International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. V, No. 1 / 2013

A METHOD TO OBTAIN A GENERALIZED MODEL OF THE PRESSURE EVOLUTION WITHIN THE BRAKING SYSTEM OF A VEHICLE

Marin Marinescu[1], Radu Vilău [1], Marian Truță [1] & Octavian Fieraru[1]

[1]Military Technical Academy, Bucharest, Romania, Department of Military Automotive Engineering and Transportation, Blvd. George Coşbuc nr. 39-49, Sector 5, Bucharest, 050141, Romania

Corresponding author: Marin Marinescu, marin_s_marinescu@yahoo.com

Abstract: Military vehicles have to travel, at least from time to time, on the national road network. Whenever that happens, the legal requirements have to be met with respect to the systems that contribute to the traffic safety. One of these systems is the braking system. On the other hand, most of the military vehicles aren't that up-to-date that the rest of the traffic partners are. Therefore, a military automotive engineer should have at hand a fast method to diagnose the technical status of the braking system even the checked vehicle is rather old. It would be also even better if the faulty party were accurately identified. The paper aims at providing a method helps the diagnosing teams to quickly compare the behaviour of an actual vehicle braking system status with a general model that had been acquired by tests. Since nobody provided that kind of information during 70's, our model derived from a large number of tests that have been performed on good technical condition vehicles.

Key words: vehicle braking system, parametric models, data-based models.

1. INTRODUCTION

In past years, the requirements that vehicles have to meet to accepted on the public roads had constantly increased. Even the military vehicles take advantage of a special position within the traffic regulations, they also have to meet some of the strictest requirements, such as the ones concerning the braking system. Since the military equipment can't be changed that easily, the Army needs to upgrade the existing one. Therefore our instituiton was aked to perform a study on his topics. This paper is presenting the procedure we used and the results we obtained.

We have used a Romanian-made reconnaissance armored personnel carrier to perform the required tests (fig. 1). These tests were part of a bigger program, aiming at updating the braking system of the vehicle.

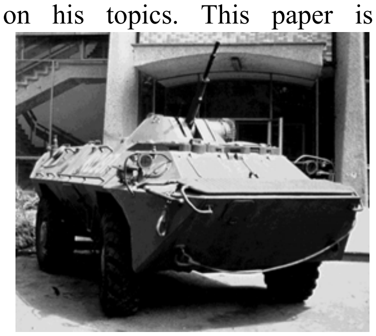

Fig. 1. TABC-79, 4x4 Reconnaissance APC

The braking system of the vehicle is a hydraulic one, assisted by an air-compressed section. So, the brake cylinders are acted by brake fluid. At its turn, the liquid is sent into the cylinders by a brake pump, pressed by the foot's force and helped by compressed air (fig. 2). The system is quite simple and already well known; hence no further details are needed.

Also, the braking mechanism at each wheel's level is a classic one, consisting of a pair of brake shoes, bolted on a brake plate, acting inside a brake drum and using a liquid-acted cylinder as a power actuator.

The working principle of the servomechanism is quite simple (fig. 2). When pressing the brake pedal 5 its pushing rod acts on the piston of the master brake cylinder (a twin one, serving a dual circuit). The master twin cylinder sends the fluid into the brake cylinders that, at their turn, act the brake shoes. When pressing the brake pedal, the pedal's lever pushes the

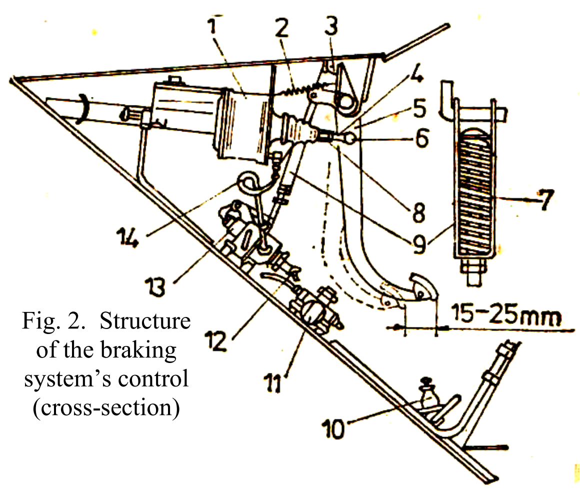

Fig. 2. Structure of the braking system's control (cross-section)

connecting rod 9, which acts on a double chamber, unbalanced, compressed air distributor 13 (that mainly works as a "faucet" or a "tap", opening and closing the way for the compressed air and also regulating the pressure). The regulated, compressed air is then sent through pipe 14 into the pneumatic chamber 1 (or item 8 in fig. 3) that assists the master

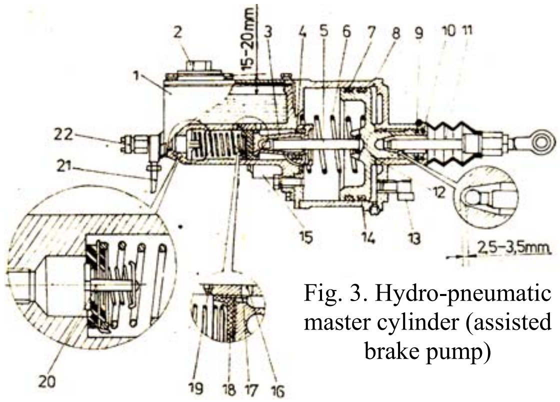

Fig. 3. Hydro-pneumatic master cylinder (assisted brake pump)

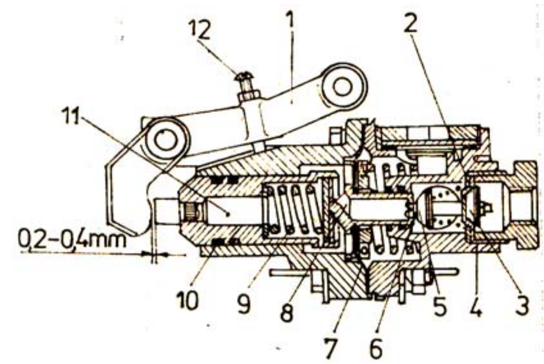

Fig. 4. Compressed air distributor

hydraulic pump (item 1, fig. 3), supplementing the force acting on its cylinder and helping the driver with the braking effort.

2. MEASURED SIGNALS

As we mentioned, the testing program was rather complex. But as far as this paper is concerned, the following parameters were needed:

- the input air pressure on the brake distributor;
- the output air pressure on the brake distributor;
- the input liquid pressure on the brake cylinders of both wheels of the real axle (the braking pressure).

The measuring equipment involved an HBM, computer aided, real-time measuring equipment. The data were recorded and post-processed on specialized software.

3. THE PRINCIPLE OF THE MODEL

We are now looking for a mathematical model based on the measured signals that describes the braking pressure evolution at the wheel's level as a function of the input air pressure on the brake distributor. As can be seen, the process involves two stages. First, determining a transfer function (Ljung, L., 2000) for the brake distributor and getting a mathematical model to describe the time history of the output air pressure as a function of the input air pressure. Second, determining a transfer function for the rest of the braking system and getting a mathematical model to describe the time history of the liquid braking pressure as a function of the distributor's output pressure. It is quite easy to notice that the transfer function of the liquid section can be a first order one (within reasonable margins of error), since the liquid can be considered uncompressible. On the other hand, for the pneumatic section, previous analysis gave us a third order transfer function to describe the phenomena. Nevertheless, it is quite useless to have a too high degree of accuracy while pushing too much the computational means (Cho, K., 2001); hence, a second order transfer function is just perfect for our needs.

3.1 Parametric models. Identification procedure

In the most cases, when describing a dynamic process, parametric models are used having vectors as arguments. If the vector is θ then its model will be known as $M(\theta)$. This approach suggests that, when the vector θ takes a set of possible values, a set of models is obtained and its structure will be M.

Therefore, if the mathematical model of the process is "parameterized " by the vector θ, the problem of the identification resides in determining or assessing the model's parameters on the basis of the experimental data of the input and output variables of the system. Usually, the procedure uses only half of the whole amount of data, the other half being used to confirm the elaborated model. The mostly used checking method is the "predicted value method ". The minimized objective function is given by $f = \arg\sum_{t=1}^{N} e^2(t)$, where $e(t)$ is the error.

There are a lot of parametric models (Bitmead, R., 1999; Ljung, L., 2000, available on http://mathworks.com). Considering the characteristic features of our mechanical system and taking into account the above mentioned reasons, we decided to use a SISO (**S**ingle **I**nput **S**ingle **O**utput) model; its general form is given by:

$$A(q)y(t) = \frac{B(q)}{F(q)}x(t-nk) + \frac{C(q)}{D(q)}e(t) \qquad (1)$$

where $y(t)$ is the system's output, $x(t)$ is the system's input, $e(t)$ is the noise (that can be interpreted as an error) and t is the independent variable (actually the time, usually given in discrete domain). Eventually, *nk* is the number of the delaying elements along the system's input-output chain (available from: http://mathworks.com).

The polynomials featuring the SISO model are given by:

$$\begin{cases} A(q) = 1 + a_1 q^{-1} + a_2 q^{-2} + \ldots + a_{na} q^{-na} \\ B(q) = b_1 + b_2 q^{-1} + b_3 q^{-2} + \ldots + b_{nb} q^{-nb+1} \\ C(q) = 1 + c_1 q^{-1} + c_2 q^{-2} + \ldots + c_{nc} q^{-nc} \\ D(q) = 1 + d_1 q^{-1} + d_2 q^{-2} + \ldots + d_{nd} q^{-nd} \\ F(q) = 1 + f_1 q^{-1} + f_2 q^{-2} + \ldots + f_{nf} q^{-nf} \end{cases} \tag{2}$$

where q is known as the delay operator and is given like: $q^{-i} x(t) = x(t-i)$, while *na*, *nb*, *nc*, *nd* and *nf* are the polynomials' orders.

3.2 Specific features of the used model

The mathematical model in (1) is the general one. It can be customized, according to the operator's needs. As we've already mentioned, the demands for a model should take into account not a too high level of accuracy, an error level lower than 3% being more than enough for our needs. In this respect, the particular ***ARX*** (**A**uto-**R**egressive with e**X**ogene inputs) model was used.

This particular model is featured by the following conditions:

$$\begin{cases} nc = nd = nf = 0 \\ C(q) = D(q) = F(q) = 1 \end{cases} \tag{3}$$

that turns equation (1) into the particular one:

$$A(q) y(t) = B(q) x(t - nk) + e(t) \tag{4}$$

We consider necessary to mention that we used a lot of other models. Their accuracy had usually been higher than the one's we mentioned but the computing resources had been too high to keep them as suitable.

Considering the previously mentioned issues, we could use two different models (a first order model for the hydraulic section and a second order one for the pneumatic section) then combine them. Thus, we actually did first time, and the results can be seen in the next sections of the paper.

We noticed that is more complicated to act that way since the signals we obtained and used were very smooth, with no needs for intense filtration. Moreover, the hydraulic section is acting rather "predictable" with no problems in its evolution. So we made the decision to issue a single model, a second order one, delivering the time history of the hydraulic pressure of the brake cylinder as a function of the input air pressure on the air distributor. This first approach in testing was perfromed to get a global view of the braking system's perfromance as a general assembly. Obviously, a more refined analysis asks for a different approach (Marinescu, M. *et al.* 2010).

4. ACHIEVED DATA. MODELS

Figure 4 depicts a sample of the measured data. Hundreds of tests were developed and the data were stored and preprocessed (that means sorting, filtering, smoothening and discharging the unsuitable ones). As can be seen, we measured the force on the brake pedal, but it is unusable from the modeling point of view, due to the fact that the driver can press completely random the pedal from test to test. It was however useful to have this signal, since it provides the starting and ending points of the braking process.

Fig. 5 and 6 provide two samples of the partial mathematical models based on the SISO structure and using ARX algorithm. For one (but the same test), figure 5 gives the time history of the distributor's output pressure as a function of its input pressure. Fig. 6 depicts in the same time and for the same test the time history of the pressure within the left wheel's brake cylinder as a function of the distributor's output pressure.

The mathematical model of the time history of the distributor's output pressure as a function of its input pressure (depicted in fig. 5) is given by: (5)

$$\frac{d^2 y}{dt^2} + 230{,}5 \frac{dy}{dt} + 6{,}768 \cdot 10^4 y = 95{,}53 \frac{dx}{dt} + 8{,}163 \cdot 10^4 x$$

In the equation above $y(t)$ is the distributor's output pressure and $x(t)$ is the distributor's input pressure.

In the same time, the mathematical model of the time history of the brake cylinder's pressure as a function of the distributor's output pressure (depicted in fig. 6) is given by:

$$\frac{dy}{dt} + 32{,}43 y = 406{,}8 x \tag{6}$$

In the equation above $y(t)$ is the brake cylinder's pressure and $x(t)$ is the distributor's output pressure. Should be mentioned that different models have been issued for left and right brake cylinders.

These two models can be lately combined and get a final one. At this stage of our research, we found to be useful to having a global model of the whole braking system instead of modeling every of its sections apart. But it's much more difficult to compose these two models and get a final one than to create from the very beginning a global model. Nevertheless, a more refined research assumes even more than two models. the influence of different factors, both constructive and functional, upon the performances of the braking system as a whole.

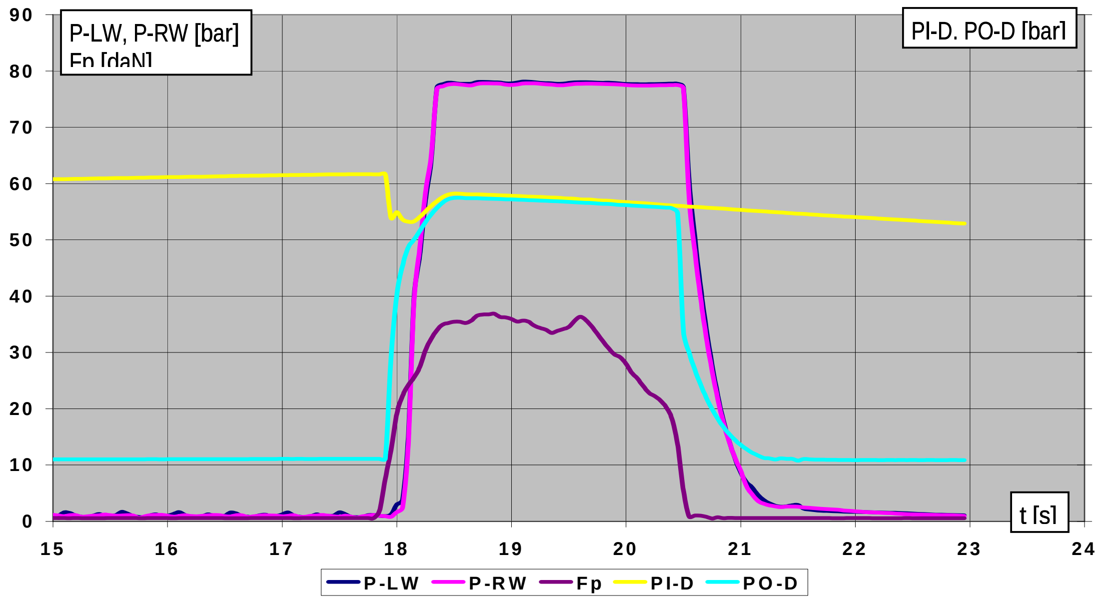

Fig. 4. Test sample

Measured parameters: P-LW: pressure on the left wheel's brake cylinder; P-RW: pressure on the right wheel's brake cylinder; Fp: force on the brake pedal; PI-D: input pressure on the distributor; PO-D: output pressure on the distributor

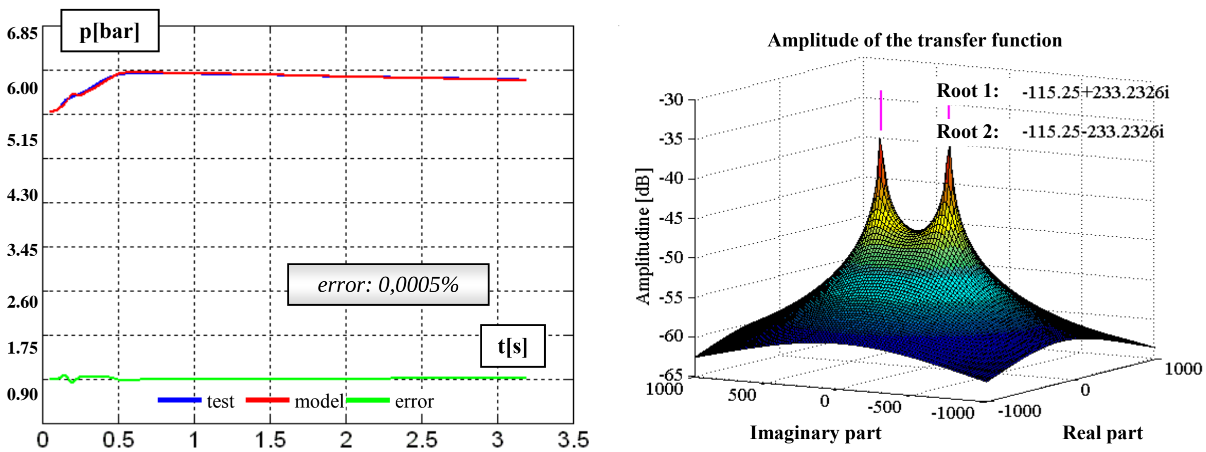

Fig. 5. Characteristic features of the mathematical model, and the time history of the distributor's output pressure as a function of the distributor's input pressure - ARX algorithm

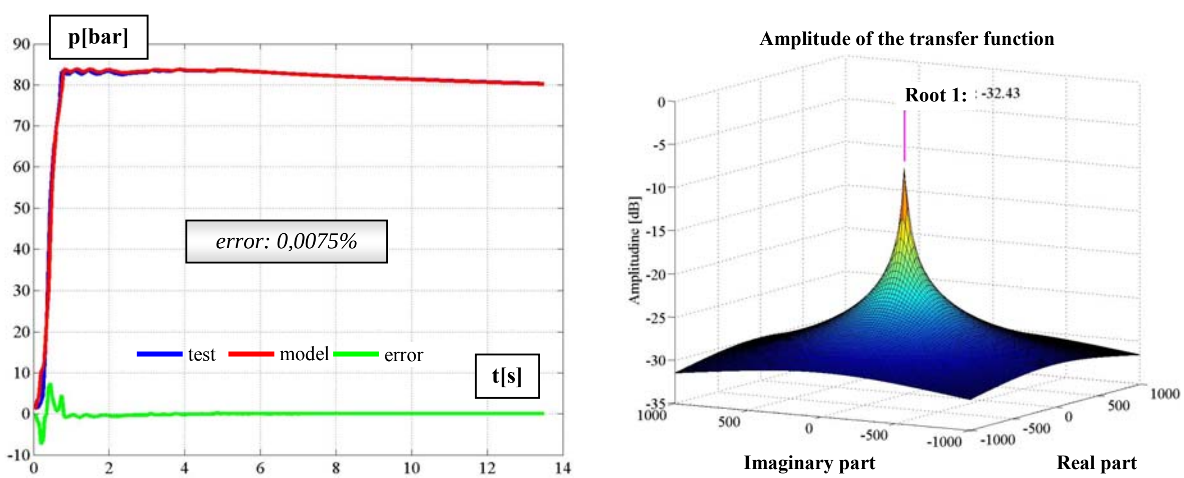

Fig. 6. Characteristic features of the mathematical model, and the time history of the brake cylinder's pressure as a function of the distributor's output pressure - ARX algorithm

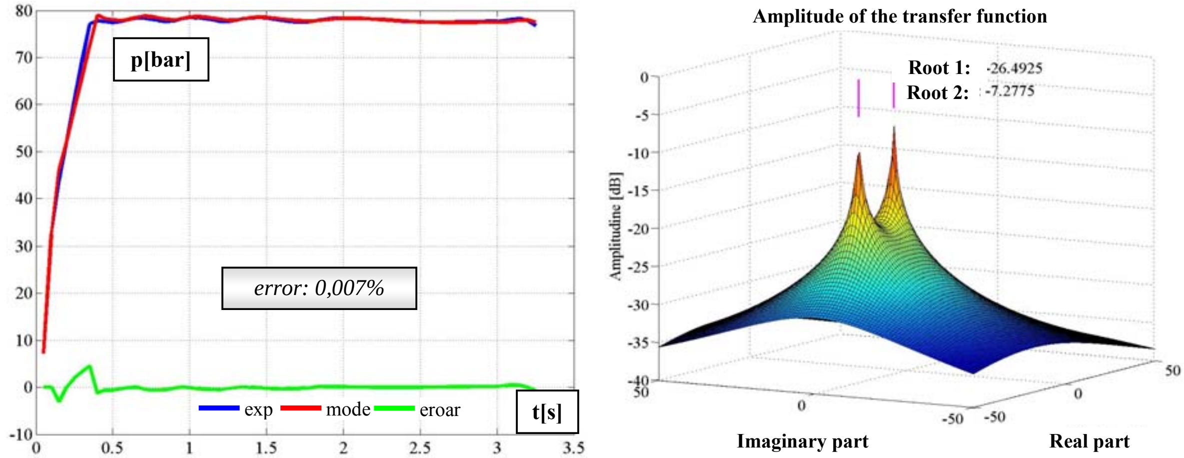

Fig. 7. Characteristic features of the mathematical model, and the time history of the brake cylinder's pressure as a function of the distributor's input pressure (global model) - ARX algorithm

Table 1. Averaging the polynomial coefficients (sample)

Test	Brake cylinder	$\frac{d^2y}{dt^2}$	$\frac{dy}{dt}$	y	$\frac{dx}{dt}$	x	Normalized modeling error [%]
…………	……	……..	………	……….	…………	……..	……….
P1_2r_pam	left	1,000	19,640	127,000	37,830	1760	0,001
	right	1,000	52,470	376,500	83,630	5216	0,002
P3_2r_pas	left	1,000	23,970	163,300	46,740	2253	0,011
	right	1,000	28,900	185,200	50,510	2546	0,020
…………	……	……..	………	……….	…………	……..	……….
Average		**1,000**	**30,970**	**206,483**	**50,851**	**2850**	**0,013**

We have to keep in mind that this kind of work should be developed for every single test then average the results to get the generalized model.

Instead of acting that way, we chose to use a global model and find (of course, for every single test) the time history of the brake cylinder's pressure as a function of the distributor's input pressure. The result, for one of the tests, is depicted in fig. 7. As can be noticed, a second order transfer function was used. For the chosen test, the mathematical model is given by: (7)

$$\frac{d^2y}{dt^2}+33{,}770\frac{dy}{dt}+192{,}280y=50{,}300\frac{dx}{dt}+2660x$$

In the equation above $y(t)$ is the brake cylinder's pressure and $x(t)$ is the distributor's input pressure. Should also be mentioned that different models have been issued for left and right brake cylinders. As a result, every test of the whole set of tests had two mathematical models of this kind: one for the right wheel's slave cylinder pressure and another for the right wheel's cylinder.

To obtain the global model, each particular model's polynomial coefficients had been set in a table according to their rank. Since the differences between the pressure value and their evolutions in each left and right cylinders weren't significant, we considered that they could be put together in the same table (a sample is further provided). Eventually, the values were averaged (Marinescu, M. *et al.* 2010). and they were used to write the final, global, generalized model: (8).

$$\frac{d^2y}{dt^2}+30{,}970\frac{dy}{dt}+206{,}483y=50{,}851\frac{dx}{dt}+2850x$$

To prove the accuracy of the generalized, global model we drew the red curve superimposed over the whole set of tests' curves, as can be seen in fig. 8. The average absolute error is lower than the previously considered 3% limit.

5. CONCLUSIONS

The research we developed on this topic had started from a MoD's need to improve the characteristic features and performances of the Army's vehicles. It is well known that, as far as the military equipment is concerned is much more cost effective to update it than to buy a new one. The life span of a piece of military equipment becomes wider and MoD can save some good money in this respect. Since the design of the braking system on the tested vehicle is quite obsolete, we suggested that the best improvement

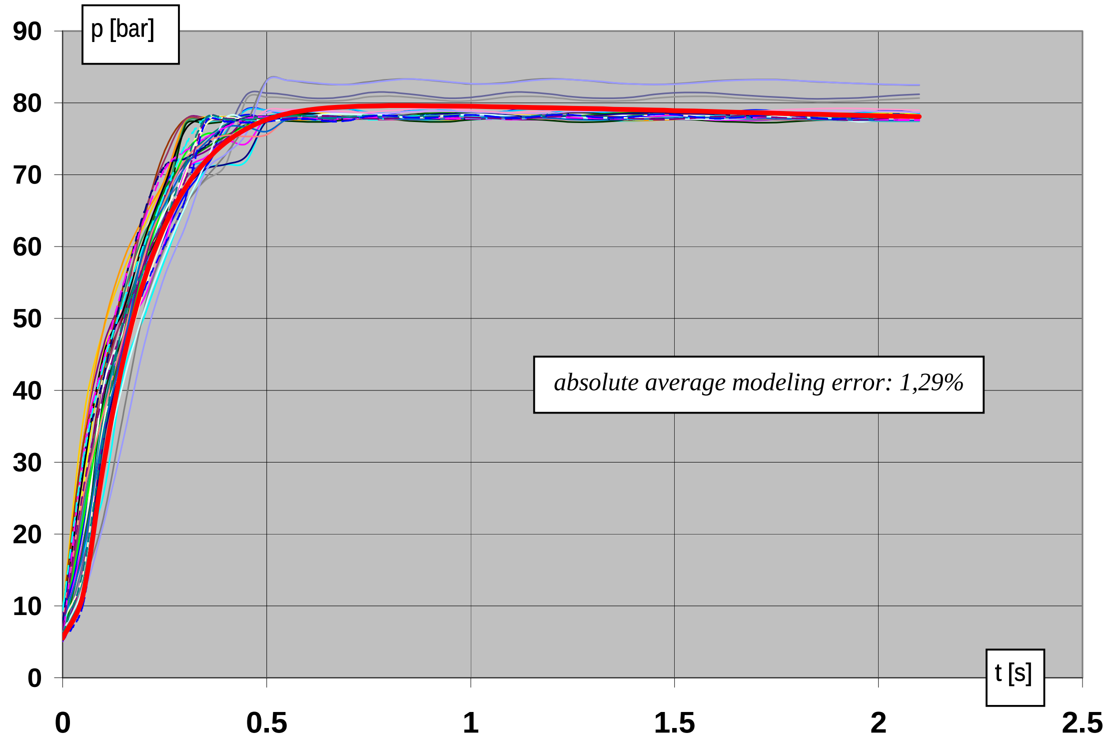

Fig. 8. Generalized, global model of the time history of the brake cylinder's pressure as a function of the distributor's input pressure

would be a complete replacement of the system with a new, air-pressure operated one.

Starting from the test data sets, excellent mathematical models can be obtained when using powerful modeling tools. If only the behavior of some system is need and no further analysis is needed, than this can be the best, the most accurate and the fastest method. For a more refined analysis the system should be subject to a peculiar "decomposition", on smaller subsystems. Eventually, a finer analysis involves the reverse procedure we have applied for this paper. As one can notice, we chose two subsystems and issued their mathematical models. Afterwards, we combined them into a single model, for the whole braking system. However, if something goes mechanically wrong with the system we won't have a high degree of accuracy to pinpoint the malfunctioning part.

This method can be also used in diagnosing a system, not necessarily the braking system. After averaging the values of a properly working system of several vehicles, for instance, the generalized model can be compared to a malfunctioning one. Our research have already taken further steps and now we can determine "what goes wrong" in a malfunctioning braking system. Of course, we can't find any type of faulty part, but at least we can refine the search at the subsystems' level.

The obtained model can be easily used for larger lots of similar products. We have undergoing tests still running on different vehicles of the same model to both prove the accuracy of the method and to generalize at a higher level the mathematical model (Marinescu, M. *et al.* 2010). As a matter of fact, we have proved that the model given by (8) is suitable for another vehicle of the same type and, after confirming it, the error was also less than 3%. But the tests are still undergoing and we'll be able to draw further conclusions on this topic.

6. REFERENCES

1. Bitmead, R., (1999), *Modeling and Identification for Control*, University of California, Berkeley.
2. Cho, K. (2001), *Prediction interval estimation in transformed linear models,* Statistics Probability Letters, 51(4), pp. 345-350.
3. Ljung, L., (2000), *System Identification Toolbox for Matlab,* http://mathworks.com
4. Marinescu, M.; Vilău, R.; Lespezeanu, I., (2010), *Modelling the pressure evolution within the braking system of a vehicle* The VIth International Symposium on Defense Technology, Budapest, Hungary.
5. * * * (1999), *Basic Steps of System Identification,* http://mathworks.com.
6. * * * *Matlab 6.5 tutorials (TM).*

Received: April 29, 2013 / Accepted: June 5, 2013 / Paper available online: June 10, 2013 © International Journal of Modern Manufacturing Technologies.