ROBUST BRAKE FEEL DESIGN

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THEME

Variational studies

KEYWORDS

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SUMMARY

This paper introduces a methodology for loosely coupled modeling and simulation of a human operating a vehicle disc brake system, aiming to resolve three issues in virtual prototyping: integration of heterogeneous modeling and simulation methods and tools, extending the deploy ability of simulations towards conceptual design, and enabling robust design based on probabilistic simulations and design of experiments (DoE). The methodology is exemplified with a simulation-driven and FEA-assisted investigation of the interactive relation between human muscular stress and technical performance of an automotive disc brake system. The actual human-artifact interaction is defined by the state of the two interface properties pedal stroke and pedal force.

1: INTRODUCTION

Disc brakes (see figure 1) are safety critical automotive components that also must satisfy tough cost, and environmental requirements.

Figure 1: A typical disc brake system, from [1].

In cars designed for the supreme market, interactive performance, such as car handling and braking, is strongly related to branding and a “feel” of high quality. For all human operated vehicles, safety is depending on the “brake-feel”, which is a perception of the system behavior. Consequently are vehicles targeted for the supreme market equipped with automatic safety control systems that range from focused solutions, such as Anti-locking Brake System (ABS), to integrated and multifunctional solutions such as Electronic Stability Programme (ESP). ESP stabilizes the car while braking and cornering simultaneously and it also integrates the ABS function.

How a brake pedal feels by a driver depends on both pedal travel (stroke) and pedal force (e.g., [2], [3], and [4]). Of quality and safety reasons, a good pedal should provide effortless and yet precise operation. The anatomical characteristics of the driver, the pedal stiffness, and the distance between the seat and the pedal directly influence the muscle effort of operating the pedal. Combined with individual psychological characteristics each driver values the perceived brake feel. Furthermore, the brake feel depends also on the relation between pedal travel and force on one side and the perceived deceleration [3]. The muscular stress is treated here, but not the perception and feel of this stress. Pedal force and stroke are systems parameters that depend on many interacting kinematical and stiffness properties, from the pedal design, the flexibility of the hydraulic lines, to the design and sealing of the main cylinder and caliper pistons, the stiffness of the caliper, and the friction between the mechanical parts. All these properties are subject to variation and drift.

A *robust brake feel* is here defined as a brake feel that is insensitive to the drift and variation in the characteristic subsystem parameters (e.g., manufacturing tolerances, material properties, environmental conditions, degradation due to wear, seat position and driver characteristics) over the normal product life. Robust design is preferably based on design of experiments and/or probabilistic simulations.

This paper introduces a methodology for loosely-coupled heterogeneous modeling and simulation of an integrated human-vehicle disc brake system, aiming to resolve three issues in virtual prototyping: integration of heterogeneous modeling and simulation methods and tools, extending the deploy ability of simulations towards conceptual design, and enabling robust design based on probabilistic simulations and design of experiments (DoE). The methodology is exemplified with a simulation-driven and FEA-assisted investigation of the interactive relation between human muscular stress and technical performance of an automotive disc brake system.

2: HUMAN-ARTIFACT INTERACTION MODELING

The base model in the presented approach is a loosely integrated hybrid model; a musculoskeletal human model on one side of the foot-pedal interface and a lumped-parameter technical systems simulation model on the other side. Nonlinear and complex component and interaction properties of the technical subsystems are defined with focused and detailed FE analyses.

The two loosely coupled models enable the pedal force and travel, and muscle effort during braking to be predicted and analyzed for discrete characteristic properties, or alternatively with probabilistic Monte-Carlo simulations.

Figure 2: A manually actuated vehicle disc brake system.

2.1: <u>The muscular stress submodel</u>

The primary human subsystems involved in human control are the brain and the central nervous system. The human brain receives input from receptors (i.e., sense organs) through the central nervous system, and provides output to effectors (i.e., muscles) through the central system. In human-controlled vehicles, the course of actions taken by the driver depends on the dynamic behavior of the vehicle. Important safety issues are thus strongly related to interactive system properties and human cognitive activities. The theory of human information processing [5] and decision making has been widely accepted in the science of human motor control (e.g., [6]) and in cognitive psychology (e.g., [7]), but it is not explicitly treated here. The scope for the human model is to enable ergonomic investigations of the effects on the required muscular braking activities caused by variations in the characteristic brake system and seat placement parameters. A musculoskeletal human model available in the AnyBody [8] example model repository [9] has been chosen and adapted to suite this purpose.

Figure 3 shows the AnyBody human-artifact interaction (HAI) model. It is based on the human muscoskeletal model, with the trunk sitting on at seat feature and a node on the right foot connected to a pedal. The pedal is hinged at the other end and equipped with a torsion spring that stretches when the pedal is depressed by the foot. The vertical and lateral positions of the seat as well as the pedal spring stiffness (k) and pedal stroke are parameterized in the HAI model. The maximum muscular activity during a predefined braking scenario has been defined as the primary solution output parameter. The developed biomechanical-based HAI submodel can, for example, be used to examine how the pedal stiffness and stroke, and the distance between the seat and the pedal influence the muscle effort of operating the pedal in various braking scenarios.

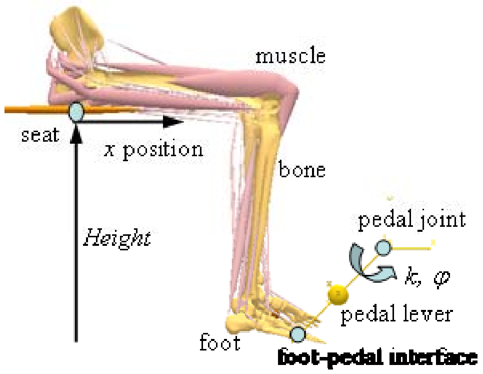

Figure 3: A human-brake pedal interaction model, adapted from [9]

Since it is possible to execute the AnyBody Modeling System in batch mode, a systematic loop of analyses for each parameter combination can be performed. For each analysis, the system stores the maximum effort of any muscle at any point of the movement of the pedal. In the presented case, Matlab [10] from MathWorks is used to drive the Monte-Carlo simulations for the HAI-model and to present the probabilistic results.

2.2: The <u>lumped parameter technical system behavior submodel</u>

Pressing the brake pedal will cause a pressure rise in the hydraulic brake lines. The pressure will actuate the disc brake by causing the brake piston to press the brake pad against the disc brake rotor (see figure 4).

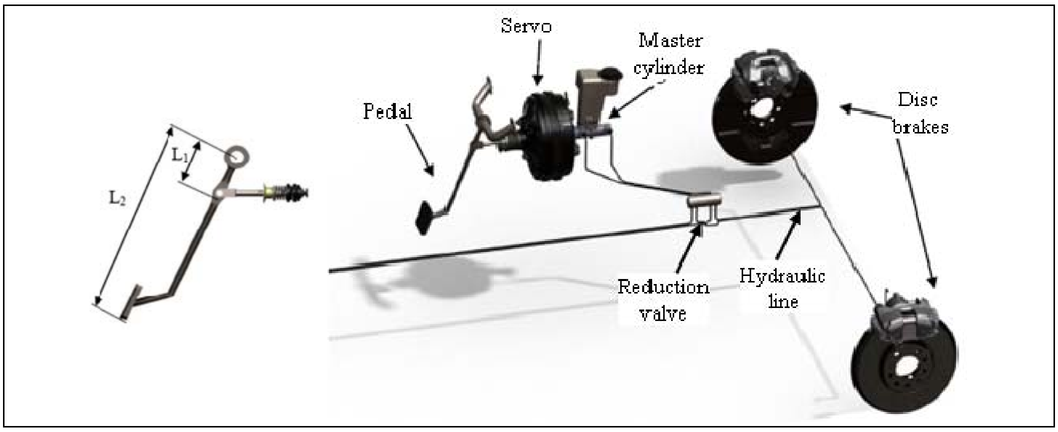

Figure 4: A conventional hydraulic automotive disc brake system [1].

The technical brake system simulation submodel is implemented as a quasi-static lumped parameter model in Simulink [11] from MathWorks. The system components in the submodel are shown in figure 5. The relation between pedal force and movement on the driver side to the actual deceleration of the vehicle is determined by the characteristic parameters of the components involved, such as the actual length (L_2) and lever ratio (L_2/L_1) of the pedal, the flow relations in various cylinders and valves, the stiffness of the caliper, the compressibility of the pad and the surface properties of the rotor, e.g. worn topography and oxide layers. Furthermore, the hydraulic actuators as well as the hydraulic lines are flexible. Hydraulic line flexibility is determined by the oil bulk modulus and the hoop stiffness of the tubes. The flexibility of the hydraulic lines is modeled analytically [12], but the actuator flexibilities are neglected in the present model.

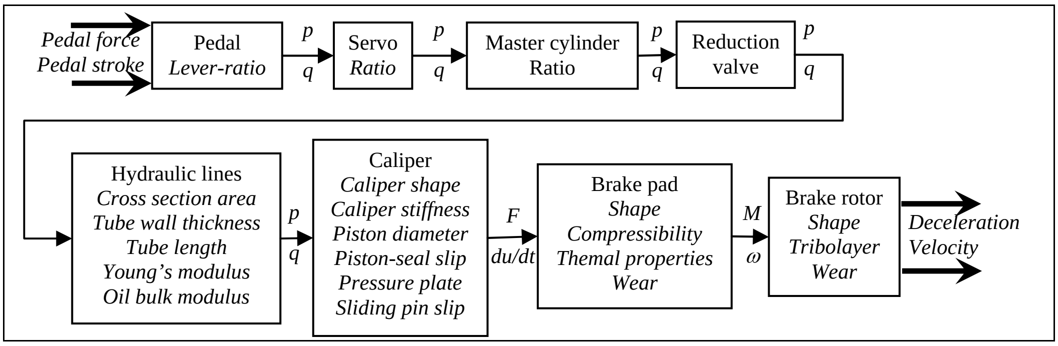

Figure 5: Brake components implemented in the Simulink model

2.3: FE models of component and interaction behavior

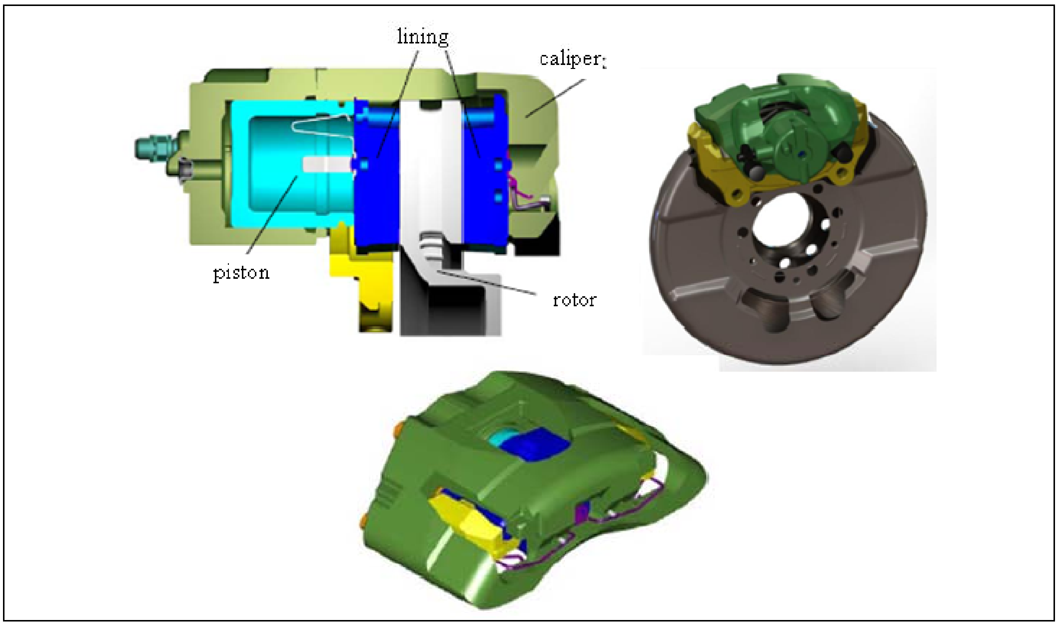

Figure 6: The main components in a disc brake, adapted from [14].

The actual choice of values for the characteristic parameters for the brake system components is based on FEA of the most important caliper components (see figure 6) and there interactions. The FEA tool used is Ansys V11 from

Ansys Inc [13]. The bending stiffness of the caliper, the nonlinear elastic shear deformation of the piston seal and the frictional force between the piston seal and caliper housing, as well as the frictional behavior between the sliding pins and floating caliper are targeted. Furthermore, to allow for predictions of the effect from pad wear-in a quasi-static pad wear routine has been developed and implemented [15].

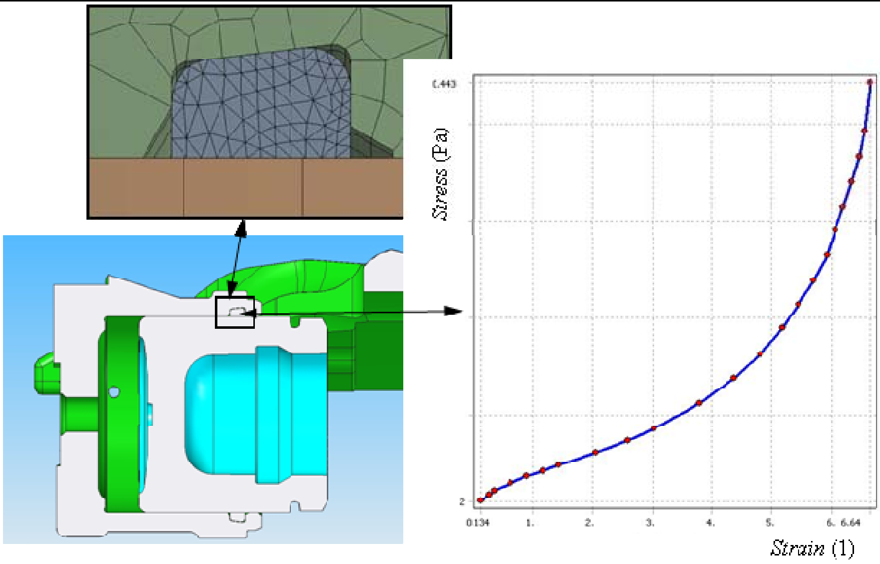

Figure 7: A nonlinear elastic seal in sliding contact with the piston

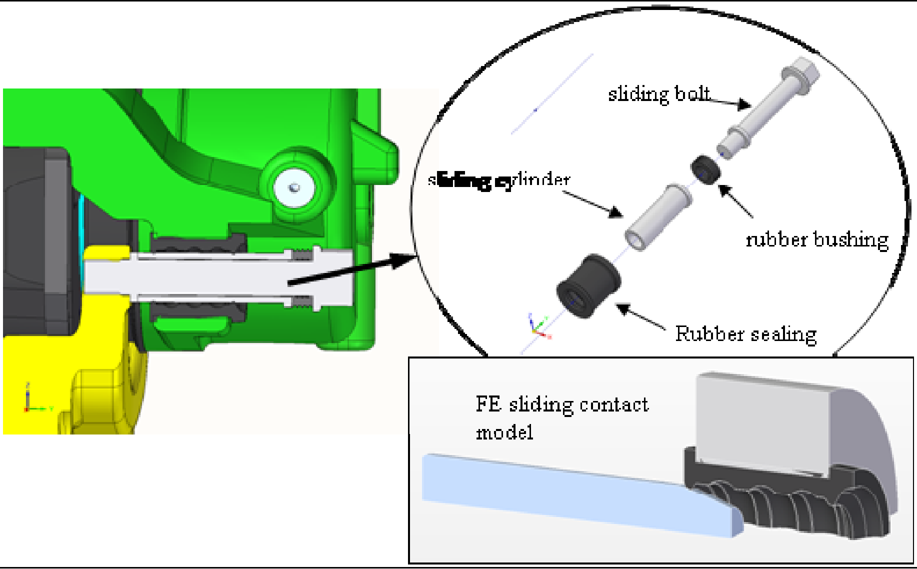

Figure 8: Modeling of the sliding pin in a floating caliper

The non-linear elastic contact model for analyzing the frictional forces and piston seal deformations during loading and unloading the brake pad is shown in figure 7. Figure 8 shows the model for analyzing the deformation and force effect from the frictional behavior of the sliding pin to floating caliper interface. The wear-in FE model, described in [15], is shown in figure 9.

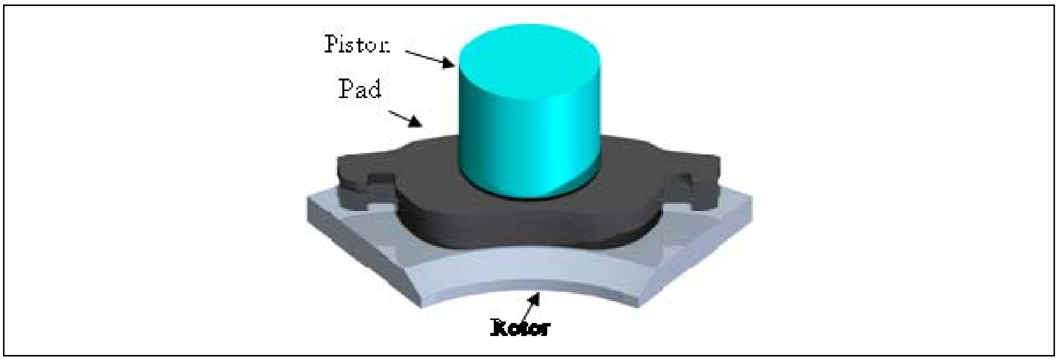

Figure 9: An Ansys FE model of quasi-static brake pad and rotor contact pad wear, from [15]

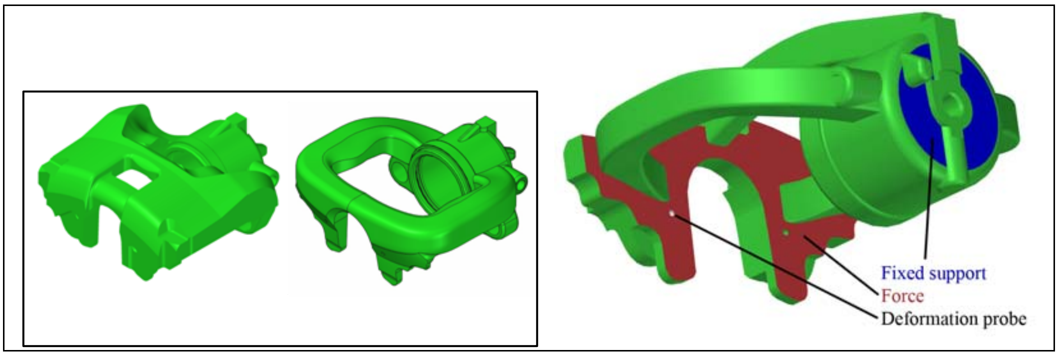

Figure 10: Two caliper concept candidates (left) and probes for detecting elastic caliper deformations during braking, from [14].

To further investigate the proposed method for concept evaluation purpose, FE submodels of two caliper concepts (see figure 10, left) and the location of probes (right portion of figure 10)for storing simulation results for elastic deformation post-processing analysis have been modeled and evaluated in context of the system.

3: RESULT

3.1: Tuning of nominal system parameters

A quasi-static simulation of a nominal and clearance-free brake system (i.e., the pads are just touching the rotor when the braking pressure is applied) gives the nominal pedal force and pedal travel pair, as shown in figure 11. The nominal pedal force and travel relation is converted to the nominal rotational pedal stiffness k_{φ} (Nm/rad), which is used as an interface property in the HAI model. The muscular activities during a predefined braking scenario are then obtained from the biomechanical components in a trailing HAI submodel simulation. Figure 12 shows the maximum muscular activities as function of the maximal voluntary contraction (MVC) as a function of pedal stiffness, seat height, and seat lateral position. The left portion of figure 12 indicates that increasing the nominal pedal stiffness with approximately 10 Nm/rad makes the maximum muscular stress less dependent on a variation in the seat height.

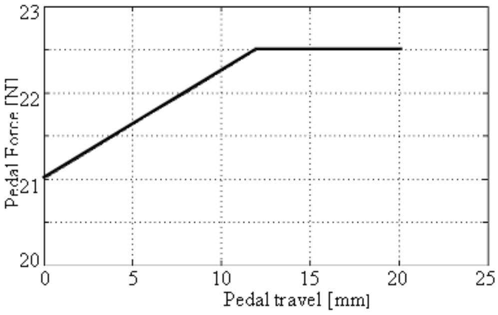

Figure 11: Pedal force and travel for a nominal disc brake system [15]

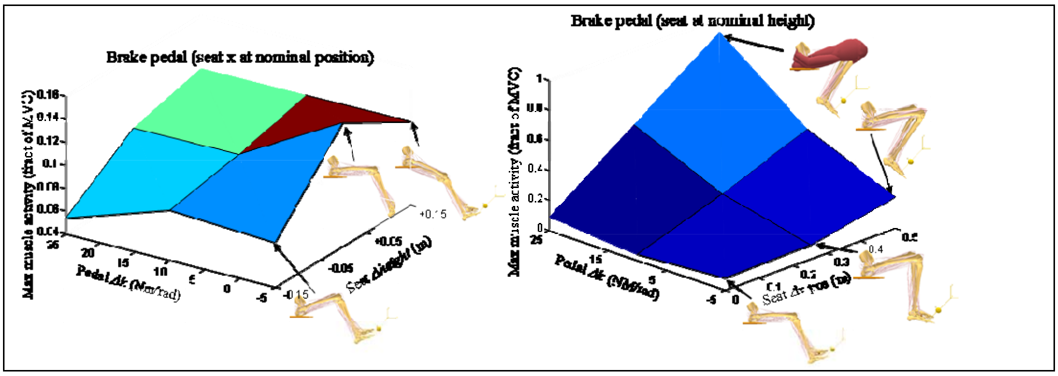

Figure 12: MVC as a function of pedal stiffness, and seat position

3.2: <u>Analyzing effects caused by variation and drift</u>

The effects on pedal force and stroke that are caused by nonlinear elastic deformation and sliding behavior of seals, sliding pins in the floating caliper etc is hard to assess without performing variational studies with a systems model. Figure 3 shows the frictional force and the relative sliding movement in the piston seal and caliper sliding interface. The graph in figure 13 gives an indication of how much the elastic strains stored in the piston seal may retract the pad from the rotor when the foot is no longer pressing the brake pedal. A too small retraction will cause drag braking and a too large retraction (c_i>0 in figure 14) will have a negative effect on the pedal stroke at the next braking sequence.

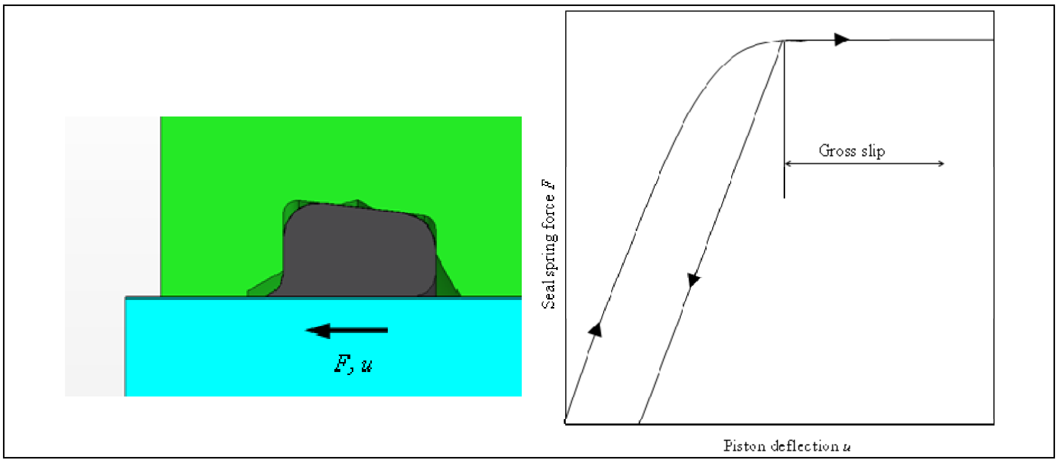

Figure 13: Simulated piston seal sliding force-deflection relation

The right portion of figure 14 shows that for c_i=0 mm, the required pedal stroke will be 20 mm, but with a total initial clearance of just 0.2 mm, i.e. c_i=0.1 mm for each pad in the floating caliper, the pedal stroke will increase to 37 mm.

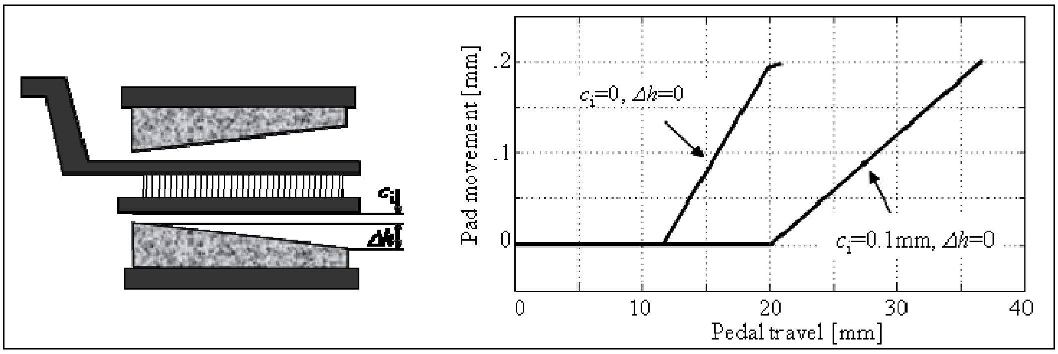

Figure 14: Initial clearance and uneven pad wear (left) and pedal travel for worn pads (right)

The simulation results show a significant variation in the brake pedal travel for a very small variation in the initial pad-rotor clearance. The performance variation can be significantly reduced with a proper choice of nominal values for the characteristic system parameters, i.e., with robust design. Furthermore, it was shown with simulations that implementation of a Quick take-up hydraulic cylinder [17] in the studied system could significantly reduce the sensitivity of the pedal travel to the variation in the initial clearance.

Thermoelastic, chemical and environmental effects will cause both temporary and non-reversal variation in pedal force and stroke. Pad wear will not only modify the thickness of the pads, but also their shape. Figure 15 shows snapshots from a quasi-static FE simulation of pad and rotor wear. Worn pads with the typical tapered shape as shown in the left portion of figure 14, modifies the stiffness of the entire system and consequently cause a variation in the pedal force and stroke relation.

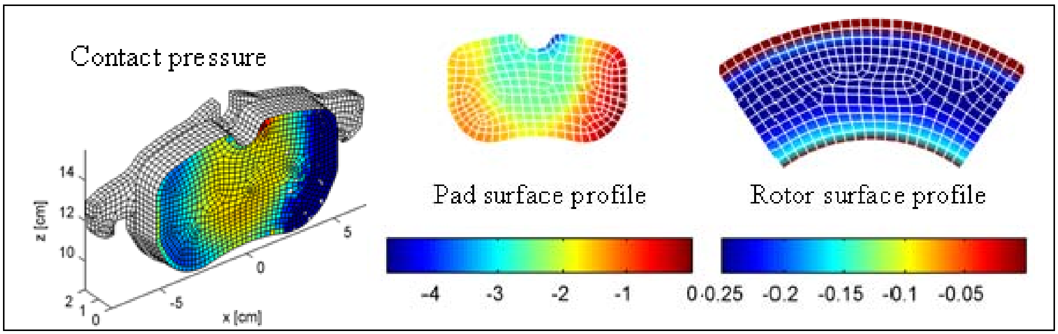

Figure 15: Pressure distribution in the pad-rotor interface during drag braking (left) and wear of pad (mid) and rotor (right) surfaces for a simulated drag brake sequence, from [15]

4: CONCLUSIONS AND DISCUSSION

The result of a tight integration of a technical system model and a human model is a very large, heterogeneous, and highly complex supermodel, which is not well suited for probabilistic simulations or highly nonlinear simulations. A methodology based on a loosely coupled approach to integrate simulations of technical systems, human bodies, and their interaction has been developed and tested for a human operated vehicle disc brake case.

Simulation experiments with the biomechanical submodel demonstrates how the pedal stiffness, the height of the seat, and the distance between the seat and the pedal influence the muscle effort of operating the pedal. It is shown that tuning of the interactive property of the technical brake system model (e.g., the pedal stiffness) can make the muscular effort during braking less sensitive to the seat position and/or the size of the human driver.

The interactive properties of the brake system are designed by identifying and tuning the characteristic internal properties of the technical brake system. From simulations the statement by [16] that the flexibility of hydraulic lines has a significant influence on both pedal force and stroke and on the braking performance was verified. Furthermore, influences of caliper stiffness, sealing behavior, pad properties and pad wear on the required pedal force and stroke could be investigated with a combination of detailed FEA and lumped brake system simulations.

The biomechanical submodel as well as the lumped-parameter technical systems model has been developed to enable probabilistic, i.e. Monte Carlo, simulations to develop robust technical solutions. The developed models and method will serve as a framework for further research on human-machine interaction modeling and simulation in general and vehicle brake system development in particular.

5: FUTURE CHALLENGES

Three highly prioritized challenges are to:

1. quantify and categorize the variation in the interactive behavior, i.e. what *is* brake-feel and *how* is it perceived by different categories of drivers;

2. enable robust ergonomic design of vehicle brake systems based on probabilistic simulations with a chosen distribution of human properties, e.g. human feature scaling;

3. refine the models of the variation in characteristic physical properties, i.e. defining the probability density functions for manufacturing tolerances, scatter in material properties (e.g., pad material compressibility), and to assess frictional variation due to dust, temperature, and fluctuating humidity, and degradation due to operational wear;

Another challenge is to include the “feel” of deceleration during braking, which is a systems behavior that depends on characteristic parameters of the entire system, such as the weight distribution, the suspension and tire properties etc. Furthermore, human behavior and habits, e.g. braking behavior, is difficult to know, but necessary to speculate on. One speculation method is to define typical human actions and the group them into scenarios and perform simulations with bundles of scenarios [18].

A totally different, but highly desirable, cause of action would be to develop and elaborate on efficient methods to use the calculated forces and segment data from the biomechanical model for FEA-based analysis of human joints and optimization of, as an example, hip implants.

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