Machine Elements – Shaping the Future through Continuous Evolution

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The well and the wheel — some of the oldest inventions of mankind — were themselves already dependent on machine elements. Over the years, ropes as the oldest class of machine elements enabled numerous innovations such as draw wells, sailing and later aircraft construction. Machine elements have always been at the center of numerous innovations. More than ever, the further development of classic machine elements, such as gears and bearings, enables innovative solutions for tomorrow's problems: a stocktaking.

Figure 1 Machine elements in everyday life as a symbol for the settings on the smartphone, in heraldry using the example of the Mainz wheel, and as a symbol of charitable organizations.

Machine Elements Are Everywhere

In everyday speech, even technophobes use machine elements in many places to figuratively represent their opinions. Sayings such as "Don't reinvent the wheel" or "Sand in the gears" are ubiquitous, generally understood and accepted. It is also impossible to imagine everyday life without the symbolism of machine elements. Just imagine searching for the settings on a smartphone without the stylized gear wheel, the Mainz coat of arms without the wheel, or the Rotary Club without the machine elements in its trademark (Fig. 1). Many people are not aware of the fact that many machine elements originate from a development spanning thousands of years and that today it is impossible to imagine modern mechanical and plant engineering products without them.

This article, developed by the Wissenschaftliche Gesellschaft für Produktentwicklung (Scientific Society for Product Development, WiGeP), analyzes the evolution of two selected classes of machine elements, formulates a law to describe their development in terms of Moore's law and extrapolates into the future. While transistors, for whose architecture Moore's law was originally formulated (Ref. 1), have now physically reached the highest spatial density, the authors believe that much is still achievable in machine elements due to the possibilities for synthesizing new system solutions. Despite the very long history of individual machine elements, they are constantly being developed further and digitalization offers machine elements a high potential for innovation.

Figure 2 Improved performance of the wheel bearing. From the unlubricated plain bearing to the lifetime-lubricated double-row angular contact ball bearing in back-to-back arrangement with form fit connection to the cardan shaft (right-hand image courtesy of SKF, Ref. 2).

Continuous Power Enhancement

The evolution of machine elements and their future as an element of design are analyzed here using the example of rolling bearings and gears. Due to the bearing as a functional unit, the invention of the wheel about 6600 years ago became a sustainable innovation. With the wheel centered and guided by the bearing, the acting forces were supported (Fig. 2, left). A modern wheel bearing has the same basic functions, can also transmit the drive power practically without loss and, in many cases, also provides high-resolution rotational speed information via specific sensors (for example, in a modern ABS system).

A similar development can be observed in the example of linear guides (Fig. 3). Whereas about 4600 years ago wooden rollers as rolling elements facilitated the construction of pyramids, with modern slides guidance accuracies in the range of micrometers are possible due to advances in manufacturing technology for the hardened and precision-ground rolling elements as well as the preload of the rolling contacts. An integrated position measurement system can resolve the same accuracy. Low-friction seals and optimized rolling contacts have made it possible to continuously reduce friction losses over the past decades.

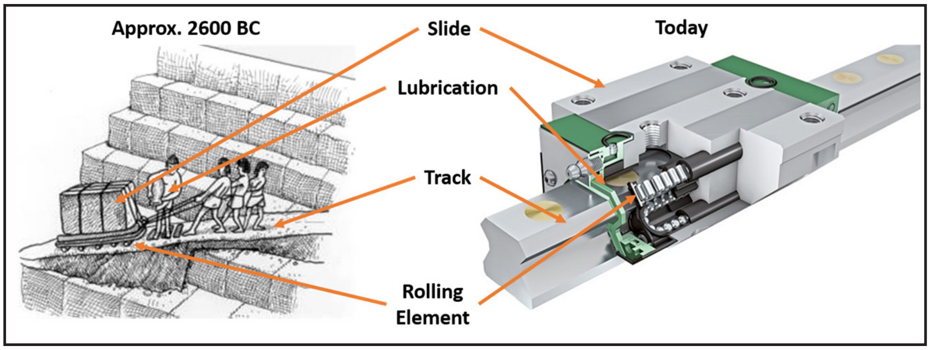

Figure 3 Performance increase using the example of the linear guide. On the left with wooden rolling elements and sand as an adhesive in the open system, on the right with grease-lubricated precision rollers as a closed system. (Left image copyright Vladimir Filipovic, ZUNS, Belgrade / La main à la pâte. Right image courtesy of Schaeffler).

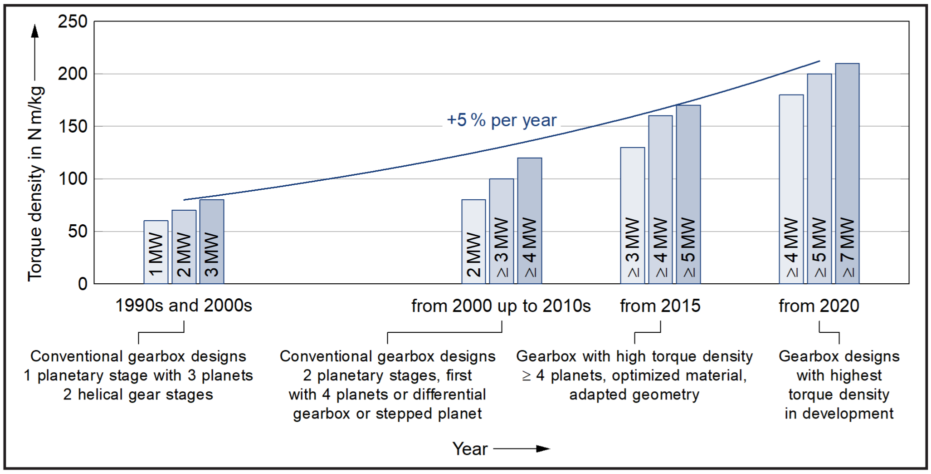

Figure 4 Development of torque density of gearboxes for wind turbines (based on Ref. 6).

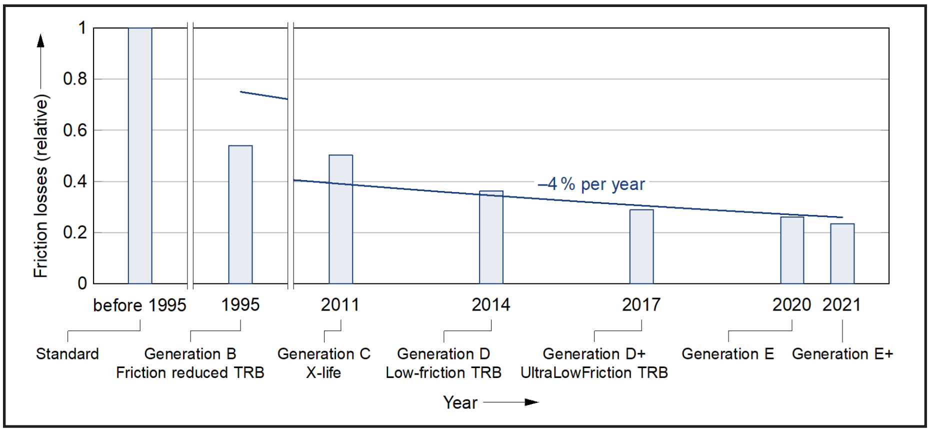

Figure 5 Development of friction losses of tapered roller bearings (TRB) (based on Ref. 8).

Moore's Law

In 1965, Gordon Moore made a prediction about the development of semiconductor technology (Ref. 1). His prediction is known as Moore's law and states that the number of transistors per unit area will double every year, corresponding to an exponential increase. Moore's law has so far proven to be largely correct. However, the further reduction in the size of transistors is likely to reach its limits in the coming years. Alternatives to conventional transistor design or new approaches to chip architecture are needed for the future (Ref. 3).

Whether Moore's law can also be applied to machine elements will be considered in this section. In order to be able to assess the further development of machine elements and the technical systems assembled from them, suitable quantification on the basis of technical characteristics is necessary.

Torque Density of Gearboxes for Wind Turbines

In wind turbines, the increasing rotor diameters led to an increase in the rated power. At the same time, a reduction of the rotor speed is necessary to maintain the permissible blade tip speed (Ref. 4). This results in a high increase in input torque. To evaluate the development of gearboxes for wind turbines, the torque density as a quotient of the rated torque of the gearbox and the weight of the gearbox is suitable (Refs. 5, 6).

Figure 4 suggests an annual increase in torque density of about five percent. This corresponds to an exponential increase as in Moore's law, although at a lower growth rate.

The development of torque density is due, among other things, to lightweight construction, new materials and coatings, and optimized macro- and micro-geometries (Ref. 6). Smaller plain bearings allow higher power densities by load sharing on more planets and enable new gear concepts (Ref. 7).

Frictional Losses of Tapered Roller Bearings

In addition to the increase in load carrying capacity, today ever greater demands are being formulated for the energy efficiency of machine elements.

Figure 5 shows the development of friction losses of tapered roller bearings over time. Friction decreases exponentially and roughly follows the plotted curve of an annual decrease of four percent.

Improvements were achieved, among other things, by improving the surface quality of bearing rings and rolling elements, adapting the flange and cage geometry and the lubricants. To reduce friction while maintaining the necessary load carrying capacity, application-related, computer-aided design optimizations are carried out (Ref. 8).

Significance of the Validity of Moore's Law for Machine Elements

For the two examples presented, a similar exponential development can be seen, albeit one that extends over a longer period of time, as with Moore's law. In the case of other industrial gear units, too, it has been possible over the years to significantly increase calculation accuracy and to incorporate application knowledge and findings from a wide variety of application areas into development, which has led to an increase in torque density and an increase in bearing service life and efficiency (Refs. 9, 10). In summary, the continuous further development is based on the one hand on an improvement of individual machine elements, and on the other hand on the development of new concepts for technical systems.

Machine Elements Open Up New Possibilities

The further development of machine elements goes well beyond increasing power density or reducing friction losses. Innovations in the field of machine elements also open up entirely new possibilities for increasing the functionality and sustainability of machines and plants.

Figure 6 Geared turbofan — planetary gear stage (left) and comparison of Airbus A320-200 and Airbus A320 neo (right). (Left image courtesy of Pratt & Whitney, Right image courtesy of Airbus).

Geared Turbofan

In aircraft engines of the latest generation, a planetary gear stage as shown in Figure 6 is used between the core engine and the fan to reduce the speed of the fan to about 1/3. Due to the lower circumferential speeds of the fan blades, the fan can be made larger and thus the bypass ratio can be increased considerably, which reduces fuel consumption by up to 20%. In addition, the larger bypass ratio results in noise emissions that are also up to 20% lower. The first generation of these engines is already on the market; the second generation of these engines — currently under development — will be able to achieve the same reductions once again and is expected to run on up to 100% synthetic fuels. The large number of aircraft equipped in this way is already making a significant contribution to the environment. Since the economic efficiency is also increasing at the same time, this technology is rapidly gaining widespread acceptance.

Figure 6 on the right shows the Airbus A320 neo (neo = new engine option) equipped with geared turbofans compared with the A320-200. The significantly larger diameters of the new generation of engines compared with the older generation can be clearly seen.

The gears thus make a major contribution to achieving today's important environmental and climate protection goals.

The Rolling Bearing as a Sensor

The integration of sensor technology is becoming increasingly important in the era of Industry 4.0 and poses challenges for design engineers, particularly in the case of limited installation space. Therefore, various approaches are being researched to integrate sensor functions into machine elements.

The rolling bearing has emerged as the preferred source of process data for parameterizing digital twins in order to obtain high-quality data with comparatively little effort. For example, conclusions can be drawn about the operating condition of the bearing by measuring the electrical properties (Fig. 7). Since the lubricant film thickness and the deformation in the contact depend on the load, the electrical properties of the rolling element raceway contact change measurably as a function of the load. The determined load data can be used, for example, for process monitoring or incorporated into a real-time service life model that enables improved estimation of the remaining life span. In addition, a statement can be made about the lubricant condition, which exhibits altered electrical properties as

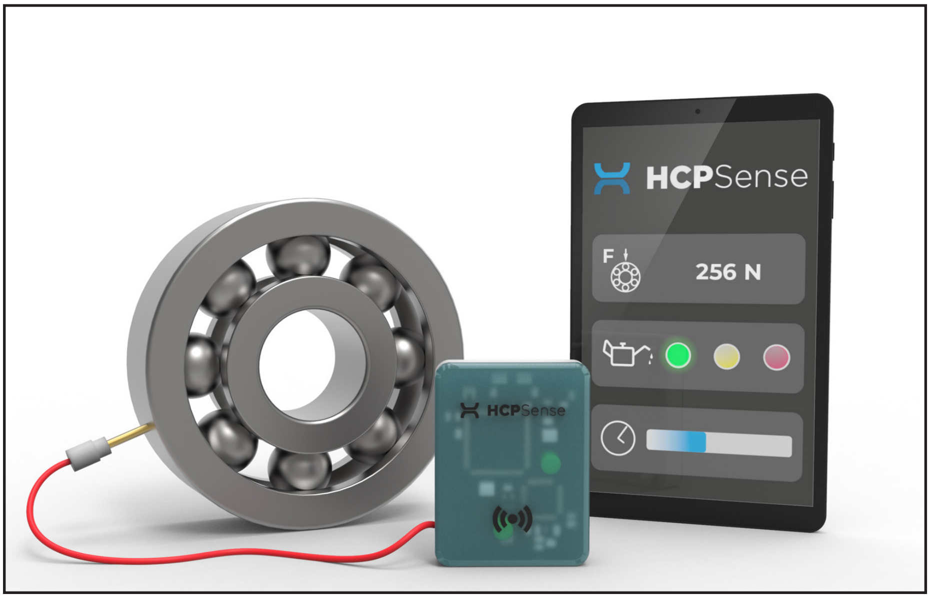

Figure 7 Sensor bearing for measuring force, lubricant condition and speed (courtesy of HCP Sense).

aging progresses.

Further research and subsequent market introduction of these approaches have the potential to make the benefits of Industry 4.0 easier and more cost-effective to harness. Desig engineers can resort to a familiar catalog of machine elements and at the same time integrate additional sensor functions into the product.

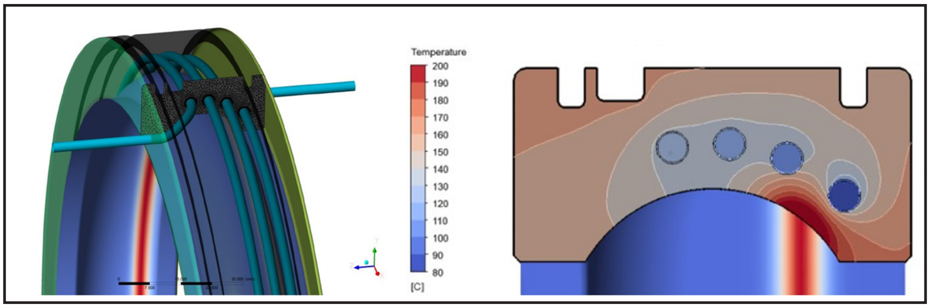

Figure 8 Additively manufactured outer ring with integrated cooling channels (Ref. 11).

Additive Manufacturing of Rolling Bearing Rings

Elsewhere, new manufacturing processes favor potential innovations in the field of machine elements. Additive manufacturing is a case in point: A process has been developed for selective laser melting of M50NiL steel, which is used, for example, in the high-temperature bearings of the main shaft of aircraft engines. Additive manufacturing of the outer ring allows targeted and efficient cooling of the bearing (Fig. 8). By separating cooling and lubrication, the weight, coolant flow and operating temperature of the bearing can be reduced and the efficiency of the engine significantly increased (Ref. 11).

Future Applications

Based on the analysis of the previous performance increase of machine elements in chapter 2, the confirmation of a Moore's law and the discussion of examples which have enabled continuous performance or functionality increases through continuous further developments in the field of machine elements, a look at the medium-term future will now be taken on the basis of an electric vehicle drive, because electric vehicles will always require machine elements and in the vast majority of cases also transmissions. If we take Moore's law as a basis for the continuous increase in the maximum speed of electric motors, which is driven by the need for powerful and cost-optimized drives with a simultaneous reduction in magnetic material for both economic and ecological reasons, we quickly recognize the growing challenges for rolling bearings, seals, gear teeth and, not least, lubricants. Rolling bearings, seals and gear teeth must be upgraded to cope with the increasing speeds in the 30,000 rpm range. The faster switching times of the converters must not lead to spontaneous discharges as a result of significantly greater voltage gradients in the functional surfaces of gear teeth or rolling bearings. In the case of the intended joint cooling and lubrication of the electric machine and reduction gearbox, the lubricant must not age to a significantly greater extent as a result of the shorter thermal load changes when passing through the drive system and oil cooler; furthermore, the reliable functioning of the lubricant must be ensured even at voltages in the kV range. Last but not least, in order to meet the demand for energy efficiency, further work should be done on friction reduction, because the ecological leverage is huge (Ref. 12).

Conclusion

Many developments that are described in public as disruptive are based on the constant progress in machine elements. The next innovation push through the digitization of machine elements is currently being prepared in basic research (Ref. 13). The measurement of previously hardly accessible quantities in direct proximity to the process will lead to a steady increase in new functions at the system level. The ability to synthesize architectures and topologies, which, as shown in the previous sections, build on the improvement of machine elements to open up significant functional progress at the system level, must include the new possibilities of machine elements in the education of students. The future validity of Moore's law for machine elements requires that the fundamentals be maintained or improved; only then can technical progress be achieved as a necessary means of solving the current environmental challenges.

Acknowledgement

The authors gratefully acknowledge the work done by Mr. Steffen Puchtler in translating the German manuscript into this English version to serve the international mechanical engineering community! **PTE**

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