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METHODICAL APPROACH FOR THE EVALUATION OF THE WEAR BEHAVIOR OF SPHERICAL JOINTS

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Abstract: The tribo-mechanical system of a spherical bearing is basically characterized by its affecting input loads and movements, and its inner influences with regard to sliding speed and surface pressure. The interacting processes, taking place inside the system while utilized, causing a change of the functional characteristic of the tribo-mechanical system. This changing's are in line with the increase of the wear rate and are characterized by an increase of elasticity and finally by backlash of the ball joint. The wear in a tribological contact involves a complex interdependence between several processes, including chemical and mechanical interactions, and depends on many physical parameters. As it is very difficult to isolate an individual parameter or process, the System approach can be a very important technique for analyzing tribo-mechanical contacts.
Keywords: Tribological system, black box, three-dimensional, sliding

1. INTRODUCTION

At a qualitative level, at least, concepts similar to thermodynamic analysis could be applied to contact problems. A system may generally be defined as a set of elements interconnected by structure and function. Therefore, given a suitable structure (A elements with *P* relevant properties and *R* relations between them), the system works as an operator suitable for transforming a set of inputs *{X}* into Outputs *{Y}*.

The dynamic behavior of tribo-systems can be characterized by means of a generalized balance of energy. This means that the net energy of the system remains constant if we consider the process of storing and transforming energy.

As already described in chapter 6 the induced energy applied to the tribo-mechanical system / ball joint, is the basis for the energetic approach of wear evaluation. Therefore appropriate methods are needed to quantify this input energy characterized by their input loads and movements.

Moreover the knowledge of the correlations between applied input energy and wear mechanisms is essentially needed in order to be able to evaluate the wear relevance of any operational demand or to evaluate if a ball joint is applicable for a given demand. At the following pages of this dissertation methods are proposed to evaluate and quantify the input parameters under consideration of the specific geometrical conditions of the tribo-mechanical system / ball joint.

2. ANALYSIS OF THE TRIBOMECHANICAL SYSTEM

The tribo-mechanical system of a spherical bearing is basically characterized by its affecting input loads and movements, and its inner influences with regard to sliding speed and surface pressure. The interacting processes, taking place inside the system while utilized, causing a change of the functional characteristic of the tribo-mechanical system. This changing's are in line with the increase of the wear rate and are characterized by an increase of elasticity and finally by backlash of the ball joint. Figure 1 depicts the mechanical system of a spherical joint with its influencing input parameters affecting wear e.g. damaging of the tribo-mechanical system.

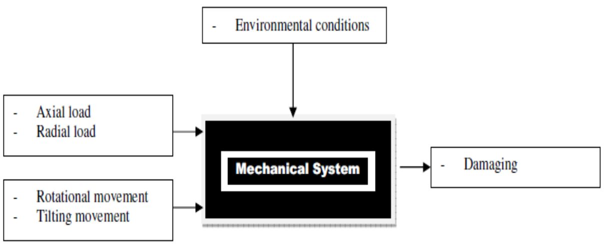

Figure 1. "Black Box" of a Mechanical System

3. IDENTIFICATION OF SUBSYSTEMS

In order to get a better understanding of the interacting processes taking place inside the "black box" of the tribo-mechanical system a methodical approach is proposed in this thesis to realize a simplification of these complex interacting processes. For this a three dimensional local systems approach has been chosen to be able to analyze the major groups of parameters. These three dimensional approach splits-up the overall system tribo-mechanical system into three subsystems, which enables the investigation of each aspect separately and detached from the overall system. Following aspects are taken into consideration:

- ✓ the **Functional Aspect**, considering the mechanical system as an operator which transforms the set of inputs *{X}* in the Outputs *{Y}*,
- ✓ the **Energy Aspect**, analyzing the exchanges and transformations between thermal system and mechanical energy, as well as the entropy variation,
- ✓ the **Tribological Aspect**, studying the exchange of materials between the two first bodies and the interfacial volume.

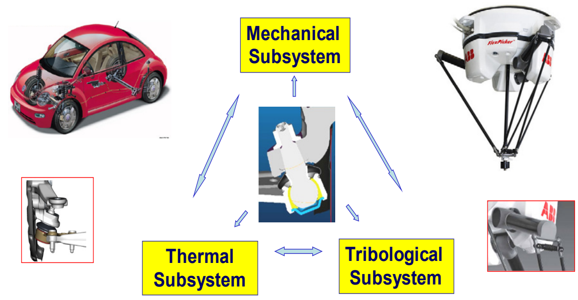

Figure 2. Three-dimensional, local approach

This brake down of the global tribo-mechanical system into sub systems enables a separate analysis and evaluation of each aspect with regard to their interactions and the damaging relevance of system inputs, e.g. operational demands.

Figure 2 shows the tree-dimensional local approach and the interactions between the tree aspects. The mechanical system can be affected by temperature and can be influence the behavior in the material plane. The thermal system is affected by the operational inputs and its mechanical system. The tribological system is affected by the mechanical system and the thermal system.

3.1. The Mechanical Subsystem

The mechanical system influences this system response mainly by its geometrical conditions and by the pre load level provided to the bearing material during the assembly of the ball joint. This pre load applied to the bearing material is causing a surface pressure between the sliding surfaces even without the existence of an external load applied during operation (Figure 3). This design caused surface pressure needs to be considered when calculating the surface pressure based on input loads. The evaluation of this pre-load level is difficult to determine as it cannot be directly measured. It can only be evaluated based on elasticity measurements and global assumptions.

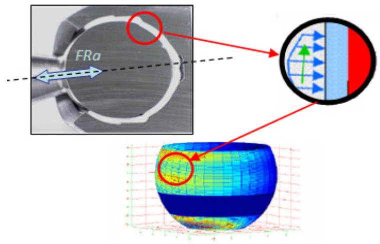

Figure 3. Surface pressure distribution

The geometry of the system provides a direct correlation between the input movements and the relative movement e.g. sliding speed between the interacting contact partners at each point of the spherical surface. This sliding speed is varying depending on the position at the spherical surface and is influenced by the input movements applied to the system (Figure 4).

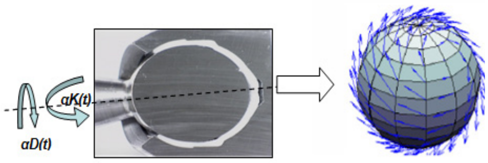

Figure 4. Sliding speed distribution

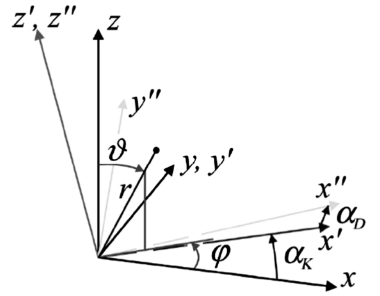

Figure 5. CCS for derivation of velocity field

The knowledge of the level of surface pressure, surface pressure distribution and the sliding velocity is mandatory for the calculation of the dissipated energy which is the basis for the evaluation of the wear relevance of the operational demand as already briefly discussed in chapter 6. Because of the spherical geometry of the system the sliding speed distribution is varying depending on the position of a any notional point at the ball surface as well as on the superposition of rotational movements *aD(t)* and tilting movements *aK(t)*. For the calculation of the sliding speed the superposition of tilting and rotational movements as well as the spherical relationship needs to be considered.

3.2. Calculation of Sliding Speed

Under consideration of the superposition of tilting movement *aK(t)* and rotational movement *aD(t)* (Figure 4) the calculation of the relative movement of a any notional point at the surface can be realized by the introduction of two additional ("movable") coordinate systems (Figure 5) with the use of two rotation matrix shown in equation 42. One Coordinate System is fixed with the housing *x′, y′, z′* and the other Coordinate System is fixed with the ball *x″, y″, z″*.

$$\underline{M}_D(t)=\begin{pmatrix} \cos\alpha_D(t) & -\sin\alpha_D(t) & 0 \\ \sin\alpha_D(t) & \cos\alpha_D(t) & 0 \\ 0 & 0 & 1 \end{pmatrix},\ \underline{M}_K(t)=\begin{pmatrix} \cos\alpha_K(t) & 0 & \sin\alpha_K(t) \\ 0 & 1 & 0 \\ -\sin\alpha_K(t) & 0 & \cos\alpha_K(t) \end{pmatrix} \tag{1}$$

Equation 1 describes the change of the CCS caused by the movements

$$\bar{x}''_{PS}=\begin{pmatrix} x''_{PS}(t) \\ y''_{PS}(t) \\ z''_{PS}(t) \end{pmatrix}=(\underline{M}_K(t).\underline{M}_D(t).)^{-1}.\begin{pmatrix} x_{PS} \\ y_{PS} \\ z_{PS} \end{pmatrix} \tag{2}$$

$$x_{PS}=r_i\cos\varphi_{PS}\sin\vartheta_{PS},\ y_{PS}=r_i\sin\varphi_{PS}\sin\vartheta_{PS},\ z_{SP}=r_i\cos\varphi_{PS} \tag{3}$$

Equation 3 describes the movement of the room and housing fixed fictive point PPS (Figure 6). After differentiation to time and following retransformation into the housing fixed (non dashed) system, equation 46 is providing a vector of the desired sliding speed distribution at first in a Cartesian coordinates.

$$\bar{v}(\vartheta_{PS},\varphi_{PS}) = \underline{M}_K(t).\underline{M}_D(t)\frac{d}{dt}(\bar{x}''_{PS})$$

$$\bar{v}(\vartheta_{PS},\varphi_{PS}) = r_i \begin{pmatrix} \dot{\alpha}_D(t)\cos\alpha_K(t)\sin\vartheta_{PS}\sin\varphi_{PS} - \dot{\alpha}_K(t)\cos\vartheta_{PS} \\ \dot{\alpha}_D(t)(\sin\alpha_K(t)\cos\vartheta_{PS} - \cos\alpha_K(t)\sin\vartheta_{PS}\cos\varphi_{PS}) \\ \sin\vartheta(\dot{\alpha}_K(t)\cos\varphi_{PS} - \dot{\alpha}_D(t)\sin\alpha_K(t)\sin\varphi_{PS}) \end{pmatrix} \tag{4}$$

with $\dot{\alpha}(t) = \frac{d}{dt}\alpha_D, \dot{\alpha}_K(t) = \frac{d}{dt}\alpha_K(t)$ and following under consideration of the spherical relationship

$$v_\vartheta = v_x\cos\varphi\cos\vartheta + v_y\cos\vartheta\sin\varphi - v_z\sin\vartheta$$
$$v_\vartheta = -v_x\sin\varphi + v_y\cos\vartheta \tag{5}$$

the tangential velocity components of the two moving contact points:

$$v_{PS,\vartheta} = r_i(\dot{\alpha}_D(t)\sin\alpha_K(t)\sin\varphi - \dot{\alpha}_K(t)\cos\varphi)\,,\; v_{PS,\vartheta} = r_i(\dot{\alpha}_D(t)(\sin\alpha_K(t)\cos\vartheta\cos\varphi - \cos\alpha_K(t)\sin\vartheta) + \dot{\alpha}_K(t)\cos\varphi\sin\varphi$$

The superposition of rotational movements and tilting movements causes an alternation of the sliding speed and thus of the direction of movement of the point PPS (Figure 7). As this might be the root cause for any interaction the quantification of this effect is essential for the evaluation of potentially critical areas at the spherical surface.

$$\overline{x_B}(t_0,t) = \underline{M_K}(t)\cdot\underline{M_D}(t)\cdot(\underline{M_K}(t_0)\cdot\underline{M_D}(t_0))^{-1}\begin{pmatrix} r_i\sin\dot{\vartheta}_{PS}\cos\vartheta_{PS} \\ r_i\sin\dot{\vartheta}_{PS}\sin\vartheta_{PS} \\ r_i\cos\dot{\vartheta}_{PS} \end{pmatrix} \tag{6}$$

The rotation matrix shown in equation describes movement of Pps as a parameterized curve related to the fixed, non-dashed coordinate system shown in figure 6.

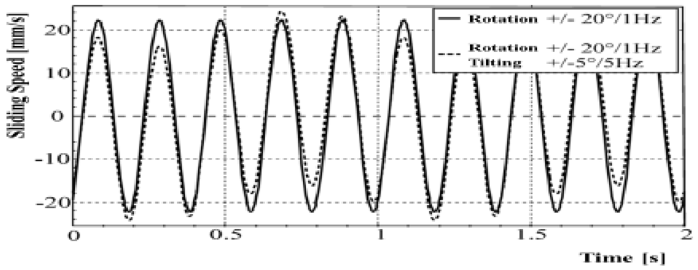

Figure 6. Sliding speed ups for superposition of tilting and rotation movements

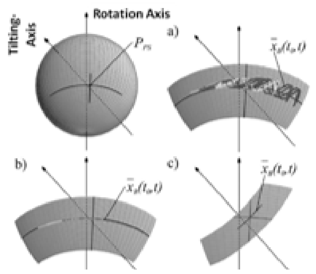

Figure 7. Path of fictive point. a) rotation and tilting b) rotation only c) tilting only

3.3. The Thermal Subsystem

The knowledge of the thermal behavior is of prime importance for the evaluation of a tribo-mechanical system as the temperature between the sliding surfaces is highly influencing the mechanical system as well as the tribological system. As in this thesis the evaluation of the wear rates is based on an energy based approach, a correlation between the wear volume and the accumulated friction work, dissipated through the interface, is assumed. This dissipated energy corresponds to the accumulated energy determined from the sum of accumulated displacements of PPs and the corresponding load. The thermal system uses as a main input parameter the dissipated power which is applied to the tribological system (Figure 7).

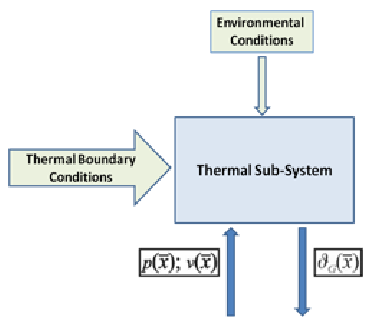

Figure 8. Thermal subsystem with interfaces

As the main portion of this dissipated power the is generated by friction, the input value can be determined by consideration of the mechanical system parameters $p(x)$, $v(x)$ and $\mu(x)$. The thermal subsystem provides the local friction rates $\mu(x)$ and wear rates

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hV(x) caused by the friction- and wear processes between the sliding contacts as well as the resulting actual temperature at the sliding surfaces as an input to the mechanical and the tribological system.

$$\vartheta_G(t)=F(t,P,\dot{Q}_1,\ldots,\dot{Q}_1,a_1\ldots,a_n,b_1,\ldots,b_m) \tag{7}$$

$$P(t)=G(t,\vartheta_M,\vartheta_1,\ldots,\vartheta_0,a_1\ldots,a_n,b_1,\ldots,b_m) \tag{8}$$

3.4. The Tribological Subsystems

The tribological subsystem describes the local, punctual behavior between the sliding partners and interrelate the occurring operational demands to the resulting local surface pressure, the sliding speed and the punctual temperature at the sliding surface including the arising friction rates and wear intensity.

This local approach enables the usage of only one tribological model for all points at the spherical surface. The functional description of the local behavior is based on empirical values determined by tribological tests with representative sliding partners under different operational conditions. Typically the determination of these values is realized by using of a pin on disk tribometer. Each relevant combination of bearing material, sliding speed, surface pressure, lubrication condition and temperature needs to be tested. The results can be transferred into a three dimensional matrix describing the correlation between friction rate, surface pressure and wear rates (Figure 9). A transformation of these data into a regression model enables the implementation of the tribological behavior into a simulation.

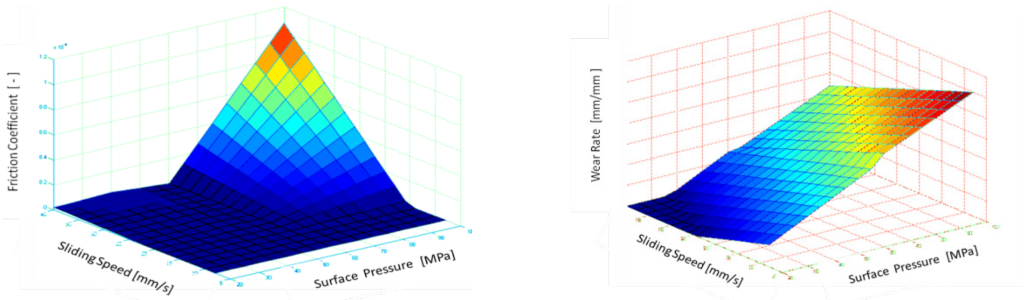

Figure 9. Regression analysis

The overall thermal dissipation loss *PV* (tribological output) can be calculated by summation of losses at each simulation point, according the following equation:

$$PV = \sum pg * Ag * \mu g * vg \tag{9}$$

where : *Pg* = Local surface pressure [MPa] ; *Ag* = Partial area of the sliding surface [mm^2]; *µg* = Friction coefficient; *vg* = Sliding speed [mm/s]

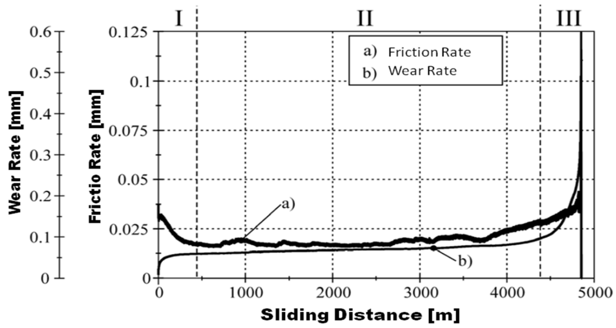

Figure 10. Wear Rate *hV* and friction coefficient *µg* vs. accumulate sliding distance

The correlation between the development of the friction ratio and the development of the wear rate is shown in Figure 10. After the typical running-in phase I, the friction ratio and the wear rate is fading into the steady wear phase II, which is representing the service live of a tribological system. Phase III describes the wear-out phase which represents the phase from end of service life until failure.

4. ANALYSIS OF SYSTEM INPUTS

Structures and mechanical components as spherical bearings are often subjected to input loads and movements varying in a quiet irregular and random manner, as those generated by road irregularities in automotive applications or with parallel robots when using them for a flight simulation for instance (Figures 11 and 12).

When dealing with these types of loadings and movements, we are faced with the need of their complete statistical characterization in terms of quantities as the number of counted cycles, their distribution and their amplitudes .

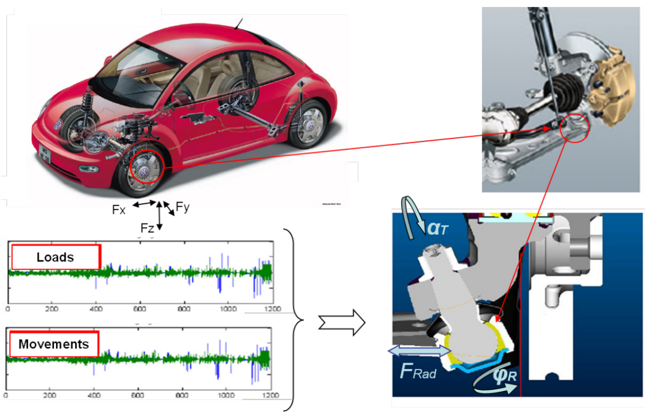

Figure 11. Operational demands applied to spherical joints in automotive application

To accomplish this needs cycle counting methods known from established fatigue assessment procedures of metallic components can be used to quantify the wear relevant system inputs as movements and loads. With the knowledge of the quantitative values of loads and movements applied to the tribo-mechanical system the system input can be evaluated regarding their wear relevance based on the cumulated dissipated energy.

To be able to evaluate this cumulated energy the sliding speed between ball surface and polymer socket needs to be calculated under consideration of the spherical relationship - which is causing different velocity distributions on the ball surface- as well as under consideration of superposition of tilting and rotational movements which influences the sliding speed rate and the direction of the movements.

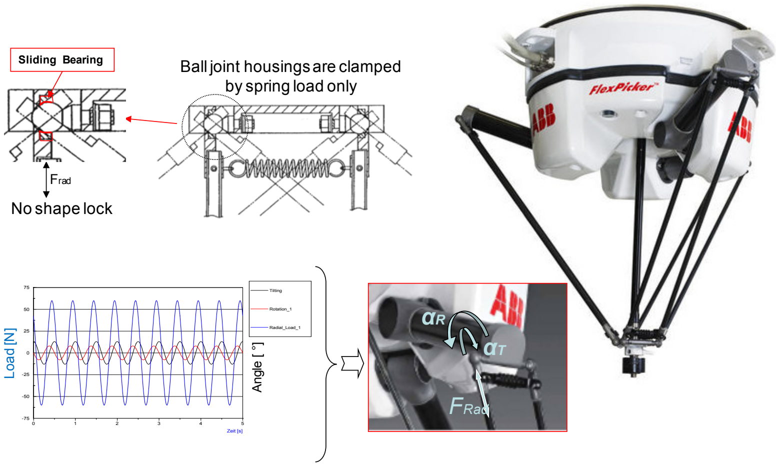

Figure 12. Operational demands applied to spherical joints in robotic application

5. CONCLUSION

Based on the knowledge of sliding speed and surface pressure the potential damaging characteristics of different operational demands can be evaluated on a global approach by comparison of the calculated dissipated energy.

For the local approach it is essential to know the sliding speed distribution and the surface pressure distribution which can be determined by finite element calculations. The local approach provides a more detailed view to the tribological conditions caused by the system inputs as it considers the local conditions between the sliding partners and allows identifying “critical” local areas which may be over stressed. As these high stress areas are the starting points for the loss of material causing finally the wear, the knowledge of those critical conditions is indispensable when designing a spherical joint.

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