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Material and frictional behavior of rubber sliding on glass surface

The Booklet of the Thesis for the Degree of Doctor of Philosophy

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I. Introduction

Rubbers are important materials in mechanical engineering, because of their favourable frictional and wear properties as well as chemical resistance, especially in the field of car, aircraft and chemical industry. In spite of the fact, that the frictional resistance of rubber is much higher than many other materials, a large number of static and sliding seals are made of rubbers. As the application range had been widened in the last century, it became much more essential to understand the complex mechanical processes, which led to the experimental and theoretical investigation of the tribology of elastomers. Besides many applications, in this dissertation a special rubber application, namely the windscreen wiper is the center of interest.

The sliding friction of wiper blade is an important field of modern tribological researches in the last few years. Because of the hyperelastic behaviour and the large inner damping the frictional behaviour of windscreen wipers differs from the one of other materials. Generally, not only the wet friction of wiper blades is reported in the literature but marginal results are also given for the dry case. Wiper blades typically work in three operating regimes. A rare case is the dry one, when solid type interaction is between contacting surfaces. A more frequent condition is when contacting surfaces are lubricated by water causing partial or total hydrodynamic lubrication. However the presents of significant amount of water reduces the optical conditions. Between these two regimes there is the so-called tacky condition, which is characterized usually by a surprisingly high coefficient of friction. In this lubrication state the sticking (dry) zones also cause friction instabilities, vibrations, inequalities in the fluid film, so deteriorating visibility. As it is well known, this complex material causes many problems in the design of rubber components, because one has to consider the low modulus, the effect of large deformation, incompressibility and temperature dependency of material properties even in the simplest cases. Additionally, one of the most typical failure mode of rubbers and rubber-like materials is the fatigue failure thus it is essential to establish an accurate material model. All in all we can conclude that it is necessary to perform the tribological and constitutive investigations simultaneously.

Fortunately, nowadays many numerical techniques (e.g. the finite element method, FEM) are available to do this.

First part of this dissertation concentrates on the mechanical characterization of rubbers and rubber-like materials and the identification of model parameters. The second part deals with the analysis of tribological processes both on specimen and structural levels. The results are based on experiments and large number of numerical and analytical calculations.
II. Objectives

The first aim of this work is to develop a method for the parameter identification of spring-dashpot models, which can be generally used to identify the viscoelastic parameters of widely accepted spring-dashpot models. During the theoretical part the Standard-Solid model and its extended version the generalized Maxwell-model –also called generalized Standard-Solid model- is used, but it is essential to see that the concepts are suitable for any other phenomenological model, which does not show permanent deformation and consists spring and dashpot elements.

The second aim is to analyse the tribological behaviour of a commercial windscreen wiper. In the specimen level examination the effect of sliding velocity, load and lubrication is tested on coefficient of friction and size of contact area and the contact parameters are calculated by numerical techniques. Contrary to the literature the tribological behaviour of windscreen wiper is analysed not only on specimen level but also on structural level in order to prove or disprove the assumption that the behaviour is identical on both levels.

The questions which will be answered in this thesis are as follows:

1. How is it possible to describe the non-linear time and frequency dependent behaviour of rubbers and rubber-like materials?
2. How is it possible to widen the measurable time/frequency domain by using the time-temperature superposition?
3. How is it possible to identify material model parameters from measurements being available in most cases and how wide is their application range?
4. How is it possible to widen the application range of these methods?
5. Which phenomenons influence the rubber-glass contact process and the frictional behaviour?
6. What is the effect of water on the tribological behaviour of windscreen wiper?
7. What is the correlation between the specimen and structural level tribological behaviour?

In order to answer the emerged questions and to understand the complex material and tribological behaviour of windscreen wiper, experiments and simulations are carried out.
III. Testing methods and the structure of the dissertation

The description of the mechanical behaviour of rubber-like materials and the connecting tribological phenomenons are very complicated, because of the different processes, which occur simultaneously. Generally it is not possible to consider all of them at the same time, so simplifications are needed. In this work, firstly I give a general outlook on the different phenomenons individually and then I connect them to each other (nonlinear elasticity, the linear viscoelasticity and finite viscoelasticity). The theoretical derivations usually are followed by experiments, which are uniaxial tensions, stress relaxations and DMTA tests. Based on the results of these experiments and further considerations, a new method is developed and tested for parameter identification using constant strain-rate uniaxial tension tests. The new method combined with the genetic algorithm can be effectively used for parameter identification in a limited frequency/time domain. In case when it is used in conjunction with the WLF theory, we can extend its application range with minimal labor input. It must be mentioned that the next chapters are restricted only to the engineering approach, so the mathematical derivations are not fully detailed and they concentrate just on the easy to understand forms, which can be directly applied in practice. During the analysis of the mentioned processes both analytical and numerical (FE) calculations are used.

The tribological part of the thesis focuses on the experimental results and their explanations. Firstly, the specimen level then the structural level examination is detailed. The measurements are carried out by means of homemade test rigs. The measurement results are compared to bibliographic data and are complemented with numerical simulations, in order to identify the apparent contact area and its change over the working conditions. The simulations give valuable informations on none-measurable parameters.

In the literature practically there is no test result on the structural level tribological behaviour of windscreen wipers. In order to fill this gap a novel test rig is used which consists of a commercial wiper blade with the arms and a rotating glass cylinder. Because of the none-circular cross section and the eccentricity a pure mathematical model is presented to evaluate the measurement results. The model leads to the coefficient of friction under different conditions. Finally the ultimate conclusions are given by the comparison of the specimen and structural level results. In this thesis the details of important publications are given in the first part of the relevant chapters as a literature survey.
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Same measurements were carried out in cooperation with the IVW (Composite Material Institute, University of Kaiserslautern, Germany), IDS (Institute of Dynamics and Vibrations, University of Hannover, Germany), and the DPE (Department of Polymer Engineering, University of Budapest, Hungary) for which I wish to thank the facility to perform measurements.
IV. Theses

1. I developed a new method for identifying the parameters of the generalized Maxwell- model based on the small strain theory from tensile tests of constant strain rate. I extended the method to large strains as well in order to determine the parameters of the Green strain tensor’s invariant-based hyperelastic model. I verified the applicability of the method using own experimental results for five or less Maxwell terms. As a result of the extension, the strain dependence of material behavior can also be described, in addition to the viscoelastic parameters, from two different tensile tests of constant strain rate.

Related chapter of the dissertation: 3.5.2.

Related publications: [B2, B3, B4]

The flow chart in Figure 1 shows all the steps of the proposed parameter identification method. As seen we need to calculate the first partial derivatives of the stress-strain curves of tensile tests measured at two different strain rates. This yields to the elastic modulus-strain curves ($E_1(\varepsilon)$ and $E_2(\varepsilon)$). Then the ratio of $E_1(\varepsilon)$ and $E_2(\varepsilon)$ values is calculated at different strains ($E_m(\varepsilon)$). The non-dimensional ratio function ($E_m(\varepsilon)$) increases or decreases in function of strain depending on the ratio of strain rates. As a next step the expression $E_m^{\text{fitted}}(\varepsilon)$ derived from the generalized Maxwell-model is fitted to the $E_m(\varepsilon)$ values obtained by substituting the time parameter $t$ with an expression including the length ($l_0$) of the specimen, the tension speed ($v$) and the strain. The fitting itself can be performed by the method of least squares for models with a smaller number of terms or by genetic algorithm in case of a higher number of terms. However, each Maxwell element (a spring and a dashpot connected in series) provides two unknowns ($\tau_i$, $e_i$), one of them namely the relaxation time spectra ($\tau_i$, $I = 1…n$) can be determined intuitively too, i.e. without curve fitting. After curve fitting, the last step is the calculation of the glassy modulus. For this purpose any of the two tensile tests can be used. The only limitation is the convergence of the curve fitting algorithm adopted.
Figure 1 Block diagram of the tensile test based parameter identification method

Figure 2 shows the measured and calculated tensile tests at 1000 mm/min and 10 mm/min tensile speed. Figure 3 shows the measured and calculated characteristics of the relaxation tests measured at 5 %, 60 % and 100 % strain, using the hyperelastic and viscoelastic parameters identified by using the method described in thesis 1.

The calculation is accomplished by the method described in thesis 1. At 10 mm/min the agreement is less good but the accuracy is still acceptable.
2. I tested the specimen-level behaviour of windscreen wipers operated in dry and wet conditions through measurements and finite element simulations. Measurements were performed on a test rig of own design. I drew the following conclusions based on the results:

2a) On the basis of the test results of wiper lips lubricated by water, I concluded that at a sliding velocity lower than a given one the load increase results not decreasing but increasing coefficient of friction. The statement above supplements and specifies the statement in the literature whereby increased loads lead to a decreased coefficient of friction at velocities between 10 and 2000 mm/s in the presence of water. The transition from increasing tendency to decreasing one is realized at 100 mm/s. Contrary to the coefficient of friction, the friction force increases with increasing normal load at any velocity between 0.1 and 150 mm/s. However, the friction force increase above 100 mm/s is much less than below it. According to my measurements the magnitude of the coefficient of friction is practically independent of the normal force at a sliding velocity of 100 mm/s.

2b) On the basics of the FE simulation, I concluded that, at constant normal load, the friction force influences not only the nominal (apparent) contact area and the location of the contact area but the relative position of the wiper blade and the glass surface. The nominal contact area can show both decreasing and increasing tendencies with increasing friction force. At a load per unit length of 37.5 N/m the tendency is increasing however, at a load of 25 N/m decreasing tendency can be observed. At the same time, the wiper gets closer to the glass surface due to the increasing friction force.

Related chapter of the dissertation: 4.7.
Related publications: [B10, B25]

The photo of the test apparatus used is shown in Figure 4. The specimen with a length of $l_0 = 40$ mm was cut out from a commercial wiper blade (SWF Duotec+). During the tests, the rubber specimen slides against a horizontally oriented flat glass, the sliding velocity of the specimen was varied between 0.1 and 150 mm/s, while its vertical position was adjusted with a precision of 10 µm. The interference ($s$) is considered to be zero when the wiper lip touches the glass plate. The interference is varied between $s = 0.3$ and 2.4 mm.
In Figure 5, the friction force values are depicted in function of normal force at different sliding velocity. The figure shows clearly that friction force increases with increasing normal force. At low forces the relation of normal and friction force is approximately linear, however, above $F_N = 1$ N the slope of the friction force vs. normal force curves changes significantly. This change in the slope yields decreasing coefficient of friction as the normal force increases. The coefficient of friction (see Figure 6) exhibits strong sliding velocity dependency at low sliding velocities ($v < 50$ mm/s) only. Contrary to normal and friction force, at constant sliding velocity, the coefficient of friction decreases with increasing interference. It is caused by the fact that the normal force increases more rapidly than the friction force.
3. I developed a mathematical model to explain the results of structural-level tribological measurements of the complete windscreen wiper. The model establishes a connection between the shape distortion / eccentricity of the rotating cylinder and the cyclic fluctuations of the measured force components. I established by applying the model that the periodic fluctuation of horizontal and vertical force components is a consequence of the shape distortion and eccentricity of the rotating glass cylinder. I further established that the measured horizontal and vertical force components can be considered as friction and normal forces.

Related chapter of the dissertation: 4.8.2.
Related publications: [B1, B12]

The test apparatus and its main components can be seen in Figure 7. The electric motor with steeples speed control rotated a glass cylinder with a nominal outer diameter of 220 mm through a flexible coupling and a gear box. The gearing ratio of the gear box was 51 while the highest rotational speed of the motor was 6000 rev/min that corresponds to a tangential speed of 1355 mm/s on the surface of the glass cylinder. The length and the wall thickness of the cylinder were 700 mm and 5 mm, respectively. Three metal rollers combined with rubber rings guided the cylinder at both ends of it. The below ones were supported by helical springs.

Experiments are conducted, and, it was found that measured force components fluctuate as the glass cylinder rotates (see Figure 8). In order to evaluate the measured vertical and horizontal force components, I have made an attempt to develop a mathematical model to predict the effect of the non-circular cross section and eccentricity on the measured force components. The mathematical model uses geometrical considerations according to Figure 9. The eccentricity of the ellipse is characterized by the horizontal
(h) and vertical (k) distance measured between the axis of rotation and the center point of the ellipse.

![Diagram of rotating eccentric ellipse](image)

**Figure 9** Rotating eccentric ellipse (this figure can be considered as the left view of the test apparatus seen in Figure 7)

In case of centric circle, the distance $A_{1y''}$ is constant i.e. does not depend on angle $\alpha$. In case of centric ellipse, the distance $A_{1y''}$ varies periodically between a minimum and maximum value. Finally, as seen in **Figure 10**, eccentricity h causes two different local maxima while eccentricity k induces two different local minima during a single revolution. The similarity between the case corresponding to non-zero h and k and the measured vertical force component (see **Figure 10**) proves that the rotating glass cylinder has an ellipse cross-section with eccentricity h and k.

![Graph of variation of $A_{1y''}$](image)

**Figure 10** Variation of $A_{1y''}$ in case of centric circle, centric ellipse, eccentric ellipse with non-zero h, and eccentric ellipse with non-zero h and k

<table>
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4. I allocated from the structural level measurement results, that in partial contact, the load per unit length value of the examined wiper blade can be considered to be independent on the working parameters which causing drastically different coefficient of frictions, because of the changing nominal contact area. This phenomenon cannot be observed in specimen level (which is examined in the literature). The test results show that under water lubrication, similarly to the specimen level results in the literature, the coefficient of friction value importantly decrease by the increasing sliding velocity or the decrease of the clamping force. In the structural level examination the contact length can change, which causes approximately constant load per unit length value at different coefficient of friction values and increasing normal forces.

Related chapter of the dissertation: 4.8.3.
Related publications: [B1, B12]

As the wiper blade slides on the rotating glass cylinder non-zero contact force can be measured in direction x and y, i.e. in horizontal and vertical direction. These forces and their normal and tangential components are shown in Figure 11.

As a first step all the experimental results measured in wet condition are collected and analysed. Each test is performed at constant s and sliding speed but their values changed test by test. By considering all the measurements we can identify an upper (F_{vmax}) and a lower limit (F_{vmin}) for the vertical forces measured. Thus we can state that the force cannot be higher than F_{vmax} and lower than F_{vmin} at none of the measurements. As a second step seven different force values (0.2, 0.8, 1.2, 3, 5.2, 11 and 16 N) were selected from the range F_{vmin}…F_{vmax}. Based on the measured force vs. time curves it is
possible to identify time instants where the vertical force measured equals to the one selected. As a next step the horizontal as well as the vertical force values measured at the time instants identified are collected. At the end of the former section it is concluded that the coefficient of friction can be computed, in the present configuration, as the measured horizontal force over the measured vertical force. Results are presented in Figure 13 and Figure 14.

![Figure 13](image1.png) **Figure 13** Coefficient of friction vs. sliding speed curves at different vertical forces (in presence of water)

![Figure 14](image2.png) **Figure 14** Coefficient of friction vs. sliding speed curves (vertical force values are substituted by the vertical force per unit length values)

As it can be seen the coefficient of friction decreases as the sliding speed or the vertical force increases. It must be noted that the specimen level investigations [9, 10, 11] show the same tendency. **Figure 14** is almost the same as **Figure 13**. The only difference is that vertical force values are divided by the length of the measured apparent contact area. While in **Figure 13** different normal force belongs to each curve this tendency cannot be observed in **Figure 14** where instead of normal force values the normal load per unit length ones are used. In other words, the curves in **Figure 14** cannot be separated from each other on the basis of normal load per unit length values. Drastically different coefficient of friction belongs to the approximately same normal load per unit length values.
V. The Potential Utilization

Basically, the work connected to an EU supported project which targeted the understanding of tribological phenomenons on reliable working. However the work also deals with such concepts and uses such models which could be also applied in many other cases when elastomeric materials are required. If we think over how many elastomeric seals, tires and other elastomeric parts work worldwide then it can be easily seen that the application of the worked out models give direct access to results which could be just expensively tested and the examined tribological phenomenons can be extended to other applications. However it is essential to see that the examination of elastomeric materials and solid bodies made of elastomers is a complicated task. Take into consideration all the influencing parameters is almost impossible and from this reason the current dissertation is focusing just on a little segment of the phenomenons. The examinations given in this work are not concentrating on the temperature dependency which could generate high change in the material properties (near to the glassy temperature the modulus of an elastomeric body could even reach the 5000 MPa or more contrary to the 20 MPa at room temperature). The best example of this temperature induced change is the car tires, where under some degree the general behaviour modifies significantly. Therefore, I am sure that the consequences of the tribological examinations also could reveal important and fascinating phenomenons if the test would be repeated on low/high temperatures.

The dissertation also does not cover the effect of rubber types, filler materials and additives in spite of the fact that those aggregates modify the mechanical and tribological performance significantly. The variety of examination and the amount of valuable and useful conclusions could be also propagated by the consideration of different cross section wiper blades. According to the best knowledge of the author, this type of examination cannot be found in the literature and could be performed by the devices introduced in this dissertation. The tribological system considered to be ideal so the contacting surfaces are not separated by outer mediums or the medium is clear water. If we think about the real application, it can be easily seen that this conditions never occur because the surfaces are contaminated and the water always contains impurities.

It is also possible to use the examined viscoelastic material models and detailed tribological phenomenons to analyse the lubrication state of different engineering components like seals [B18] or a wiper blade [B13]. The mentioned lubrication analysis
requires the pressure distribution, which can be effectively obtained by the worked out models, given in this work. By most simple approaches the leakage value of other lipped seals can also be determined which calculation also requires the pressure distributions as it is described in [B18, B25]. However, the current work does not cover the three dimensional (3D) existence of pressure distribution. The application of finite element simulations also could be used to examine the tribological system of windscreen wiper blade acoustically (as it is given in [9]), dynamically (like stick-slip vibration) or thermally but these examinations also could go beyond the border of this work.

VI. References
VII. List of publications

Papers:

Conferences with proceedings:


Submitted paper:

Acknowledgements

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Finally but foremost I dedicate these theses to my mother and sister, and would like to thank the unremitting encouragement and gave me more than possible.

Thank you ever so much!
Review of the doctoral dissertation and vindication records are available for inspection at the Dean’s Office of the Faculty of Mechanical Engineering of Budapest University of Technology and Economics.