Dynamic Modelling of Disc Brake Contact Phenomena

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An interaction between a brake disc and friction material of automotive brake is characterized by a number of braking phenomena. These phenomena are influenced by brake operation conditions (applied pressure, speed, and brake interface temperature) and material characteristics of a friction couple. The dynamic and highly non-linear changes occurred in the contact of the friction pair, provokes hard-to-predict change of braking torque as the most important brake's output performance. Complex disc brake contact situation is causing sudden change of braking torque and could not be easily modelled and predicted using classical mathematical methods. That is why, the possibilities for development of the method for prediction of influence of braking regimes on generation of the stick-slip phenomena during a braking cycle has been investigated in this paper. Dynamic neural networks have been employed for development of the model of influences of the disc brake operation conditions on contact phenomena generation and "nature" of braking torque change.

Keywords: *dynamic modelling, disc brake, contact surfaces.*

1. INTRODUCTION

The increasing requirements related to active safety, stability, and comfortability of modern vehicles makes them become more complex. These high and primarily diverse requirements are largely reflected on the automotive braking system, and in particular on its brakes. In order to make the braking system able to satisfy these increasing demands, many important tasks have to be taken into consideration. The coefficient of friction should be relatively high and keep a stable level irrespective of temperature change, humidity, age, degree of wear and corrosion, presence of dirt and water spraying from the road, etc. Additionally, requirements for long life and high comfort, as well as absence of vibration and squeal noise become very important [1]. Tribological processes occurring at the contact of friction pair unite questions from different physical fields, such as mechanics, thermodynamics and chemistry [2,3]. The friction pair's contact situation is not well understood so far. The real contact area is far from constant, very small compared to the total contact area, and highly dependent on changes of pressure, temperature, deformation, and wear [4-7]. The contact plateaux are dynamically changing from place to place in fractions of a second during brake applications. Thus the true contact area is unknown. Furthermore, frictional heat is generated at the sliding interface when two bodies slide against each other with a relative speed and positive contact pressure. The subsequent thermo-mechanical deformations between the rubbing surfaces modify the contact profile. The pressure distribution is then changed, altering the distributions of temperatures generated during braking. It is causing dynamic change of the brake contact situation.

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On the other hand, as in all other sliding contact situations, the area of real contact transfers the friction forces. Moreover, dynamic change of the size and composition of the contact area has a crucial influence on the friction behaviour of the disc brake and accordingly braking phenomena generation.

Automotive brakes constitute one of the few applications, where a material is supposed to slide against another at high sliding velocities with a high coefficient of friction [6-8]. This puts extreme demands on the friction couple and its tribological performance. Change in a disc brake coefficient of the friction, as a function of sliding speed and/or applied pressure and/or brake interface temperature, is very important issue because drivers expect a relatively constant level of friction force at various braking conditions. Furthermore, the manner of change of the coefficient of friction may provoke brake phenomena such as noise, anti-fade, and vibration [9]. One of the most important braking properties induced by complex tribological behaviour of a friction couple is speed sensitivity. It is closely related to stick-slip phenomena [10]. While stick-slip is highly dependent on system dynamics, it is well-known that the ingredients in the friction material strongly affect the stick-slip phenomena as well [9-11]. The creep groan is a typical example of a self-excited brake vibration caused by the stick-slip phenomena at the friction interface and is closely associated with the difference ($\Delta\mu$) between "static" (at the end of braking cycle) μ_s and kinetic μ_k coefficients of friction. A negative μ – velocity relation, $d\mu/dv < 0$, or a higher static than dynamic friction coefficient was one of the first friction characteristics identified as increasing the squeal propensity [8].

All these 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 behaviour of disc brake operation should be subjected to further investigation in the sense of modelling, prediction, and control of disc brake performance during braking. Providing possibilities for prediction of braking torque versus influence of applied brake pressure, sliding speed, and brake interface temperature, for the specific material characteristics of a friction pair, is a main precondition for future dynamic control of disc brake performance. Modelling of disc brake output performance could be very complex if using the conventional analytical modelling techniques, regarding the complexity of requirements imposed to brakes [12,13], 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 [14]. As it is discussed in detail in [12-16], the 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 [17]. 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 [18]. They could be considered as a tool for systematic parameter studies based on parallel processing property and very popular applications of biological understanding to engineering [19]. The non-dynamic nature of popular network architectures can be a constraining factor for the application of neural networks technique for modelling of dynamic system behaviour, such as automotive brake, for instance. Many difficulties, like large network sizes, long training times, and a large number of data can be overcome with dynamic artificial neural networks [20,21]. 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 [22,23]. These network properties could be particularly addressed to dynamic recurrent neural networks, whose application has been discussed in detail in [24,25].

In this paper, our attention has been focused on investigating the possibilities of modelling the disc brake contact surfaces interaction, i.e. prediction of the disc brake contact phenomena affecting the braking torque. Thus, the complex tribological processes between the disc brake contact surfaces interaction has been dynamically modelled. It means that synergistic influence of applied brake pressure, sliding speed, and brake interface temperature on braking torque change has been modelled as a consequence of braking phenomena that occurred in the contact. Special attention was paid to investigation of the disc brake performance sensitivity against pressure – speed dynamic change during a braking cycle.

2. EXPERIMENTAL SETUP

The behaviour of nonlinear dynamical system, such as an automotive brake, is very demanding and difficult to model. The basic precondition is related to developing a dynamic model able to learn and generalize complex tribo behaviour of the disc brake in dynamic operating conditions. In order to better investigate how braking regimes influence the disc brake performance sensitivity, experimental data has been provided. Single-end full-scale inertial dynamometer was used for testing of the brake under different operation conditions, see Fig. 1. The disc brake has been tested using a previously defined methodology, where application pressure has been varied between 20 and 100 bar, initial speed between 20 and 100 km/h, and brake interface temperature between 25 and 100 °C.

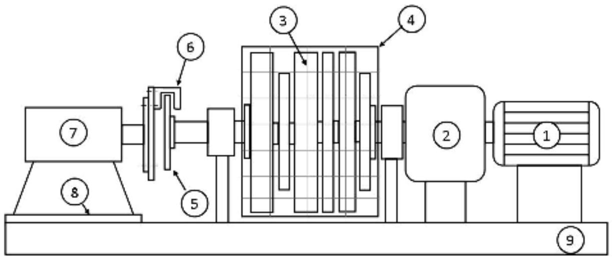

Figure 1. Single-end full-scale inertial dynamometer

Regarding Figure 1, its main components are the electromotor (1), power carrier (2), set of flywheels for providing different inertial masses (3), protective cage for flywheels (4), firmly jointed brake disc (5), and stationary part of the tested brake – calliper (6). Additional components are the system for braking torque measurement (7), axial slider (8), and common foundation (9). The tested disc brake was designed for mounting on the front axle of passenger car with static load of 730 kg. The disc brake testing conditions have been established according to the range and distribution of data that are going to be collected. The total number of braking cycles was 100.

3. DYNAMIC MODELLING

As above mentioned, an appropriate tool should be used for modelling the complex dynamic process such as automotive braking. Artificial neural networks have shown to be an effective and proven method for prediction of time series events. Neural networks can be classified into static and dynamic categories. Static neural networks (known as feedforward networks) have no feedback elements and contain no delays – the output is calculated directly from the input through feedforward connections. As explained in [15], static neural network could be used for resolving some engineering problems. Dynamic neural networks are generally more powerful than static networks (although somewhat more difficult to train), and have memory that can remember the past values and states of the network [21]. Traditional research in this area uses a network with a sequential iterative learning process based on the feedforward, back-propagation approach. Regarding Figure 2, 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, usually called tapped delay line or TDL [21]. 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.

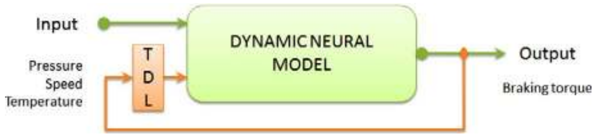

Figure 2. Dynamic model of disc brake operation

Dynamic neural networks can be generally divided into two types: (i) Feed-forward Time-Delay Neural Networks, and (ii) Feedback or Recurrent Neural Networks [26,27]. The network function is determined largely by the interconnections between neurons, widely known as connection weights. According to [21], 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 indirect effect (implies using dynamic backpropagation to compute the gradients, which is more computationally intensive).

In this paper, the non-linear autoregressive network with exogenous inputs has been used to model the braking torque during dynamic change of influencing factors such as applied brake pressure, sliding speed, and brake interface temperature. This type of network architecture is a part of recurrent dynamic networks with feedback connections enclosing several layers of the network. Schema of the network architecture shown in Figure 2 represents original (closed loop or parallel) form of NARX neural network, which will be further discussed. This model is based on the linear ARX model, which is commonly used in time-series modelling [26]. The next value of the dependent output signal is regressed on previous values of the output signal and previous values of an independent (exogenous) input signal. The NARX network is commonly used for many applications, and in particular for modelling of nonlinear dynamic systems [21]. One more reason why this type of dynamic neural network was used is the possibility to create a series-parallel architecture that is very useful for training (see Fig. 3). The series-parallel network architecture has two advantages: (i) the input to the feedforward network is more accurate, and (ii) the resulting network has purely feedforward architecture, and static backpropagation can be used for training. Regarding Figure 3, the true output (real braking torque) is used for neural networks training (as secondary input value) instead of feeding back the estimated output, i.e. braking torque predicted by neural network. Applied brake pressure, sliding speed, and brake interface temperature have been used as primary input to recurrent neural model, see Fig. 3.

The experimentally obtained data have been divided into training and testing data sets in order to train and furthermore test recurrent neural models. Since dynamic neural networks contain delays, the input to the network must be a sequence of input vectors that occur in a certain time order. The order in which the vectors appear is extremely important [21]. The training of neural networks has been done with the initial input delay of 0.1 seconds. The measured value of braking torque also delayed 0.1 s as the input of NARX series-parallel network architecture (see Fig. 3).

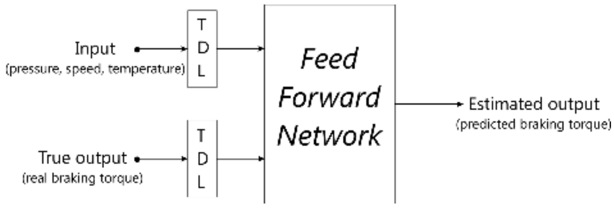

Figure 3. Benefits of series-parallel architecture

To ensure good training of neural networks, sufficient amount of data points versus all available data have been used. The amount of data used for training equals approximately 60 % (60 braking applications), while the rest of data were used to test neural networks' generalization capabilities. These two data sets were carefully formed with the aim to establish relative uniform distribution of certain brake operating regimes. The training process of developed neural model included a supervised learning, which means that training was performed off-line, so that each output unit is told what its desired response to input signals ought to be. The network has been firstly trained in a series-parallel structure, and then rearranged in an original closed loop (parallel) form to enable prediction over many time steps.

Since the proper combination of neural network's architecture and learning algorithm are unknown in advance, a trial and error method has been employed to select the neural model with the best predictive abilities. Twenty recurrent neural network architectures with one, two, and three hidden layers have been investigated in this paper. Dynamic neural networks could be trained using the same gradient-based algorithms like static neural networks. In this paper, each of the considered recurrent neural networks has been trained by Levenberg-Marquardt, Bayesian Regularization, and Resilient Backpropagation learning algorithm. These dynamic neural models were developed using the program package Matlab 7.11.0.584 (R2010b). As a transfer function between the input and the first hidden layer, as well as between the hidden layers, *tansig* transfer function has been chosen. A pure linear transfer function has been employed between the hidden and the output layer.

4. RESULTS AND DISCUSSION

All considered dynamic neural networks have been tested versus data included in the test data set (enclosing 40 braking applications). Accordingly, their capabilities for predicting the braking torque variation in a braking cycle have been evaluated. Among 60 recurrent neural models being investigated, three-layered neural networks trained by Resilient Backpropagation algorithm reached the best prediction capabilities. This confirms the well suited capabilities of this learning algorithm to deal with large network structures and high amount of network parameters. The best prediction results of the braking torque were achieved by the recurrent neural network with 10 neurons in the first, 6 neurons in the second, and 4 neurons in the third hidden layer. The regression plot shown in Figure 4 illustrates the linear regression between each value of the network response, and the corresponding target value, i.e. the real braking torque.

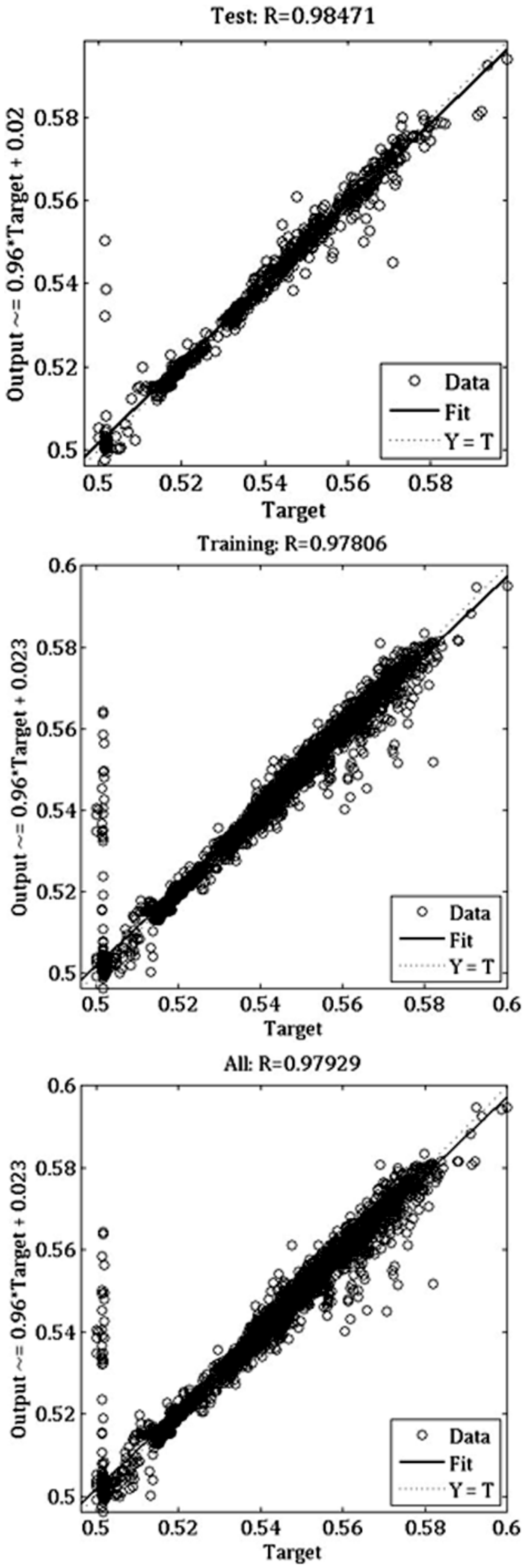

Figure 4. The regression plot of the best neural model

The regression is represented versus training and test data sets, as well as the overall data presented to network. It is evident that data used for testing has better regression (R = 0.98471), where R = 1 means that values related to network outputs and data related to targets overlap completely (see Fig. 4). Because of the series-parallel configuration, this regression plot is valid only for one-step-ahead prediction. Thus, the network was rearranged into the original parallel (closed loop) form in order to perform an iterated prediction over many time steps. Note that obtained results are valid only for this specific combination of the brake disc and pad properties, and observed operating regimes.

In order to investigate the phenomena induced by complex friction pair's contact situation, the developed dynamic model of disc brake contact surfaces interaction has been used to predict the braking torque in a braking cycle. The dynamic model has been tested versus its prediction capabilities related to the braking torque oscillation as well as the prediction of dynamic change of the braking torque during a braking cycle. It was especially important to model the synergistic influence of pressure – speed change on braking torque. Importance of the model abilities to generalize these influences is related to the fact that the dynamic model of braking torque variation opening possibilities for its better control. Moreover, negative effects of the stick-slip phenomena occurred in the contact of the disc brake could be suppressed at the end of braking by modulation of the brake application pressure.

The model has been tested under braking regimes which could induce conditions for generating the stick-slip phenomena. Firstly, the braking torque was predicted for relative low sliding speed of 35 km/h and mean maximum value of applied pressure of 23 bar (see Fig. 5). It can be seen that the braking torque had intensive oscillation, especially at the end of the braking cycle. As a consequence of the braking torque change, speed also oscillated particularly for values below 20 km/h. It is evident that these fluctuations of the braking torque are primarily influenced by speed sensitivity of friction pair that could be caused by the stick-slip phenomena occurred at the contact of the brake disc and pads. Moreover, the speed fluctuations, showing increasing tendency to the end of braking, indicate existence of self-excited vibrations (see Fig. 5). Regarding the real braking torque, its increasing, expressed as a relation between the maximum and the minimum value of the braking torque (T_{max}/T_{min}), was 1.32 in the observed range of speed decreasing (Δv = 30 km/h), see Fig. 5. On the other hand, increasing of predicted braking torque, in the same range, was 1.21. The model recognized how these brake operation conditions affect the braking torque.

Further increasing of the applied pressure to 42 bar, for an initial speed of 55 km/h (see Fig. 6), caused higher increasing of the braking torque versus speed decreasing. It is especially noticeable for the speed below 20 km/h. Coefficient of real/predicted braking torque increasing in this case was 1.5/1.375 versus speed decreasing. It is evident from Figure 6 that braking torque was suddenly increased below 20 km/h. It means that stability of the braking torque was not

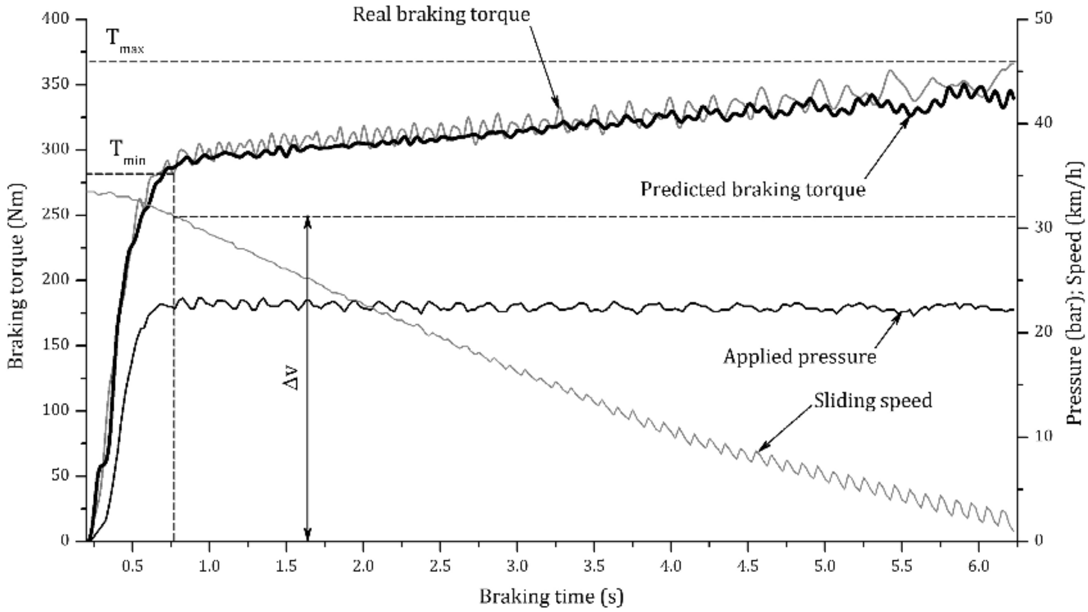

Figure 5. Comparison: Real and predicted braking torque (mean maximum pressure 23 bar, initial speed 35 km/h)

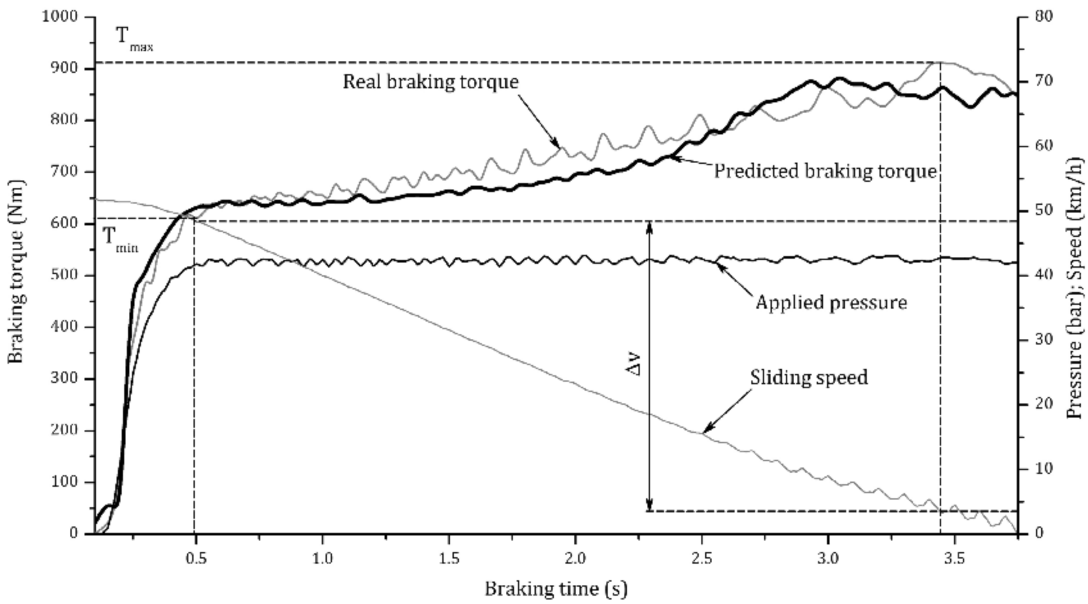

Figure 6. Comparison: Real and predicted braking torque (mean maximum pressure 42 bar, initial speed 55 km/h)

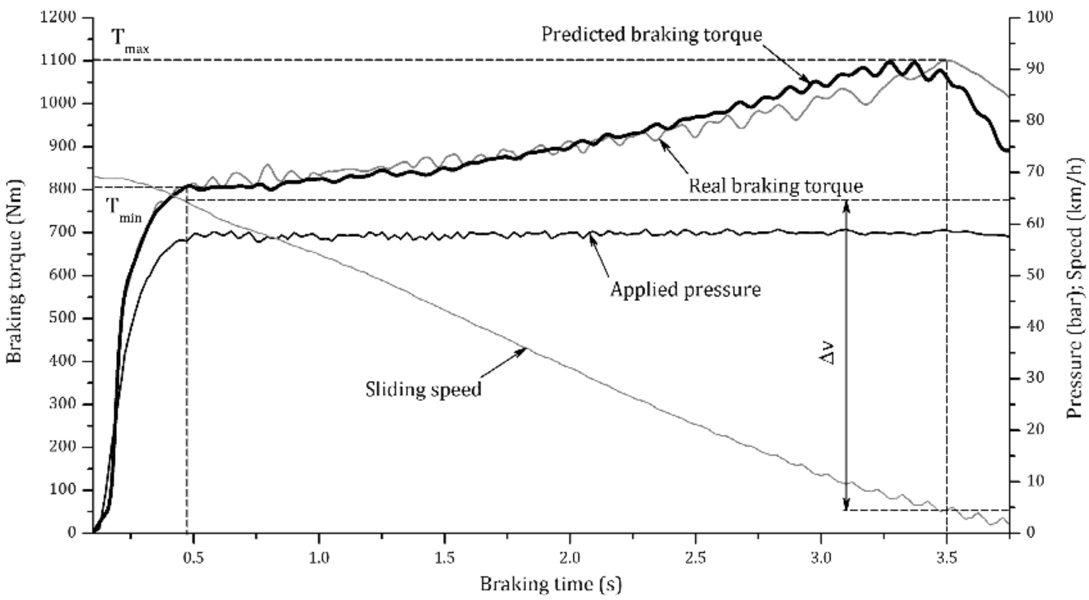

Figure 7. Comparison: Real and predicted braking torque (mean maximum pressure 58 bar, initial speed 70 km/h)

provided under these braking regimes. Such tribo behaviour of the disc brake is unwanted because it is causing self-excited vibrations, noise, deteriorates driver braking conformity and brake pedal feel. The dynamic model recognized how the pressure and the speed affect the braking torque change during a braking cycle under these braking conditions. Generalization of capabilities of the dynamic neural model are on the acceptable level. It was able to deal with large fluctuations of the braking torque during a braking cycle in a wide range of changes of the influencing parameters (see Fig. 6).

According to Fig. 6, the most common braking regime is characterized by intensive oscillations of the braking torque, especially at the end of braking. It can be seen that the friction pair has propensity towards increasing the braking torque with speed decreasing. The disc brake has also shown high sensitivity to sliding speed decreasing for the brake application pressure of 58 bar and initial speed of 70 km/h (see Fig. 7). From Fig. 7 it can be seen that the braking torque oscillations have been suppressed with the brake application pressure increasing from 42 to 58 bar. Due to explained tribo behaviour of the friction couple, the braking torque still increases (coefficient of braking torque increasing was 1.375) with the speed decreasing. The dynamic model has shown enough flexibility to be able to adapt its prediction potential to predict the disc brake behaviour. These predictive abilities of dynamic model could be used for fine-tuning of the disc brake braking torque and correction of consequences of the stick-slip phenomena occurred in the contact of friction pair due to change of the brake operation conditions (pressure, speed, and temperature).

5. CONCLUSIONS

In this paper, the dynamic behaviour of the disc brake contact surfaces interaction has been investigated under different braking regimes during a braking cycle. The dynamic model able to predict and control the braking torque has been developed. The influence of braking regimes on generation of the stick-slip phenomena of the disc brake was identified and modelled. Using the proposed approach for modelling the disc brake contact surface interaction, the influence of applied pressure, speed, and the brake interface temperature on braking torque change has been generalized. This dynamic model offers important possibilities of intelligent controlling of the brake tribo behaviour during a braking cycle. Based on the model developed in this paper, high fluctuation of the braking torque as well as the stick-slip phenomena generated in the contact of friction pair could be suppressed and/or eliminated. It would provide more comfortable braking process without vibrations and noise.

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ДИНАМИЧКО МОДЕЛИРАЊЕ КОНТАКТНИХ ФЕНОМЕНА ДИСК КОЧНИЦЕ

Велимир Ћировић, Драган Алексендрић

Интеракција између диска кочнице и фрикционог материјала диск кочнице моторних возила се одликује великим бројем контактних феномена. Настанак ових феномена је везан за радне услове кочнице (притисак активирања, брзина, температура у контакту) као и за карактеристике материјала фрикционог пара. Динамичке и изражено нелинеарне промене, које се дешавају у контакту фрикционог пара, изазивају тешко предвидиву промену момента кочења, као најважније излазне перформансе кочнице. Сложена ситуација у контакту фрикционог пара се не може лако моделирати и предвидети коришћењем класичних математичких метода. Због тога су истраживане могућности развоја методе за предвиђање утицаја радних режима диск кочнице на појаву тзв. „stick-slip" феномена током циклуса кочења. Коришћењем динамичких неуронских мрежа, развијен је динамички модел утицаја радних услова диск кочнице на појаву контактних феномена и начин промене момента кочења.