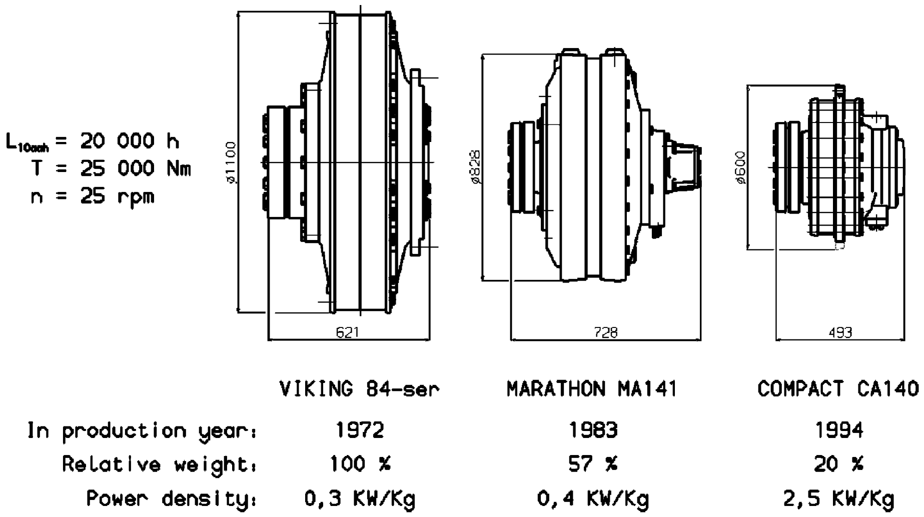

Fig. 1. Development trend of Hägglunds hydraulic motors (courtesy of Hägglunds Drives).

smaller components. Development trends in rolling element bearings give an illustrative example, (Fig. 2). During a period of 40 years bearing weight has reduced by more than three times. This continuous trend towards more compact mechanical systems and their components results in higher power densities and consequently increased thermo-mechanical loads. At the same time, there are strategic concerns about future alternative designs as power densities cannot be increased indefinitely.

In order to resolve this problem and to cope with the ever increasing rate of technological progress, improved lubrication techniques and, more importantly, pioneering approaches and solutions to the design and operation of tribological contacts in various types of machinery must be found. Present tribological contacts are passive, i.e. their performance cannot be tuned online. Geometry, material and oil properties are all pre-determined so that a system is sensitive to any increase in severity of operating conditions. There is then a question of what can be done to promote improved safety, performance and reliability of tribological contacts. Can we affect in some way those pre-determined parameters? A solution is to use tribotronics.

2. Definition

The term tribotronics, coined at the Division of Machine Elements, Luleå University of Technology, applies to the integration of tribology and electronics. Electronic control is required to transport tribological systems to a dramatically higher level of performance. The definition of tribotronics may resemble a mechatronic system but there exists essential differences. A mechatronic system uses only information from inputs and functional or useful outputs of a mechanical system to control its operation. The functional outputs include rotational speed, torque, load, etc. The main principle of tribotronics is to use additional so-called loss outputs. These outputs are friction, wear, vibration, etc. The purpose of tribotronics is to control these loss outputs and through doing so considerably improve performance, efficiency and reliability of the tribological units and therefore the entire machinery.

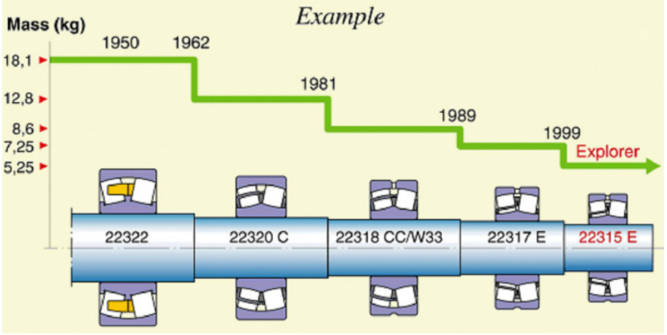

Fig. 2. Development trend of rolling element bearings (courtesy of SKF ERC).

3. Design philosophy

A tribotronic system includes four central components interacting as shown in Fig. 3. The conditions of a tribological system are monitored by sensors that provide information on temperature, pressure, friction, vibration, oil properties such as total acid number or additive depletion, and other parameters of interest. The signals from these sensors are processed and transmitted to the control unit.

In the computational or decision making part, real-time software based on tribological algorithms calculates the required action which is then implemented by actuators. Such a system is thus autonomous and self-adjusting. This allows for on-line tuning of the tribological system for the best performance. Such self-adjusting systems can be found in nature, in living creatures. A human knee joint is a typical example of a natural tribotronic system.

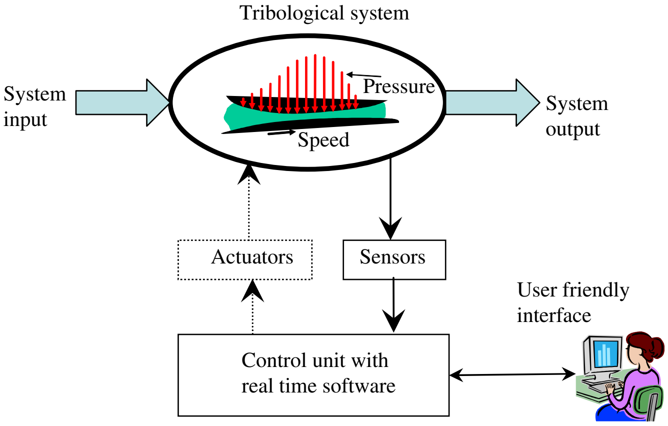

Fig. 3. Tribotronic system and its elements.

4. Implementation

The type of tribological system defines interface components, namely sensing and actuating parts. For example, a non-conformal contact requires much smaller sensors than a conformal contact. In both cases, the correct choice or design of sensors is essential since sensors in the tribotronic systems are as important as the senses are to the human being.

The sensing part can be designed using knowledge and experience accumulated in condition monitoring, which is now widely used in industry to identify the nature and severity of machinery faults and to prevent machinery breakdown. A substantial quantity of faults are due to tribological problems so sensors employed for monitoring can be adapted for tribotronic applications. Decision making algorithms that are in use in modern monitoring systems can also be completely or partly utilised.

The decision making or computational part of a tribotronic system should however be more versatile as its fast response is a necessity. Of course, pre-tribotronic systems with the in-built ability for regulation can be found. This can be illustrated by a clutch used in some four-wheel drives.

A schematic of the clutch is shown in Fig. 4. The clutch is mounted on the drive shaft. The shaft on the left-hand side in the figure is connected to the rear axle of the vehicle whereas the right-hand shaft is connected to the front axle via the drive shaft. When a speed difference occurs between the front and rear axle, a cam on the rear axle causes a pumping action on the hydraulic piston pump. The hydraulic pressure generated by the pump is applied to the clutch pack, which causes a reduction in the speed difference between the shafts, thus engaging the all-wheel drive.

A throttle valve allows for the torque transmitted by the clutch to be controlled. The main limitation of this system is that computation or decision making is performed in the same medium where the main effect flow takes place. The cam, or more exactly its shape, performs the role of computation. This causes significant loss of efficiency. In a tribotronic system this computation would be done by a microprocessor and executed by an actuator that must have enough power to engage the clutch.

Choice of actuators for tribological contacts is the most difficult stage as there is no general concept of their design. The question is that of how we can affect loss outputs such as friction, wear and vibration and develop corresponding actuators.

Some examples can flesh out the concept of tribotronic systems and the feasibility of the active approach.

5. Examples

A common way of managing friction and wear is by eliminating mechanical contact between the moving surfaces by means of a thin film of oil, water or even air. In this case, wear is eliminated completely while friction is limited to viscous shear forces within a thin fluid film. The main tribological problem is then to retain the lubricant in the contact as the lubricant is squeezed out of the contact under the action of a load force. Generally, this can be achieved by increasing lubricant viscosity and/or sliding speed and/or reducing the applied load. Unfortunately, this is rarely possible as the load and speed are predetermined parameters and cannot be altered, whereas too thick lubricant causes significant power loss.

Is it then possible to control oil flow in the contact? There are two illustrative examples that show the feasibility of the active flow approach. The first example is performance of a typical hydrostatic bearing that can be affected externally by changing flow rate and pressure of incoming oil. In this way its load carrying capacity and film thickness are controlled on-line. Depending on bearing design it can also have an in-built, passive ability to accommodate misalignment.

Another example is a tilting-pad bearing. Pads of the bearing are able to change inclination depending on operating conditions in such a way that an optimum load carrying capacity is always achieved. This passive ability of the bearing to adapt itself to changes in operating conditions provides its excellent performance characteristics. Some researchers enhanced this ability by creating an actively controlled bearing, (Fig. 5). The idea is to change oil film geometry by forcing the pads of a journal bearing to move in the radial direction. Pressurised hydraulic cylinders [3] or piezoelectric actuators [4] were used in place of the conventional fixed pad pivots. Another approach is to use a mechanical device [5], which can change pad inclination and thus film geometry. The imposed variations in the film geometry can then be used to enhance bearing operating characteristics, e.g. dynamic properties or load carrying capacity.

These "geometry" methods have one thing in common: they use a change in oil film wedge, in this case at the inlet and outlet, to affect system performance. Indeed, if we are

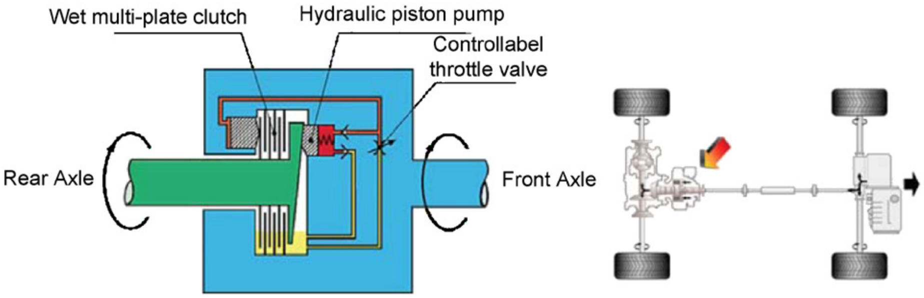

Fig. 4. Schematic of a limited slip clutch [2].

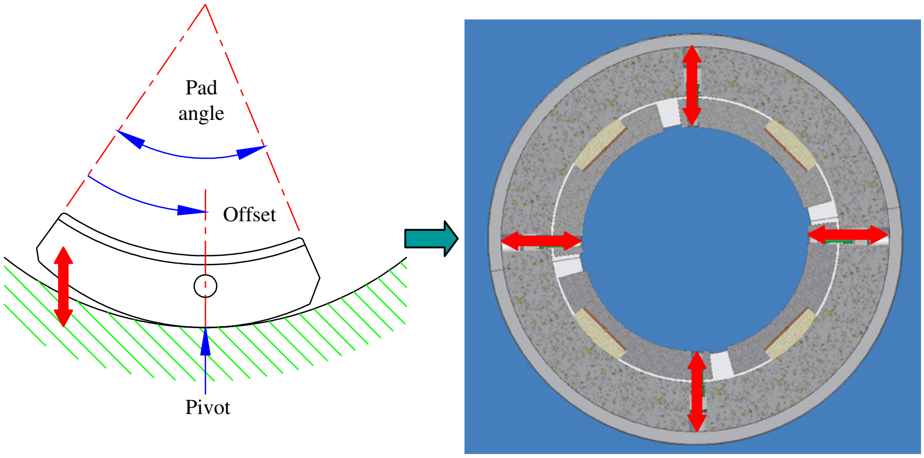

Fig. 5. An adjustable tilting pad journal bearing.

able to affect conditions at the oil film boundaries we may be able to improve performance of a tribological system.

Some possibilities have already been reported in literature. Apart from changing the film geometry as discussed above, a powerful technique for altering the fluid flow pattern is to introduce slip at the fluid–surface interface. This means that it will be possible for the fluid molecules immediately adjacent to the surface of a solid to move with a different velocity to that of the solid. The velocity profiles and fluid flow rate can thus be changed giving a possibility to control load carrying capacity and other tribological characteristics of the contact.

The tribological implications of slip have been studied by several authors. It was shown that if a heterogeneous surface is constructed on which slip occurs in certain regions and is absent in others, the contact will have an increased load support, substantially larger than that produced by a conventional contact.

There are also other methods that can be employed to affect the flow pattern in the contact. Electro- and magneto-rheological fluids can be used for this purpose. These fluids respond to an applied electric or magnetic field with a reversible dramatic change in rheological behaviour. In a strong field their viscoelastic properties are changed as fast as the field can be applied. This makes them very attractive for use in the “smart” tribological contacts. Hydrodynamic bearings with liquid crystal film controllable by an electric field show promising results as reported in [6,7]. A preliminary comparative study of the boundary lubrication performance of typical electro- and magneto-rheological fluids was reported in [8]. The results show that magneto-rheological fluids have some advantages over their electro-rheological counterparts.

At very high load or/and low-sliding speed the average thickness of the lubricant film becomes much smaller than the surface roughness with the load distributed only by asperity contact. This is the region of boundary layer lubrication. Under these conditions, the function of lubricants without special additives is to try to maintain an atomically thin film that can prevent metal-to-metal contact. A further increase in load produces metal-to-metal contact and rapid failure. Antiwear and extreme pressure additives are highly effective at extending the load carrying capability of many metal surfaces in the regions of mixed and boundary layer lubrication.

Generally, it is thought that antiwear tribofilms are formed due to additive decomposition caused by local heating. This takes place at high-power dissipation, which is a product of load, speed and friction. Additive activation is thus passive in a way similar to the tilting-pad bearing that adapts itself to changes in operating conditions due to variable pad inclination. Once again, it may be possible to control additive activation by, for example, providing local heating by an external energy source. Performance of tribological contacts can thus be tuned and continuously adapted to current operating conditions. This is especially useful during start-ups when contact temperature is low and tribofilms have not yet been formed. Using an external trigger, additive decomposition may be activated even at lower temperatures to form tribofilms and consequently reduce friction and wear.

Right choice of additives for boundary lubricated contacts is also essential from the vibration point of view. A typical problem in wet clutches that may arise during operation is shudder or friction-induced vibration. The onset of vibration depends on the slope of friction-velocity characteristic. If the slope is negative the risk is high. A conventional or passive way to solve the problem is to select an appropriate package of oil additives. An alternative active approach to control vibration was presented in [9]. The idea is to apply a small dynamic load, 50 times smaller than the static normal load, to suppress self-excited vibration. It was demonstrated that fluctuations of the normal load can change damping from negative to positive eliminating a risk for the onset of shudder. The method reported can be applied to the clutch considered in Section 3, (Fig. 5).

Another illustrative example of an active tribological system can be found in [10,11]. This was designed for space applications where reliability and durability of tribological contacts are critical. Generally, solid lubricants are employed to lubricate various tribocontacts in this application. They are applied before the launch of a space system and contact lubricity cannot be controlled afterwards. In addition, the coating wears out with time which leads to increased friction. Such contacts are thus passive. An innovative way is to provide lubrication on demand when, for example, friction starts increasing. A ball bearing with such a system is shown in Fig. 6. Solid lubricant, in this case indium, is applied by a micro heater. The heater is activated by the control system box depending on friction measured by the friction sensor. Indium is evaporated and lubricates the bearing resulting in lower friction. The micro heater performs a function of a tribo-actuator.

This system also allows for remote control which makes it very flexible. Another important advantage is that coefficient of friction obtained by such in situ lubrication is lower compared to pre-coated surfaces. This exemplifies the high potential of active tribological systems for improved performance.

Friction of carbon nitride coatings can be controlled by gas lubrication as shown in [12,13]. In particular, coefficient of friction in a carbon nitride/silicon carbide, CN_x/Si_3N_4, contact can be decreased from 0.2 to 0.01 by changing the rate of nitrogen gas flow and the blow angle. The lowest coefficient is reached at a certain optimum flow rate. This technology of absorbed gas lubrication may lead to efficient friction control in MEMS and precision machinery in the future.

All these examples taken together show that implementation of the tribotronic concept will be a vital step towards the more sustainable and "smart" machines and mechanisms of the next generation. There is therefore an urgent demand for a combined fundamental and applied study of the concept of actively controlled tribological contacts.

6. Challenges

The overall challenge is to ensure joint efforts of tribologists and electronic/software engineers for efficient development of tribotronic systems. An important issue is coordination of this work. Tribologists can take responsibility for this process especially in view of the efforts required for design of novel tribo actuators. It is also necessary to combine the knowledge that tribologists possess with the knowledge accumulated in mechatronics. Mathematical models developed by tribologists to describe the relationship between the input and output of tribomechanical systems must be adapted for use in control/decision making systems. The models are also required to accurately describe tribological system dynamic response to changes in input parameters. Software must operate within timing and response constraints imposed by the tribological system being controlled. In other words, the software must embody the concept of duration.

The hardware interface between a tribomechanical system and an electronic control system must also be further developed. As was mentioned previously, sensors used in condition monitoring/maintenance can be employed to a certain extent. Over the years, industry has

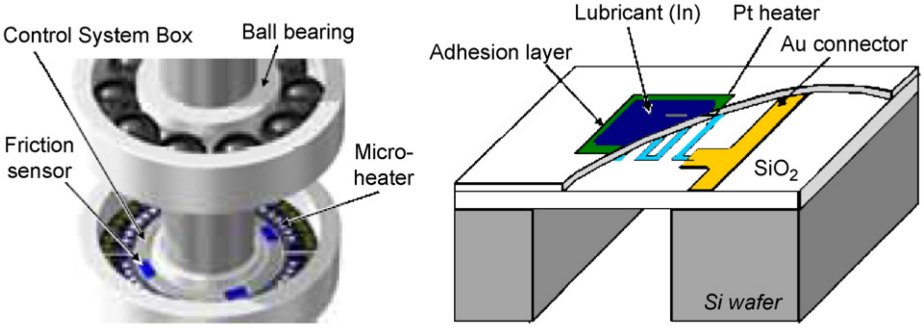

Fig. 6. Schematic of the self-lubricated ball bearing and a micro heater device [11].

made a shift from periodic to proactive maintenance. The level of maintenance is very high and upcoming failures can be monitored while remedial actions can be planned. However, it is still a challenge to properly and timely identify tribological problems that make up a significant portion of all machine faults. The reason for this is, in part, a lack of robust and reliable sensors. Further development work is thus required in this direction with a special focus on more versatile sensors that can monitor more than one parameter at a time.

Today actuators responsible for transforming the output of a control system into a controlling action on a tribological unit remain the most underdeveloped component, shown by a dotted line in Fig. 3. Thus, more research should be focused on the methods and means of affecting tribo-contact performance. Actuators are undoubtedly the most serious challenge to deal with.

Finally, all these parts, models, sensors, actuators must then be synergistically combined with controllers into actual tribotronic systems, tested and introduced to industry.

7. Summary

The concept of tribotronics and an approach to the design of tribotronic systems have been presented. The purpose of introducing this concept is to define the guidelines for development of smart tribological systems of the next generation and to consolidate engineering efforts from the relevant fields for realisation of this vision. Rapid developments in machine design, e.g. continuous trend to higher power densities, demand pioneering, innovative solutions to keep pushing the boundaries of what is achievable. Intelligence, flexibility and controllability are now the key issues.

A successful combination of the knowledge accumulated in tribology, electronics, control engineering and mechatronics will create an opportunity for development of new types of embedded tribotronic systems that can be used to improve functional performance of industrial machinery. With this novel active insight the design tribologist will be better equipped for reaching innovative solutions to extend the limit of machine service life, durability and reliability.

Acknowledgements

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