Computers and Structures 165 (2016) 10–23

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Numerical optimization of wear performance – Utilizing a metamodel based friction law

Aleksandra Serafinska, Nermeen Hassoun, Michael Kaliske *

Institute for Structural Analysis, Technische Universität Dresden, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 18 August 2015
Accepted 25 November 2015
Available online 28 December 2015

Keywords:
Optimization
Finite element analysis
Wear
Friction
Metamodels
Tire mechanics

ABSTRACT

In this contribution, a structural design optimization approach focusing on the enhancement of wear performance, which employs the finite element analysis and a genetic optimization algorithm, is presented. The numerical wear analysis between two sliding bodies is based on constitutive wear and friction equations. Since local stress concentrations are identified as the origin of wear, the local characteristics of tangential stresses should be appropriately captured by means of the constitutive equation for friction. Therefore, a new friction model is developed, enabling to account for the nonlinear dependency of the friction coefficient on the local contact pressure and sliding velocity in the contact interface through the utilization of metamodels, especially artificial neural networks. With the help of the proposed constitutive equation for friction, the energy dissipation rate due to friction, which is utilized for the evaluation of the wear rate within the wear model, can be properly calculated. The numerical wear analysis is coupled to an optimization approach based on a binary coded genetic algorithm. Since geometrical configuration changes due to wear can be modeled with the help of the utilized wear analysis, criteria to pursue a reduced wear volume and a regular wear distribution are developed and implemented into the formulation of the optimization task. The application of the presented methods to a pneumatic tire design task is shown as an example.

1. Introduction

Pronounced and uneven wear lead to significant durability and service life reduction of products and structures. Thus, the development of methods for the enhancement of wear performance is of prime importance. An efficient strategy, in comparison to extremely expensive and time consuming experimental wear investigations, is to accomplish a study based on a coupled approach of optimization and numerical wear analysis. The numerical design optimization approach is utilized for the enhancement of wear performance of structures within different engineering fields. Exemplary in [1], the wear of carbide inserts during the machining process is minimized utilizing the finite element analysis and the design of experiments strategy. In [2], an approach for the railway vehicle wheel profile design focusing on optimization of wear characteristics and employing a multibody modeling is presented. Since the reduction of wear is a significant goal also for the pneumatic tire design, several tire optimization approaches can be found in the literature. Exemplary, in [3], the enhancement of wear resistance is achieved by means of the solution of a tread design optimization task with a multi-objective genetic algorithm and self organizing maps. In [4], a tire crown shape optimization is performed with the help of an iterative incremental scheme employing a finite difference sensitivity algorithm to yield a uniform wear distribution in the tire footprint. In [5], an approach for a robust design of tires focused on the improvement of tire durability through the enhancement of wear and fatigue resistance is presented.

A purposeful design optimization with respect to wear requires a reliable modeling of the wear process [6], e.g. by means of the finite element method (FEM) [7–10]. The FE wear investigations and its various applications are shown in [11–14]. In the present contribution, a finite element wear analysis is developed, which aspires to fulfill several requirements on a realistic modeling of this phenomenon. First, the ability to perform an iterative adaption of the geometrical configuration due to material removal, based on a wear rate calculation within a constitutive wear equation is given. Second, the friction-wear interaction is considered within the FE wear analysis, since wear and friction phenomena exhibit a strong correlation. Third, the influence of local frictional

* Corresponding author. Tel.: +49 351 463 34386; fax: +49 351 463 37086.
E-mail addresses: aleksandra.serafinska@tu-dresden.de (A. Serafinska), nermeen.hassoun@tu-dresden.de (N. Hassoun), michael.kaliske@tu-dresden.de (M. Kaliske).
URL: http://tu-dresden.de/isd (M. Kaliske).

http://dx.doi.org/10.1016/j.compstruc.2015.11.013
0045-7949/© 2015 Elsevier Ltd. All rights reserved.

phenomena on wear is taken into account in friction-wear interaction since local stress concentrations are identified as the origin of wear.

The geometry adaption due to wear is crucial for the development of a realistic wear modeling and reliable wear optimization procedure. However, most optimization approaches evaluate only simplified wear criteria computed with respect to the unworn geometrical configuration. The formulation of the constitutive wear equation required for the volumetric wear loss calculation and geometry adaption has evolved over the years [15]. The initial pioneering work in this field is done by Reye [16], who discovered that the depth of the worn material is proportional to the tangential stress $\mathbf{t}_T$ and, therefore, to the contact pressure p_N. Furthermore, he concluded, that the volume of the worn material V is linearly dependent on the work W done by the tangential force. Later contributions focused on the investigation of the influence of contact area topology defined by surface asperities on the wear phenomenon [17]. A hypothesis, that the formation of wear particles is a result of separation of single atoms or aggregates of atoms from surface asperities is given in [18,19]. An established wear model, which considers a sliding process as a continuous creation and destruction of asperity contacts is developed in [20]. This wear model, denoted as Holm-Archard wear equation, defines the volume of the worn particles

$$V = K\,\frac{F}{H} \tag{1}$$

in dependency on the wear coefficient K, the normal force F and the hardness of the worn surface H. Archard postulated, that the volume of the wear particles in a single asperity contact is proportional to the cube of the asperity contact radius and can be formulated as a half-sphere. Another class of wear models are equations based on material failure mechanisms, which follow the theory, that the wear phenomena depend on the fracture mechanical properties [15]. Respectively, more attention is payed to quantities such as fracture toughness or fracture strain, followed by studies on fatigue, dislocation analysis and brittle fracture. Recent wear models in [21,22] account for the third body theory for the consideration of the wear debris effect on the interfacial interactions.

In this contribution, a wear model is selected, which considers the friction-wear dependency. In general, the friction-wear interaction in the contact interface is fully coupled and defined by the wear-friction and friction-wear relation. The first dependency quantifies the effect of wear on the friction process and is based on an assumption, that during the sliding wear, the friction coefficient is permanently changing as a result of surface topology alteration. This phenomenon is considered in [23] by means of a functional relation of the friction coefficient μ and the density of the frictional work or energy dissipated in the contact interface $\mathcal{D}^s$. The developed expression for the friction coefficient dependent on the wear effect is comprised in the slip criterion

$$f_s(\mathbf{t}_T) = \|\mathbf{t}_T\| - \mu(\mathcal{D}^s)p_N. \tag{2}$$

The assumption of a constant frictional characteristic during the wear process is an important limitation of the Holm-Archard wear equation.

In fact, the changing frictional characteristic influences the magnitude of the wear rate distinctively, which could be shown in experimental investigations discussed in [24]. Thus, in the present contribution as well as in [14], the opposite relation – friction-wear dependency – is considered within the FE wear analysis. Therefore, a constitutive wear equation, including a proportionality relation between the mean rate of wear $\dot{V}$ and the energy dissipation rate $\mathcal{D}^s$ due to friction is applied

$$\dot{V} = k_{wear}\,\mathcal{D}^s = k_{wear}\,\mathbf{t}_T\,\dot{\mathbf{g}}_T, \tag{3}$$

where k_{wear} is the wear parameter and $\mathcal{D}^s$ is a function of tangential contact stresses $\mathbf{t}_T$ and the tangential slip rate $\dot{\mathbf{g}}_T$. Thereby, $\mathbf{t}_T$ is calculated based on the utilized constitutive equation for friction and on the definition of the friction coefficient.

The third requirement for a realistic wear modeling is the consideration of local frictional effects in the contact interface within the friction-wear interaction. Especially, the capturing of the frictional characteristic at each finite element node in the contact interface is crucial, since local stress concentrations induce the occurrence of wear. Thereby, the friction coefficient is not constant in the entire contact patch but for elastomers, e.g. rubber, is a function of local contact pressure p_N and sliding velocity $\mathbf{v}_T$, as shown in [25]. Thus, a new friction model is proposed in this paper, approximating the nonlinear relation between the friction coefficient μ_{ann} and the aforementioned factors by means of artificial neural networks (ANNs)

$$\mathbf{t}_T = \mu_{ann}(|p_N|, \|\mathbf{v}_T\|)\,|p_N|\,\frac{\dot{\mathbf{g}}_T}{\|\dot{\mathbf{g}}_T\|}. \tag{4}$$

Due to an extraordinary adaptivity and information processing capabilities analogously to the human brain, ANNs are able to capture even very specific forms of nonlinear relations [26]. The metamodel based friction coefficient formulation is implemented into the FE contact approach. Thus, a definition of an algorithmic tangent including the linearizations of the contact contributions to the weak form of balance of momentum is provided for the Newton method.

In the present contribution, three novel developments enhancing the numerical wear modeling and optimization are introduced. Firstly, the application of a local contact pressure and sliding velocity dependent constitutive equation for friction to a numerical wear analysis is accomplished. Secondly, an improved approximation of the mentioned nonlinear friction coefficient relations is achieved within the constitutive equation for friction through the application of metamodels. Thirdly, a FEM based structural analysis accounting for the geometrical configuration changes due to wear is coupled to an optimization approach. The utilized binary coded genetic optimization algorithm is suitable especially for nonlinear optimization problems with a discontinuous design space. The proposed structural optimization approach aiming at wear performance improvement is originally developed for a tire design task. Though, due to the general form of the given formulations, the application to other engineering design problems is possible without difficulties.

2. Modeling of wear by finite element simulation

FE wear analysis can be conducted by means of two different methods. The first method presumes the execution of the wear analysis in a post processing step evaluating the contact problem of the frictional analysis. The application of this method is restricted to problems, in which the normal load applied to the worn body remains constant throughout the analysis. In contrary, in the second method the computation of wear rate is accomplished within the incremental solution of the frictional contact problem. Thus, the effect of the contact pressure redistribution in subsequent time steps τ_n, τ_{n+1} of the wear analysis on the magnitude of wear rate calculated at τ_{n+1} is considered. The redistribution of contact pressures results from the geometry modification due to material abrasion. In this contribution, the second method is followed. For the considered FE wear analysis with iterative geometry adaption, an expression for a wear rate, applicable to a node to simulate wear, is assumed.

The FE wear simulation of a rolling tire, which is utilized in this study as a model problem, is conducted by means of the steady state transport analysis. Thus, the wear rate computation is