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Energy Saving through Emulation of Low-friction Biological Joints

Bioengineering Division

1. Overview-

The fields covered by the Bioengineering Division are extremely broad-ranging, and it would currently be difficult to provide a general overview of its technologies development effort or to present and discuss their key parameters. Therefore, we shall focus on biomimetics as a development field that shows the overall effort. Biomimetics is devoted to achieving an understanding of biological principles and mechanisms and then applying them to the development of technological processes, materials, and designs. This report focuses on the “Lubrication Problem” and in particular, the achievement of energy savings through emulation of the low-friction joints prevalent in natural life forms.

In 1966, H.P.Jost who had made a significant contribution to the edifice of knowledge of “Tribology”; the science and technology of interacting surfaces in relative motion and of related subject and practices, reported the broad economic effect of the Lubrication Problem (Jost report). The economic impact of the Lubrication Problem in Japan has been also estimated by the Technical Research Institute (TRI) of the Japan Society for Promotion of Machine Industry (JSPMI) to account for 3% of the Japanese Gross Domestic Product (GDP), or approximately 15.5 trillion yen in fiscal 2007. (The TRI report described the effect in terms of Gross National Product (GNP), but it has been converted to a GDP base here in view of the trend toward increasing globalization.)

2. Social and technological needs and technological tasks

There are more than 500 million cars on the road worldwide, and losses due to friction and heat account for two-thirds of their fuel consumption. Estimates indicate that if the annual fuel consumption of these cars could be reduced by 10% by reducing friction, the conserved energy would be sufficient to provide electric power for all households in Japan for a year or more.

The automotive industry has made progress in reducing fuel consumption through improvements in engine, transmission, and clutch efficiency. However, breakthroughs that go well beyond present technologies will be necessary for any approach to the ultimate goal of “zero (motive) friction/zero wear” in their sliding components.

Reduction of energy consumption through reduction of friction does not represent the full economic effect of improvements in lubrication technology. As reported by Jost, it accounts for only about 14% of the total economic effect. The largest gain, representing some 50% of the total economic effect, is the result of reduced component wear and related maintenance and replacement costs. This is followed by the reduction of consequential losses due to malfunction, which represent about 25% of the total.

3. Possible mechanisms for enhancement of key parameters

Bearings are one of the mechanical components most intimately related to the Lubrication Problem. They may be broadly classified as either plain (slide) bearings or rolling (ball or roller) bearings. Unless accompanied by a pressurized lubricant supply system, plain bearings are prone to lubricant film rupture during low speed operation, which inevitably leads to high friction and high wear. Their performance improves during high speed operation, but shear resistance of lubricant increases and the energy loss becomes a matter of concern. For rolling bearings, on the other hand, the level of standardization and mass production is one of the most advanced among mechanical components, and their performance at low operating speeds is excellent. During high-speed operation, however, limitations arise due to centrifugal forces on their rotating bodies and their retainer lubrication.

Biological joints in the human body are constantly exposed to severe fluctuations in load, sliding speed and direction, and motive friction. Despite this, they exhibit low friction ($f < 0.001$) and low wear (service life: more than 70 years) due to the superior complex of effective interactive lubrication systems throughout the range from boundary to fluid lubrication regions. Joint cartilage, composed of collagen fibers, forms bearings with a porous structure that is low in elastic modulus (<10 MPa) and contains lubricants composed of proteoglycans (sugar-protein complex). When bearings come into direct mutual contact in the boundary lubrication regions, the bearing surfaces deform and simultaneously exude these lubricants, thus moderating the state of lubrication. In the mixed lubrication regions, the low elastic modulus bearing surfaces promotes the rapid generation of a lubricating film. In the full-fluid lubrication region, the synovial fluid (natural joint lubricating fluid), with its non-Newtonian nature, behaves as a low-viscosity fluid under high shear, minimizing the shear resistance of the lubricant film and thus reducing energy loss.

The development and introduction of lubricating systems with a performance matching that of biological joints will require the development of new materials and other advances, and practical implementation is not expected before 2020 at the earliest. Furthermore, if the replacement of conventional lubricating systems is limited to service environments similar to those of biological joints, they may be expected to account for about 2% of the Lubrication Problem. Improvements to conventional lubricating systems by incorporating the possibilities suggested by biological joints and for which investigations can already be initiated, such as mechanisms for exudation of lubricating fluids from bearing surfaces and the use of non-Newtonian flow mechanisms in lubricating oils, may be expected to account for a further 2%. Derivative technologies may account for another 3%. In total, then, energy-saving technology resulting from emulation of low-friction biological joints may ultimately represent a contribution of 7% to resolution of the Lubrication Problem. This equates to about one trillion yen when calculated on the basis of the Japanese GDP in fiscal 2007.

4. Outlook on future social aspects

Living bodies are constructed primarily from organic compounds containing large amounts of water. If it becomes possible to mimic their material composition, it will eliminate the requirement for mineral lubricating liquids and it will also mimic their promotion of the decomposition of product components and thus emulate their low environmental burden.

Internal combustion engines, the traditional power source for automobiles, inherently require careful consideration of heat resistance in the development of their lubrication components. With the adoption of fuel cells or other power sources, areas that are free from heat resistance problems will expand, and the number of areas in which lubrication systems emulating living bodies can be utilized can be expected to increase.

Adoption of electrical drive systems may also be expected to lead to simplification of mechanical components, elimination of cams, tappets, crankshafts, gear pumps, and other components requiring oil-based lubricating liquids, as well as an expansion of the areas amenable to the utilization of water-based lubricating liquids. All of this will present new opportunities for taking advantage of the secondary effects of lubricating systems that emulate those of living bodies, such as their biodegradability and their low environmental burden in disposal and other phases.

In the manufacture of parts and components, the cutting, milling, pressing, rolling, and other processes are all affected by the Lubrication Problem. This is another field in which favorable conditions are emerging for development of lubrication systems emulating those of living bodies, and the development of the seeds for derivative technologies.

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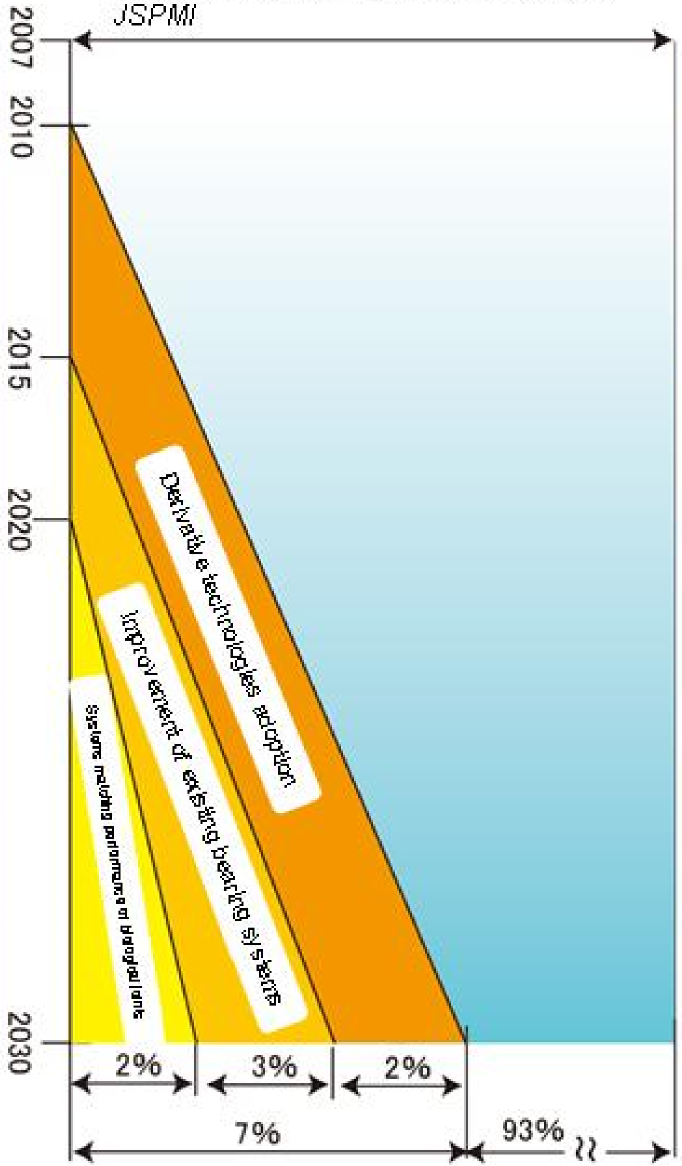
Society and market evolution	Technological breakthroughs	Social and technological needs
▪ Energy/environment measures	▪ New materials, more efficient R&D configurations	▪ High-performance low-cost bearings ▪ Proliferation of hybrid cars, etc.
▪ Shift from internal combustion engines to electric motors ▪ Interest in biomimetic products ▪ Growing interest in wastes and emissions	▪ Advanced high-performance lubricating liquids development ▪ Composite materials inspired by biological systems	▪ Biodegradability, low environmental burden ▪ Carbon-free & petroleum-free technologies ▪ Popularization of plug-in hybrid cars
▪ Popularization of biomimetic products ▪ General awareness of relationship between lubrication and economics	▪ Oil-containing bearing materials inspired by biological joints ▪ Development of non-mineral oil-based lubricating liquids	▪ Practical fuel-cell and other petroleum-free technologies ▪ Superior ecosystem balance, covering all phases from production to disposal
▪ Expansion of application range of biomimetic technology ▪ Revolution in production and material processing methods	▪ Development and proliferation of new materials and lubricating liquids inspired by biological systems ▪ Establishment of technological branch specifically for engineering inspired by biological systems	▪ Biomimetic advances to breakthrough saturation points (impasses in current industrial products and technologies) ▪ Emergence of completely maintenance-free products

Estimated effect of Lubrication Problem solution on Japanese economy: 3% of GDP (thus, JPY 15.5 × 10^9, fiscal 2007 base). *Jost Report and report by TRI of JSPMI*



Contribution of biological joint-emulating lubrication systems and derivative technologies: 7% of total Lubrication Problem solution; thus JPY 1 × 10^9 (fiscal 2007 Japan GDP base)