

Dynamic Control of Disc Brake Performance

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ABSTRACT

Since the driver obtains an important feedback of vehicle dynamics and its braking capabilities depending on a brake performance change, it represents an important aspect of vehicle performance and its quality of use. Regarding modern automotive brakes, the extreme demands have been imposed on the friction couple and its tribological performance. Different sensitivity of braking torque, i.e. a disc brake performance versus the influence of the friction couple interaction, under different braking conditions (applied pressure, speed and brake interface temperature), is one of the most important the disc brake properties. That is why, control of braking performance in the sense of providing stable braking performance during a braking cycle and their dynamic adaptation to the driver demands and/or demands imposed by ABS/ESC, are very important. Investigation presented in this paper contributes to the efforts in the direction of intelligent dynamic control of automotive braking systems performance. The dynamic model has been developed in the paper in order to provide dynamic prediction and control of the disc brake performance during a braking cycle. This model provided stabilization of the brake performance and their maximization versus the brake pedal travel, selected by a driver, and influence of the current values of initial speed, the brake activation pressure, and the brake interface temperature.

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INTRODUCTION

Today's motor vehicles become considerably more complex due to increasing requirements related to active safety, stability, and maneuverability. These high and often diverse requirements can be largely reflected on the automotive braking system, and in particular on its brakes as its main operating components. In order to make the braking system able to satisfy these increasing demands, many important tasks, such as sensitivity of a brake performance against the different brake operation conditions, have to be considered. Regarding the friction couple interaction, the most important demand relates to value of the coefficient of friction. It should be relatively high and keep a stable level irrespective of various influences. There are also additional requirements such as long life and high comfort, as well as absence of vibration and squeal noise [1,2]. Tribological processes occurring at the contact of friction pair can span over a different disciplines such as the mechanics and/or thermodynamics and/or chemistry. According to [3,4,5,6], the real contact area of the friction couple is far from constant, very small compared to the total contact area, and highly

dependent on changes of pressure, temperature, deformation, and wear. In addition, frictional heat is generated at the sliding interface when two bodies slide against each other with a relative speed and positive contact pressure. A dynamic change of the brake contact situation, represented by dynamic change of the size and composition of the contact area has a crucial influence on the friction behaviour of the friction couple and accordingly the disc brake tribological performance. This means that friction pair's contact phenomena may be responsible for highly dynamic and stochastic variations of braking torque during braking. To overcome this problem, the dynamic behavior of disc brake operation should be subjected to further investigation in the sense of modeling, prediction, and control of a disc brake performance during a braking cycle. Providing possibilities for prediction of braking torque versus influence of the brake actuation pressure, sliding speed, and brake interface temperature is the main precondition for future dynamic control of disc brake performance.

Significant research in this area has been conducted in order to control braking torque and braking forces [7,8,9,10] in attempts to improve vehicle braking performance. Modelling of disc brake output performance could be very complex if using conventional analytical modelling techniques, regarding the complexity of requirements imposed to brakes [11,12], and highly non-linear phenomena involved in the field of tribological interactions. Thus, prediction of synergistic effects of all influencing parameters on disc brake performance in dynamic operating conditions requires accurate and effective tools [13]. As it is discussed in [8,14], conventional analytical approaches cannot be able to handle modelling errors and suffer from lack of accuracy and robustness. Artificial neural networks have shown to be effective and very useful for nonlinear dynamic modelling of time series events, due to their excellent ability of non-linear mapping, generalization, self-organization, and self-learning [15]. The universal approximation capabilities of multilayer neural networks have made them a popular choice for modelling of nonlinear systems' operation in dynamic environments, where unpredictable and sudden changes may occur [10]. Besides, many of difficulties related to dynamic control, like large network sizes, long training times, and large number of data can be overcome with dynamic artificial neural networks [16,17]. Dynamic neural networks have memory that can remember the past values and states of the network. The output of the dynamic network depends not only on the current input values but also on the previous inputs, outputs or states of the network [18,19]. These abilities of dynamic neural networks could be particularly suitable for control of braking torque realized in the disc brake during a braking cycle.

In this paper, our attention has been focused on dynamic modeling, prediction, and control of braking torque of the disc brake during a braking cycle. Thus, the complex tribological processes between the disc brake contact surfaces interaction has been dynamically modelled involving the influence of the brake actuation pressure, the sliding speed, and the brake interface temperature. In addition, special attention was paid to the disc brake performance sensitivity against pressure - speed - temperature dynamic change in a braking cycle. This could allow better control of the disc brake performance and provide possibilities for adjusting of the brake actuation pressure according to the driver demands, vehicle speed, and the real values of braking torque realized in the disc brake. The developed dynamic model was employed for dynamic control of braking torque in different braking conditions. It was done to test its ability to learn and predict dynamic change of braking torque versus pressure - speed - temperature change during a braking cycle.

EXPERIMENTAL RESEARCH

The dynamic behavior of automotive brake makes the modelling process very demanding and difficult. The basic precondition related to control of disc brake performance comprises developing of a dynamic model able to learn and generalize complex tribological behavior of the disc brake in dynamic operating conditions. Taking into account their functional properties, recurrent neural networks were employed to achieve this goal. The basic precondition for developing of dynamic neural model of disc brake performance, i.e. change of braking torque is related to training of artificial neural networks with input data organized as time series. Thus, brake actuation pressure, sliding speed, and brake interface temperature have been varied in certain order to define different conditions of the disc brake operation. It means that the disc brake has been tested using a testing methodology where application pressure has been varied between 20 and 100 bar, initial values of speed between 20 and 100 km/h, and brake interface temperature between 25 and 100°C. Output performance of the disc brake was represented by the braking torque. In order to better investigate how different braking conditions influence the disc brake performance sensitivity, experimental data have been provided. Thus, a single-end full-scale inertial dynamometer was used for testing of the brake under different operation conditions, see Fig. 1.

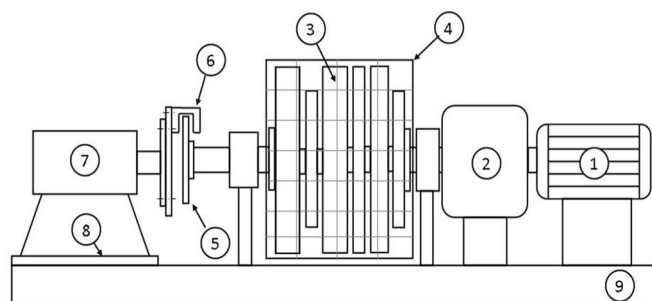


Figure 1. Single-end full-scale inertial dynamometer.

Regarding Fig. 1, components of the dynamometer are: 1 - the electromotor, 2 - power carrier, 3 - set of flywheels for providing of different inertial masses, 4 - protective cage for flywheels, 5 - firmly jointed brake disc, 6 - brake caliper, 7 - system for braking torque measurement, 8 - axial slider, and 9 - common foundation. The disc brake being tested on the dynamometer was designed for mounting on the front axle of passenger car with static load of 730 kg. The total number of braking cycles that have been done under different braking conditions was 50. In this way, it is possible to identify influences of different values of brake actuation pressure and speed on the braking torque change. In this paper, this was performed in the case of so-called cold brake (brake interface temperature was below 100° C). Each of these four parameters, whose functional dependence was modeled by recurrent neural networks, was measured by appropriate

pressure, speed, temperature and torque sensor. The brake interface temperature has been measured by thermocouple sensor, mounted in the hole that was drilled in the brake pad. The temperature that was measured corresponds to the value measured at 1 mm from the contact of brake disc and pad, where the probe of the sensor was placed. Actual brake interface temperature is very difficult to be measured by the thermocouple sensor due to very high temperature gradient between the contact surfaces. Two examples of change of all relevant parameters that were measured during a braking cycle where the disc brake was activated by low (Fig. 2) and moderate pressure (Fig. 3). It can be seen that changes of the disc brake performance (represented by braking torque) versus influence of braking conditions (defined by the brake applied pressure, sliding speed and the brake interface temperature) have been considered as a function of time. This is very useful because dynamic neural networks have memory, and, therefore, they can be trained to learn sequential or time-varying patterns. The complexity of change and index of braking torque increasing during a braking cycle (see Figs. 2 and 3), indicates that development of dynamic model able to establish the functional relationship between parameters with such complex change, and particularly in dynamic operating conditions, is not an easy task. In order to be further used to control of disc brake performance, a dynamic model should be able to learn the nature of change of these measured parameters, but also to adapt and predict change of braking torque during a braking cycle. Moreover, it should be able to store the knowledge about the braking process and exploit capabilities of recurrent neural networks to use the history of previous changes of input/output parameters.

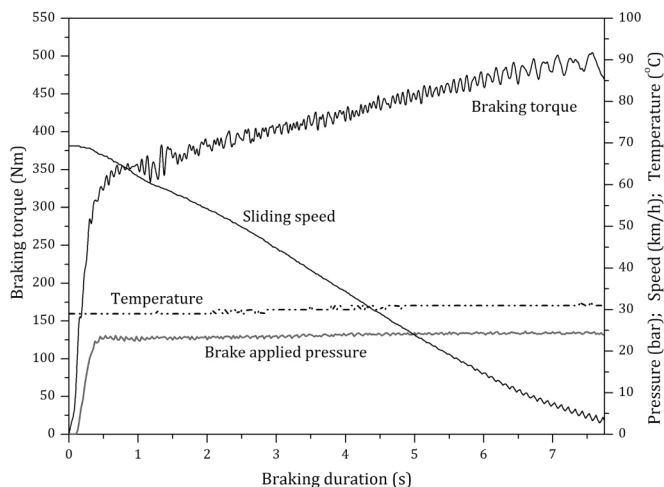


Figure 2. Measured the inputs/output parameters of a braking cycle (low brake applied pressure).

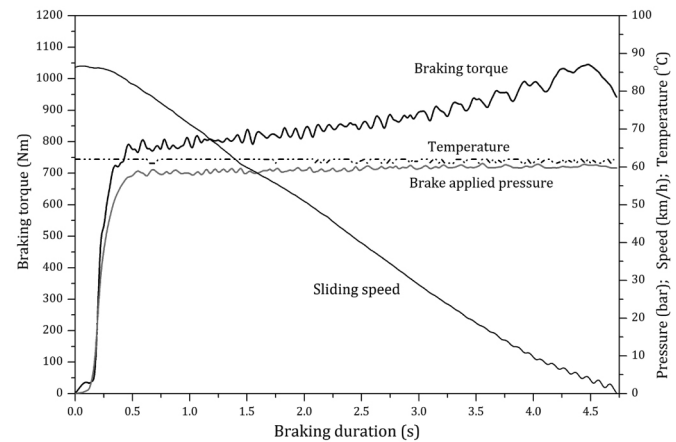


Figure 3. Measured the inputs/output parameters of a braking cycle (moderate brake applied pressure).

DYNAMIC MODELLING

Modelling of highly dynamic change of braking torque during a braking cycle can provide preconditions for more precise control of the disc brake performance in different braking situations. Since artificial neural networks have shown as an effective and proven method for prediction of time series events, they have been employed for modelling of such complex dynamic process. In general, artificial neural networks can be classified into static and dynamic categories. The main difference is related to the fact that static, i.e. feedforward networks have no feedback elements and contain no delays - the output is calculated directly from the input through feedforward connections. They could be used for resolving some steady-state engineering problems only. On the contrary, dynamic neural networks are generally more powerful than static networks (but also more difficult to train), due to memory that can remember the past values and states of the network. Regarding Figs. 4 and 5, the output of the dynamic network depends not only on the current input values but also on the previous inputs, outputs or states presented to network using a time delay vector TD. This enables the network to learn complex, dynamically changed, influence of different braking conditions on the dynamic brake behaviour. Since dynamic neural networks could be trained using the same gradient based algorithms that are used for static networks, performance of the algorithms on dynamic networks can be quite different, and the gradient must be computed in a more complex way. Dynamic neural networks can be generally divided into two types: (i) Feed-forward Time-Delay Neural Networks, and (ii) Feedback or Recurrent Neural Networks [20,21]. The network function is determined largely by the interconnections between neurons, widely known as connection weights. The weights have two different effects on the dynamic network output: (i) the direct effect (a change in the weight causes an immediate change in the output at the current time step, and therefore, can be computed using standard backpropagation) and (ii) the