

PNEUMATIC REGENERATIVE BRAKE SYSTEM

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Abstract. *The energetic efficiency of automotive vehicles can be increased through the use of regenerative brake systems. Usually, traditional regenerative braking systems consist of electrical generators linked to the traditional vehicle brakes. These systems are applied to store electrical energy in chemical batteries. In this paper we introduce a new regenerative concept, based on pneumatic (air pressure) energy storage. The pneumatic energy is stored in small pressure vessels and can be further applied to supply pneumatic driven actuators in the vehicle operation system (pneumatic brake assistance, automatic doors system, etc). A mathematical model of the pneumatic regenerative brake applied to a theoretical urban bus system model is presented. Results of simulations using the model with the pneumatic regenerative brake were compared with results of simulations using the model with passive brake only, showing the energy efficiency of the proposed regenerative system.*

Keywords. *Regenerative Brake Systems, Energy Efficiency, Pneumatics, Automotive Vehicles*

1. Introduction

Fossil fuels, the mainly source of energy today, are limited. High investments are dispensed by companies, institutes and universities on researches that seek for its substitution and the creation of more efficient systems. The technology of regenerative brakes is located in this area of development. Regenerative brakes save the dynamic energy, transform it in potential energy that is accumulated for subsequent application. The traditional brakes are based on the friction phenomena, dissipating the dynamic energy that causes important losses in the energy efficiency of the global system.

Nowadays there are few known commercial applications of regenerative brake systems. Most of the regenerative brakes studied are electrical, based on the use of electrical generators and chemical batteries. These systems are usually applied in hybrid vehicles (Otto motors and electric motor) and electric trains.

In this work it is introduced another category of regenerative system, based on pneumatics. The proposed system consists of a pneumatic compressor connected to the vehicle's transmission system. When the traditional brake is actuated, the compressor is linked to the transmission. So, the compressor works as a brake auxiliary system, and the compressed air is stored in a pressure vessel for subsequent use in other applications.

In the section 2 of this work there is a small explanation about regenerative brakes technology. In section 3, it is presented the problem and the objectives of the study. The mathematical model is accomplished in the section 4, while the results and analyses are presented in section 5. Finally, in the section 6, it is presented the conclusions of the present work.

2. Regenerative Brake Systems

Brake systems of standard automotive vehicles convert kinetic energy in heat, dissipating it to the atmosphere. The brake actuation can be divided in two thermodynamical processes. The first is the friction phenomena. In this process, the dynamic energy is converted in thermal energy. The second process consists of the heat transference from the brakes to the surrounding ambient.

The qualitative benefits by the use of regenerative brakes in vehicles can be easily discussed. On the other hand, it is hard work to determine the quantitative data to be used to characterize it. An analysis in this sense should involve requirements of vehicle potency as a function of the transport cycle aiming the determination of the energy ratio that can be absorbed by the brakes.

Wicks and Donnelly (2002) determine the work cycle for an urban bus and present a potentiality analysis of the application of regenerative brakes. They show that the portion of 91% of total kinetic energy is wasted by the brakes, being the remaining energy dissipated by the air and tire-soil frictions. It is also verified that 59% of the work produced by the motor is consumed by the brakes, being, in an ideal situation, the potential of energy that can be saved. These results indicate a plain justification for the research in this area.

Today, the most advanced works in this subject are in the application of electric regenerative systems. This technology is based on the use of the electric current induced by the speed difference between a rotaries axis and a fixed magnetic field. Previously, in former systems, the current induced during the activation of the brake in electric motors was dissipated by Joule effect in benches of resistors, being the energy wasted. Due to the technological progress of electronics and control techniques, it is possible today to absorb and store this electrical energy in chemical batteries.

In Flinders, Mathew and Oghanna (1995), it is presented the use of regenerative systems in trains. This work is based on the application of modern tiristors, which allows high potency rectification. The regenerative system used in the north track of New Zealand railroad had provided a reduction of 13% in the energy's waste. In the same paper, it is

also shown the measurement of energy losses during the application of dynamic brakes in the main line of Central Queensland. In this railroad, the coal is transported by a distance of 400km. The total waste of energy during the activation of the brake is of about 8,7MWh. Taking into account the whole process during a year, approximately 100GWh are wasted.

Besides its application on trains, regenerative systems are used in hybrid vehicles (HEV, hybrid electric vehicles), where there is an auxiliary electric motor coupled to the combustion motor. This vehicle's conception presents advantages, as smaller dimensions and weights, and an appropriate control of rotation of the combustion motor, causing the economy of fuel and emission reduction as said by He and Hodgson (2002). In Cikanek and Bailey (2002), a regenerative braking system is proposed to be assembled to a Parallel Hybrid Electric Vehicle (PHEV). The results of simulations using a dynamic model for the PHEV with regenerative braking system are presented in this paper.

Panagiotidis, Delagrammatikas and Assanis (2000) report fuel savings of 15% in some HEV vehicles configurations. These values are much more conservatives than the ideal 59% presented previously, but are still very significant concerning energy efficiency performance. Nowadays, the high cost of this advanced technology of hybrid systems limits its application to few commercial vehicles.

The approach adopted in this work is alternative because it is proposed the use of a flow-mechanic system. This study is based on the analogy with the electric regenerative systems, aiming costs decreasing with faster and easier application.

3. Regenerative Brake Design

The pneumatic regenerative brake system is design to be applied in a commercial vehicle. The proposed pneumatic system must be installed in parallel to the traditional brake, seeking the improvement of global energy efficiency. Therefore it is necessary to choose a system with high potential application, involving economical viability and achievement of the energetic efficiency with the regenerative system integration. The efficiency's study is done through simulations using a model of the vehicle's dynamics integrated with a regenerative system's model. A private transport vehicle (urban zone bus), which works with compressed air to execute some actions, as automatic door driving and in the pneumatic actuation brake system (air brake), was used.

The solution of the equations, seeking the determination of the dynamic system's behavior, is accomplished with the use of the numeric integration software Matlab® (2002). Through the Simulink module, the block's diagrams are built and the group of associated differential equations is solved. The simulation results allow the observation of the influence of the regenerative system in the dynamic behavior and in the energetic efficiency.

The parameters of the dissipative brake were defined in such a way that the system behavior performs accordingly to the Brazilian National Standards (ABNT, 2004). The regenerative brake system was incorporated in such a way that the modified system maintains the same operational and functional characteristics of the previous system. The simulations were done using a particular transport cycle model. The results were analyzed considering the energy saved in the braking process and in the global context, aiming at the evaluation of the economical potential of the regenerative system application.

Automotive vehicles can be used in several environmental conditions, so their requirements can vary significantly. The energy consumed in a vehicle dynamic process is mainly due to the resistance of the air, to the friction of the tires with the soil and to the internal dumping of the mobile parts, besides the amount consumed by the brakes. Therefore, it is not appropriate the use of a regenerative system for vehicles that travel large distances because the braking action is not frequent in this operational situation. Smaller vehicles have space restriction, hindering the application of the proposed pneumatic regenerative system. So, the most appropriate vehicles for the proposed system's implantation are buses and urban trucks that have intense accelerations cycles and, therefore, substantial efficiency losses caused by the frequent activation of brakes. This is the main situation usually mentioned in the electric regenerative brakes' bibliography. Thus it was convenient the choice of an urban bus operating in a city.

The proposed regenerative brake system is composed by a compressor, a pressure vessel and a clutch that links the transmission axis to the compressor. It was chosen an alternative double action piston-type compressor. In this preliminary proposal only the back wheels of the vehicle are coupled to the regenerative brake system. The scheme of the proposed system installed in the vehicle is presented in the Fig. 1.

After the brake pedal is pressed in the braking action process, besides the dissipative brakes actuation, the vehicle transmission system disconnects the motor of the transmission train. Then, through the clutch action, the compressor is coupled to the transmission axis. So, the compressor initiates the process of sending air to the vessel, generating an opposite torque to the motor axis. At this time, the dissipative brake is also operating, and the two systems take action together, slowing down the vehicle.

The traditional electric regenerative systems are similar. In the electric systems, during the braking action process, the electric generator is driven by the vehicle motor transmission system, applying a negative torque that causes the slow down of the vehicle. In these systems, the generated electric charge is stored in batteries for subsequent application.

4. The Model

In this section, the mathematical model of the system is presented and some considerations are specified for simplification purposes. The first condition is that the coupling between the compressor and the transmission is already done and the motor is already disconnected from the other parts of the system. Therefore, in the initial instant the acceleration is null (the vehicle speed is taken constant).

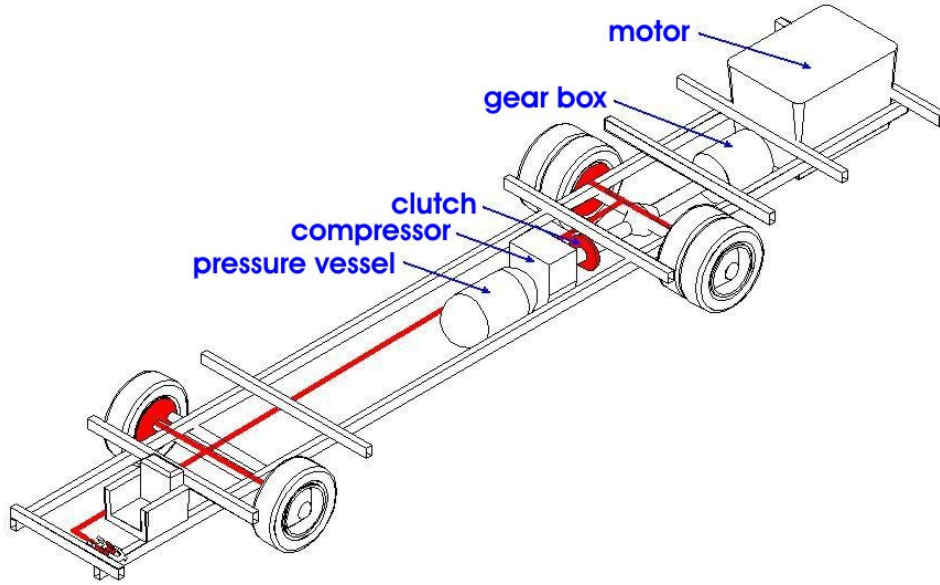


Figure 1 - Proposed regenerative brake system

The main objective is to study the variation of the performance due to the action of the regenerative brake with respect to the traditional passive brake system. The system's free body diagram is presented in Fig. 2.

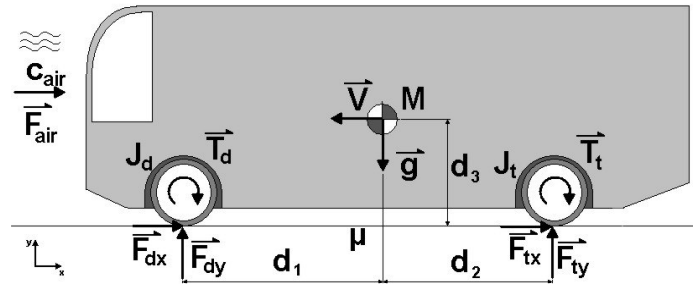


Figure 2 – Free body diagram of the vehicle.

From the vehicle's free body diagram we can establish the equilibrium equations. The horizontal forces can be expressed through Eq. (1),

$$M \frac{d^2 x}{dt^2} + C_{ar} \frac{dx}{dt} + F_{dx} + F_{tx} = 0 \quad (1)$$

where M is the mass of the vehicle, C_{ar} is the damper's coefficient of the air, F_{dx} and F_{dy} are the reactive forces of the friction between the tire and the ground.

In the vertical direction, it can be expressed as

$$F_{dy} + F_{ty} - Mg = 0 \quad (2)$$

where g is acceleration of the gravity, F_{dy} is the front reaction force in the vertical direction and F_{ty} is the back reaction force in the vertical direction. The torque due to the contact forces with the ground by the front wheel are described by

$$-(M \frac{d^2 x}{dt^2} + C_{ar} \frac{dx}{dt})d_3 - Mg d_1 + F_{ty}(d_1 + d_2) = 0 \quad (3)$$

where d_1 is the distance of the center of gravity to the front axis and d_2 is the distance of the center of gravity to the back axis. The torque in the back wheel can be described by

$$-J_t \frac{d^2\theta}{dt^2} - T_f - C_{ang} \frac{d\theta}{dt} + F_{tx} r_t = 0 \quad (4)$$

where T_f is the torque due to the application of the brake, J_t is the rotational inertia with respect to the back axis, C_{ang} is the internal friction's dumping coefficient and r_t is the radius of the back tire.

The horizontal forces F_{tx} and F_{dx} are proportional to the friction contact's coefficient and to the normal forces F_{ty} and F_{dy} , respectively. The force F_{tx} is expressed by

$$F_{tx} = \mu F_{ty} \quad (5)$$

Equations (1) to (4) allow the composition of the diagram of block elaborated for Simulink/Matlab implementation. Figure 3 presents the system's main diagram of blocks.

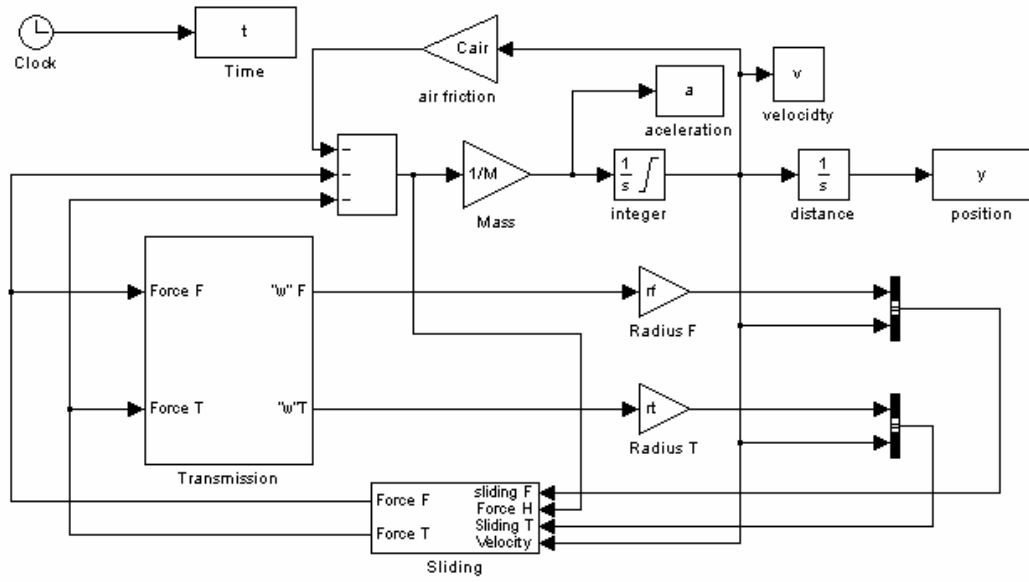


Figure 3 – Main diagram of block

The friction's coefficient μ is a function of many parameters like environment conditions, vertical loads, surface types, translation speeds and internal pressures of the tires. In this study it is only used the relative sliding, aiming the analysis of two types of brakes (the other parameters are maintained constants). The braking action is simulated in the dry asphalt condition. The calculus of the coefficient is done through the following correlation graph between relative sliding and friction coefficient, given by Gillespie (1992) and reproduced in Fig. 4.

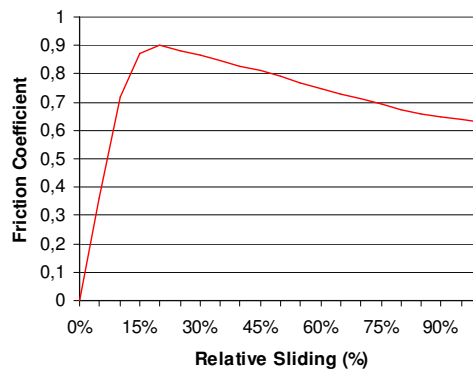


Figure 4 – Relative Sliding versus Friction Coefficient

The sliding is defined by Gillespie (1992) as

$$desl = \frac{v - wr}{v} \quad (6)$$

where v is the tangent velocity, w is the angular velocity of the wheel and r is the radius of the wheel. In the sliding subsystem, the horizontal front and back forces are calculated using the tangent speed of the vehicle, the equivalent tangent speeds of the front and back wheels and the horizontal force of the vehicle. The vertical reactions are calculated in each wheel using the model of suspension of Maclay (1997), where the stiffness, dumping coefficients of the suspension and the center of gravity's position are considered. The reactions are multiplied by the friction coefficients and the result is used to calculate the front and rear friction forces. To avoid singularity in Eq. (6), the zero value is imposed to the sliding movement when the speed meets the null value.

The transmission system is structured based on the generalization of the Eq. (4). In this system, the torque due to the action of the brakes T_f is calculated in a subsystem block (the "brake subsystem block", presented in Fig. 4). In the transmission block, the back and front horizontal forces are applied to calculate the equivalent angular speeds in each wheel which depend on the action of the dissipative brakes, on the loss for the internal friction in the two wheels and on the action of the regenerative brake in the back wheels.

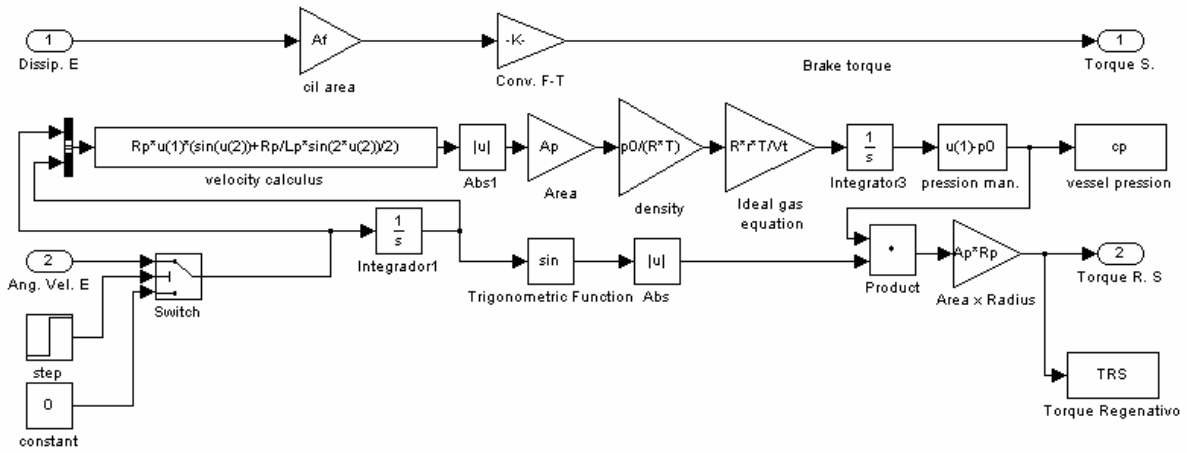


Figure 5 –Brake subsystem's diagram of block

This diagram of blocks is a subsystem of the transmission system. The drum brake equations are presented in the superior part of the block. The hydraulic pressure of the brake's action is multiplied by the actuator cylinder piston's area, resulting in the equivalent force. This force, through the equation for drum brake given by Gillespie (1992), results in the equivalent torque.

In the inferior part of the Fig. 5, the diagram of blocks of the regenerative brake system is presented. It is based on the analysis of the free body diagram presented in Fig. 6.

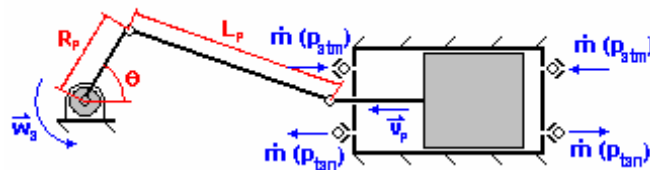


Figure 6 – Free body diagram of the air compression system

The relationship between the angular speed w_a of the axis and the translational speed of the piston v_p given by Mabie (1980) is presented in Eq. (7):

$$v_p = -R_p w_a (\sin \theta + \frac{R_p \sin 2\theta}{2L_p}) \quad (7)$$

where R_p is the radius of the "crank", L_p is the length of the "connecting rod" and θ is defined in Fig. 6.

The relationship between the mass flow $\dot{m} = dm/dt$ and the translational speed is presented in Eq. (8):

$$\dot{m} = \rho A_p v_p \quad (8)$$

where ρ is the atmospheric air density and A_p is the traverse area of the piston.

The variation of the pressure in the pressure vessel (Eq. (9)) caused by the injection of this mass flow, being considered an adiabatic isentropic process with small temperature variation, is given by Perondi and Guenther (2003).

$$\frac{dp}{dt} = \frac{RrT}{V_t} \dot{m} \quad (9)$$

In Eq. (9), R is the constant of the air, r is the relationship among specific heats, T is the absolute temperature and V_t is the volume of the pressure vessel. This pressure variation, integrated in time, represents the reactive pressure against to the movement of the piston. This effect results in the braking action. The reactive equivalent torque is presented in Eq. (10):

$$T_{regen} = p_{tan} A_p R_p \sin \theta \quad (10)$$

This torque is then added to the torque given by the traditional dissipative brakes. These equations allow us to structure the diagram of blocks presented in Fig. 5. The pressure generated by the regenerative system is accumulated in the pressure vessel (Fig. 5). The elastic potential energy accumulated in the pressure vessel through the increasing of pressure is expressed by Eq. (11):

$$E = p V_t \quad (11)$$

5. Results and Analysis

Table 1 presents the parameters' values used in the system simulations.

Table 1 – List of Parameters

$L_p = 0,20$ [m]	$M = 12000$ [kg]	$n = 0,150$ [m]	$A_f = 0,005$ [m ²]	$K_f = 480000$ [N.m]
$p_0 = 101325$ [Pa]	$Car = 40$ [N.s/m]	$m = 0,150$ [m]	$mif = 0,41$	$K_t = 720000$ [N.m]
$r_t = 0,49$ [m]	$J_1 = 25$ [kg.m ²]	$rr = 0,304$ [m]	$e = 0,300$ [m]	$C_{vf} = 40000$ [N.s/m]
$d_1 = 2,95$ [m]	$J_2 = 105$ [kg.m ²]	$V_t = 0,1$ [m ³]	$d_2 = 2,5$ [m]	$C_{vt} = 45000$ [N.s/m]
$R_p = 0,07$ [m]	$C_{ang} = 20$ [N.m.s]	$A_p = 0,12$ [m ²]	$d_3 = 1,5$ [m]	$R = 287$ [J/kg.K]
$R = 1,4$	$r_f = 0,49$ [m]	$v_0 = 16,66$ [m/s]	$I_{yy} = 88500$ [kg.m ²]	$T = 298,15$ [K]

The analyses are performed using Dormand– Prince method (Matlab/Simulink User's Guide (2002), accurately for convergence of 10^{-9} . The braking action is modeled by a ramp curve, which reaches its maximum value in 2s. The analyzed system has 8 cylinders with piston radius of 70mm. The proposed vessel volume is $0,1\text{m}^3$.

The comparison of results is accomplished between the traditional system and the proposed regenerative brake system. The brake operation conditions are taken from the Brazilian heavy vehicles braking' standards (portaria nº 30, INMETRO (2004) that establishes the maximum brake distance of 36,7m for a vehicle of the N3 class (where it is the urban bus proposed in this study) with an initial speed of 60km/h, or 16,66m/s. In all figures below, the red lines represent the vehicle with traditional brake and the blue line the vehicle with the addition of the regenerative system. Figure 7 shows that the vertical reactions forces of both systems are similar. These vertical reactions are applied to calculate the horizontal friction reactions that break the vehicle.

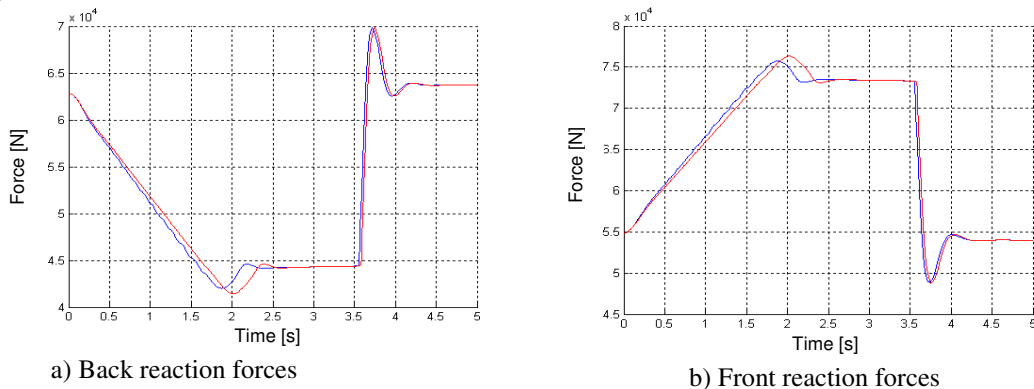


Figure 7 – Reaction forces

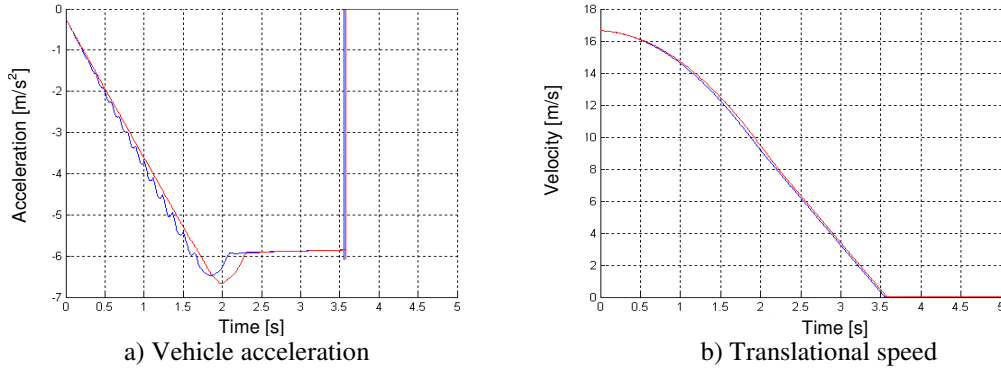


Figure 8 –Acceleration and translational speed

The acceleration curves are plotted in Figure 8-a. Note that there is the presence of oscillations in the blue curve caused by the alternative loading of the compressor action. The translational speed is presented in Figure 8-b.

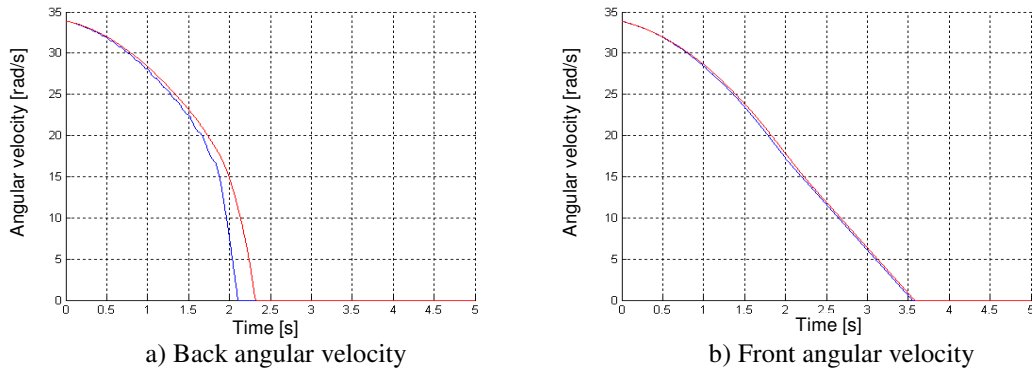


Figure 9 –Back and front angular velocities

Figure 9 shows the back and front angular velocities. The angular back wheel's speed of the regenerative system decreases faster than the system with traditional brakes, as can be observed in Figure 9-a. This effect is caused by the action of a superior torque in this axis. It can be also seen that the inertia of the vehicle increases the vertical front reaction and reduces the vertical back reaction, causing the same behavior in the horizontal friction forces.

Figure 10-a shows the internal vessel's pressure for the ramp braking curve while Fig. 10-b presents the internal vessel's pressure in another test case in which a pulsed braking action is simulated.

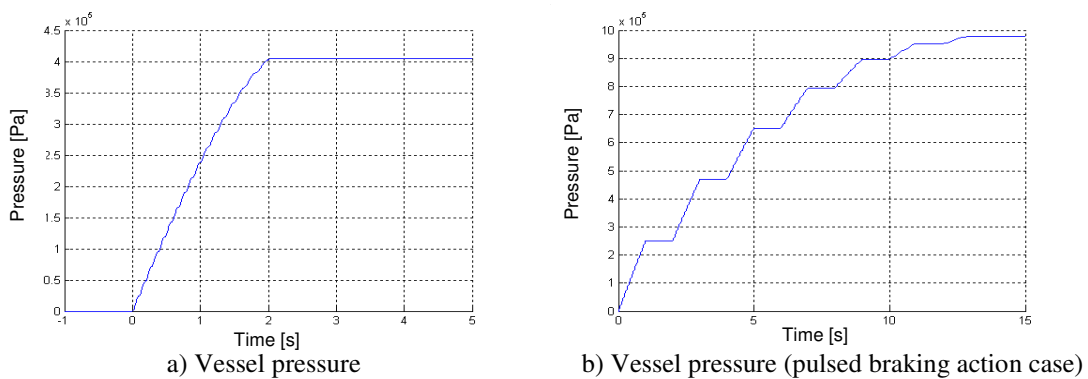


Figure 10 – Internal vessel pressures for two different braking actions.

Figure 10-b shows that the pressure in the vessel at the end of compression process is 0,40MPa (equivalent to 4,0 bar). This pressure is accumulated in the 0,1m³ vessel. The stored energy is calculated through Eq. (11), and it is equal to 40kJ. The total initial kinetic energy present in the vehicle is of 1653kJ, that represents a conservation of 2,45% of energy. In the simulation presented in Fig. 10-b, the brake is actuated in intervals of 2s with period of 1s. As it can be verified in Fig. 10-b, the final pressure is approximately 0,98 MPa, corresponding to 98kJ in accumulated energy. This

final pressure represents the conservation of 5,92% of the available kinetic initial energy. The correct relationship for the dimensioning of the group compressor- pressure vessel should be determinate by an economical analysis. Larger pressure vessels use more space, decreasing the bus transport capacity. On the other hand, compressors with high compression ratio are more expensive. The economical analysis and energy saving balance are not accomplished in this work.

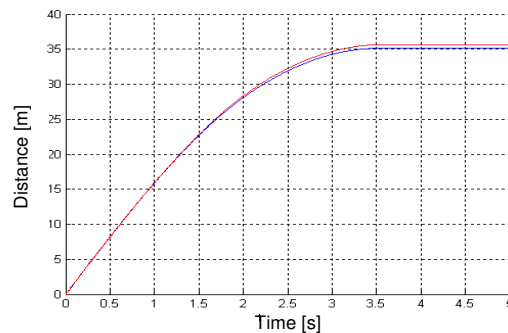


Figure 11 – Wheels translational trajectory

Figure 11 shows the translational trajectory along time for the ramp braking case. This figure shows that the vehicle with regenerative system stops 3,5 s before the traditional system.

6. Conclusions

The results calculated using the proposed system allow us to conclude that the use of the pneumatic regenerative system reduces approximately 2,45% the energy consumption during a standard brake period. The pneumatic stored energy can be used in the actuation of the brake system and in vehicle accessories, as the windshield wiper, the compressor of the air conditioner, in the doors drives, etc. There is also the possibility for the use in combustion motor, improving the efficiency through compressed air injection, increasing the thermal efficiency by a major compression ratio.

Further studies can accomplish the design of a smoothing actuation system for the compressor to be applied to avoid oscillations in the acceleration curve, as shown in Fig. 8-a. Also, anti-lock braking systems (ABS) can be adopted, in parallel to the regenerative system, to avoid the blocking of the wheels. Alternatives, as the use of small and multiple dispersed pressure vases along the structure of the vehicle should be considered for the warranty of the equality of the operation of the brake. Other necessary study can accomplish the global transport system with emphasis in the use of the pneumatic energy saving. This study must involve the quantification of the amount of air consumed by the accessories in most of the urban transport vehicles to investigate the economical viability of the proposed system. The design and construction of a prototype for experimental tests is also necessary to verify the system viability.

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