Modeling and simulation of hydraulic buffering valve for power-shift transmission

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Abstract:

Introduction/purpose: The hydraulic buffering valve has the greatest influence on the dynamic characteristics of power-shift transmission. The hydraulic buffering valve is a transmission element that controls increase in pressure in friction assemblies during the gear shifting process. By choosing the optimal control of pressure increase during shifting, reduction of dynamic loads in gear transmissions and thermal loads in friction assemblies is achieved.

Methods: The paper analyzes the principle of one of hydraulic buffering valve solutions as well as the influence of certain parameters on the control of pressure increase. After the analysis of the working principle of the hydraulic buffering valve, a simulation model was developed in the MATLAB/Simulink software package.

Results: The results obtained using the simulation model were compared with the experimental results of the selected pressure modulator solution. The selected hydraulic buffering valve was developed as part of the development of a device for power-shift transmission. The simulation results showed a satisfactory match with the experimental results.

Conclusion: The developed simulation model enables a relatively easy and quick change of the parameters of the hydraulic buffering valve as well as a possibility of a faster and better understanding of the influence of individual parameters on pressure increase during the gear shifting process.

Key words: power-shift transmission, pressure control valve, simulation.

Introduction

Gear shifting in the transmission of a motor vehicle is a process in which power parameters are changed in order to adapt the vehicle to road conditions (Balau et al, 2011). The way the transmission management system is implemented significantly affects the traction and dynamic characteristics of the vehicle, which is particularly pronounced in tracked vehicles where the transmission management system, in addition to gear shift, also ensures the turning of the vehicle. Increasing demands for high-performance tracked vehicles in terms of mobility have imposed the need to improve their subsystems, primarily the engine and the gearbox.

The improvement of the gearbox is of particular importance because, depending on its performance, the traction and maneuvering characteristics of the vehicle can be significantly increased or decreased, and the steering system has a special place in this (Grkić et al, 2009). The hydraulic buffering valve is one of the most important elements of the power-shift transmission system. The quality of the transition process of gear shifting depends on its characteristics, which directly affects the traction and maneuvering characteristics of the vehicle (Meng et al, 2015).

Working principle of the hydraulic buffering valve

Figure 1 shows the hydraulic buffering valve which consists of a regulator piston (a), an accumulator piston (b), springs (c) and (i), an orifice (d) and (f), and a non-return valve (e). The channel (g) is connected to the valve for gear selection, and the channel (h) to the corresponding friction clutch assembly. Figure 1 shows the position of the elements at the time of the beginning of the pressure modulation process. From that moment, the modulation of the pressure p_1 in the channel (h), and therefore in the cylinder of the friction clutch assembly, takes place in accordance with the movement of the piston (b) and the stiffness of the springs (c) and (i). The pressure modulation process will be completed when the piston (b) rests on the piston outlet (a), after which the nominal pressure is established in the cylinder of the friction clutch assembly (Jian et al, 2018).

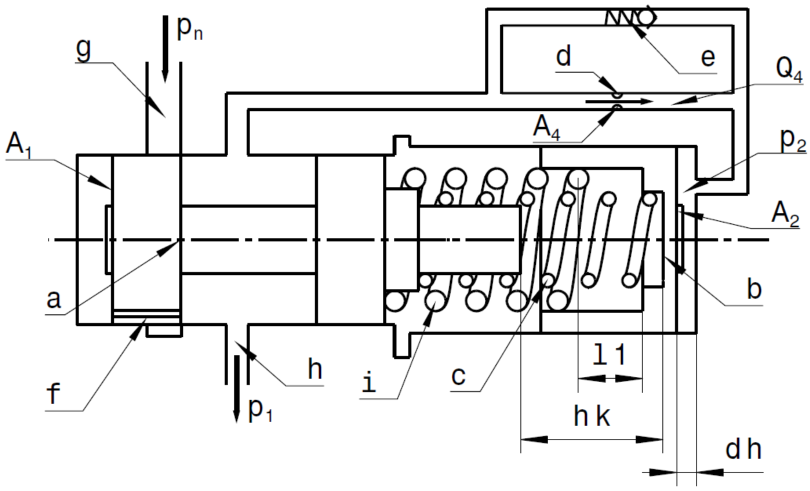

Figure 1 – Positions of the hydraulic buffering valve elements at the beginning of the pressure modulation process
Рис. 1 – Положение деталей модулятора давления в начале процесса модуляции давления
Слика 1 – Положај елемената модулатора притиска на почетку процеса модулације притиска

The orifice (f) in Figure 1 determines the movement speed of the piston (a), and the orifice (d) determines the pressure change in the process of pressure modulation. The non-return valve (e) is intended to assist in the process of turning off the friction clutch assembly, to help discharge the volume of the accumulator (b) faster and to prepare the pressure modulator for reactivation.

The character of the pressure change in the modulation process depends primarily on the design parameters of the hydraulic buffering valve elements (front surfaces of the regulator piston (a) A_1 and the accumulator piston (b) A_2, the stiffness of the spring (c) C_1 and the spring (9) C_2 and their preloads, the piston stroke accumulator dh and the orifice (d)).

The general character of the pressure change in the friction assemblies during gear shifting is shown in Figure 2 (Baogang et al, 2019).

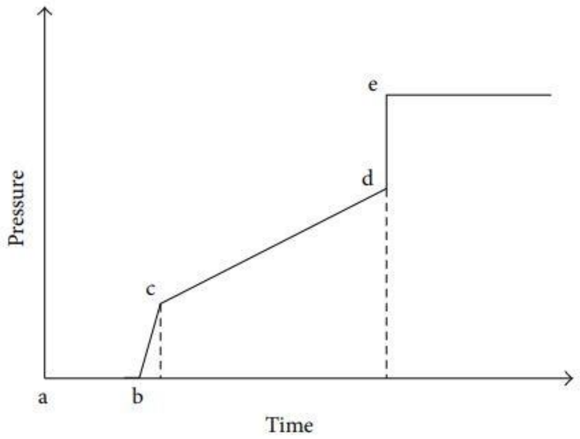

Figure 2 – Pressure change in the process of pressure modulation
Рис. 2 – Изменение давления в процессе модуляции давления
Слика 2 – Карактер промене притиска у процесу његове модулације

Phase a-b – represents the filling of the volume of the pipeline and the initial volume of the clutch cylinder with the motionless piston of the friction assembly.

Phase b-c – represents the filling of the volume of the clutch cylinder, followed by the movement of the piston of the friction assembly from the initial to the end position, when the pressure increases due to the compression of the spring in the friction clutch assembly.

Phase c-d – represents the process of pressure modulation in the clutch cylinder of the friction clutch assembly followed by the slippage of its elements. The pressure modulation process takes place in accordance with the movement of the accumulator piston (b) and the stiffness of the springs (c) and (i). This phase has the greatest impact on the quality of the gear shifting process (Walker et al, 2011). The duration of the gear shift depends on the character of the phase c-d, as well as the increase of the friction moment and the dynamic loads of the elements.

Phase d-e – indicates the establishment of the nominal pressure, after the completion of the pressure modulation process, which is equal to the working pressure (Liu et al, 2014).

Mathematical model of the hydraulic buffering valve

The initial pressure in the process of engaging the friction clutch assembly, the final pressure and the character of the pressure change during the pressure modulation have a direct impact on the performance of the hydraulic buffering valve. The transient process, the pressure modulation process, is described by a simplified mathematical model (Živanović, 1991). Friction and inertial forces are neglected in the calculation, the working fluid is incompressible and the hydraulic pipeline is absolutely rigid. Taking into account the equilibrium condition of the piston (a) and the piston (b), as well as the continuity equation, the following system of differential equations can be written:

$$\begin{aligned} Q_4 dt &= A_2 dh \\ A_1 dp_1 &= c dh \end{aligned} \tag{1}$$

where:

A_1 and A_2 – surfaces of the pistons (a) and (b),

c – spring stiffness (d) and (i),

dh – elemental displacement of the piston (b),

dp_1 – pressure increase in the channel (h) which corresponds to the displacement of the piston (b), and

Q_4 – flow through the orifice (d), determined by the equation:

$$Q_4 = C_{d4} A_4 \sqrt{\frac{2}{\rho}(p_1 - p_2)} \tag{2}$$

where:

C_{d4} – flow coefficient through the orifice (d),

A_4 – orifice surface (d), and

p_2 – pressure in the accumulator chamber (b).

If substitution is introduced into the equation:

$$\xi = C_{d4} A_4 \sqrt{\frac{2}{\rho}} \tag{3}$$

where ξ represents the flow through the orifice at a pressure difference of 1 bar, then:

$$Q_4 = \xi \sqrt{(p_1 - p_2)} \tag{4}$$

If expression (4) is included in the first differential equation of system (1) and dh is replaced from the second equation (1), we get:

$$c\xi \sqrt{p_1 - p_2}\, dt = A_1 A_2 dp_1 \tag{5}$$

From the balance of the piston (b) of the accumulator, the equation can be written:

$$p_2 = \frac{F_o}{A_2} \tag{6}$$

where:

F_o – the force of the springs (c) and (i) of the accumulator (b) in an arbitrary position.

The spring force Fo can also be expressed through the pressure p_1, setting the equilibrium condition for the piston (a).

$$F_o = p_1 A_1 \tag{7}$$

Putting the value of Fo in expression (6) and then in expression (5) we get:

$$c\xi\sqrt{p_1 - p_1\frac{A_1}{A_2}}\,dt = A_1 A_2 dp_1 \tag{8}$$

and that is:

$$\mathrm{dt} = \frac{A_1 A_2}{c\xi\sqrt{p_1 - p_1\frac{A_1}{A_2}}}\mathrm{dp}_1 \tag{9}$$

In order to determine the total duration of the modulation process t_{mod} with the specified hydraulic buffering valve, equation (9) will be integrated. The limits of the integral for the left side of the differential equation are from 0 to t_{mod}, and for the right side from p_{10} to p_{1mod}, where:

t_{mod} – duration of the pressure modulation process,
p_{10} – pressure at the beginning of the modulation process, and
p_{1mod} – pressure at the end of the modulation process.

The pressure value p_{10} corresponds to the rightmost position of the accumulator piston (b), while the pressure value p_{1mod} corresponds to the pressure at the end of the pressure modulation process, that is:

$$\mathrm{p}_{10} = \frac{\mathrm{F}_{0\mathrm{mod}}}{\mathrm{A}_1}; \quad \mathrm{p}_{1\mathrm{mod}} = \frac{\mathrm{F}_{0\mathrm{mod}} + \mathrm{c}_1 \cdot h_k + c_2 \cdot (h_k - l_1)}{\mathrm{A}_1} \tag{10}$$

where:

F_{omod} – the force of the spring (c) of the accumulator (b) at the beginning of the pressure modulation and
l_1 – distance between the springs (c) and (i) in the accumulator (b).

Integrating equation (9) with replacement and introducing the specified limits of the integral for the first stage gives the duration of the pressure modulation process:

$$\mathrm{t}_{mod} = \frac{\mathrm{A}_1\mathrm{A}_2}{c\xi}\frac{2}{\sqrt{1-\frac{\mathrm{A}_1}{\mathrm{A}_2}}}\left(\sqrt{\mathrm{p}_{1\mathrm{mod}}} - \sqrt{\mathrm{p}_{10}}\right) \tag{11}$$

in which:

$$c = c_1 + c_2 \tag{12}$$

where:
c_1 – spring stiffness (c) and
c_2 – spring stiffness (i).

In order to obtain the dependence of the pressure change during the modulation process, differential equation (9) will be integrated in the limits for the left side from 0 to t and the limits for the right side from p_{10} to p_1, where t and p_1 are current variables and the result will be:

$$t = \frac{A_1 A_2}{c\xi} \frac{2}{\sqrt{1-\frac{A_1}{A_2}}} \left(\sqrt{p_1} - \sqrt{\frac{F_{omod}}{A_1}}\right) \tag{13}$$

and that is:

$$p_1 = \frac{F_{o0}}{A_1} + \frac{\left(\frac{c\xi t}{2}\right)^2 \left(\frac{A_2}{A_1}-1\right) + c\xi t\sqrt{F_{omod} {A_2}^3 \left(\frac{A_2}{A_1}-1\right)}}{A_1 {A_2}^3} \tag{14}$$

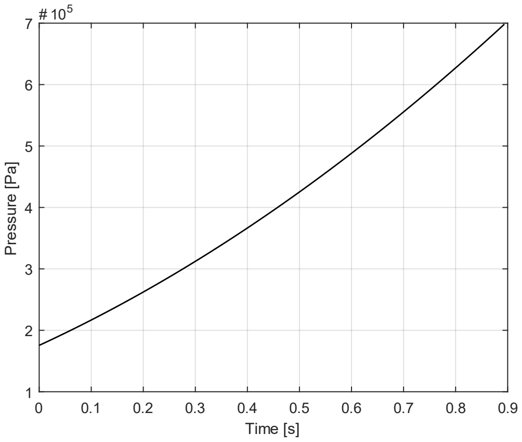

Figure 3 – Dependence of pressure increase on time during the pressure modulation process
Рис. 3 – Повышение давления в зависимости от времени процесса модуляции давления
Слика 3 – Зависност прираштаја притиска од времена у току процеса његове модулације

Equation 14 represents the pressure change in the friction clutch assembly during the process of pressure modulation with the described hydraulic buffering valve. Figure 3 shows the dependence of the pressure fit on time during the pressure modulation process obtained by solving equation 14.

Simulation model of the hydraulic buffering valve in MATLAB/Simulink

The simulink module developed in the MATLAB environment enables modeling, simulation and analysis of various dynamic systems. It supports linear and nonlinear systems modeled in both continuous and discrete time (Grkić et al, 2011).

Modeling in simulink uses a graphical environment, as well as „click-and-drag" mouse operations for block drawing. Simulink contains a large library of generators of input excitations, displays of output variables as well as linear and non-linear components of the system (Raikwar et al, 2015). By means of block diagrams from the library, a simulation model of the pressure modulator shown in Figure 4 was developed.

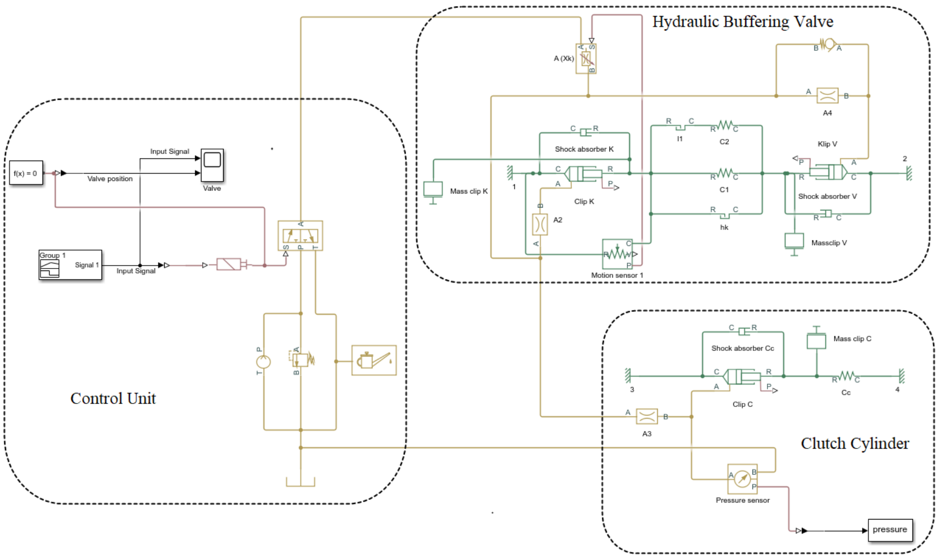

Figure 4 – Simulation model of the hydraulic buffering valve
Рис. 4 – Имитационная модель гидравлического модулятора давления
Слика 4 – Симулациони модел модулатора притиска

The simulation model consists of three parts. The first unit is the part for managing the system and consists of a hydraulic pump, a hydraulic distributor, a safety valve and components that manage the aforementioned. The second unit is represented by the hydraulic buffering valve, while the third unit is represented by the piston model of the friction clutch assembly that is activated in the process of pressure modulation. The results obtained through simulation are shown in Figure 5.

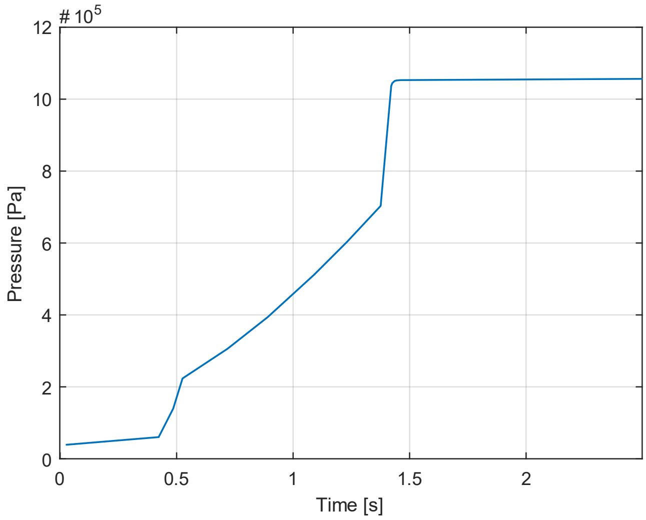

Figure 5 – Simulation results in MATLAB/Simulink
Рис. 5 – Результаты моделирования в MATLAB/Simulink
Слика 5 – Резултат добијен симулацијом у MATLAB/Simulik

The parameters used for the simulation as well as for solving equation (14) are shown in Table 1.

Table 1 – Parameters of the hydraulic buffering valve
Таблица 1 – Параметры гидравлического модулятора давления
Табела 1 – Параметри модулатора притиска

Fluid density	830	kg/m^3
Surface area of the piston (A_1)	4.9	cm^2
Surface area of the piston (A_2)	7.1	cm^2
Surface area of the orifice (A_4)	0.0113	cm^2
Discharge Coefficient (C_{d4})	0.7	
Stiffness of the spring (c)	4.21	N/mm
Pre-tightening force of the spring (c)	38	N
Stiffness of the spring (i)	10.8	N/mm
Pre-tightening force of the spring (i)	0	N
Distance between springs (c) and the piston (b) (l_1)	4.5	mm
Distance between the piston (a) and (b) (h_k)	23.5	mm
Force at the beginning of modulation (F_{omod})	86	N

Experimental research and simulation model validation

Experimental studies of the operation of the hydraulic buffering valve were carried out as part of the study of the possibility of applying a power-shift transmission.

The entire experimental research was carried out in laboratory conditions, through two stages and several test blocks with a larger number of experiments, on a real gearbox.

The results of the experimental test of the hydraulic buffering valve are shown in Figure 6 (Živanović, 1991).

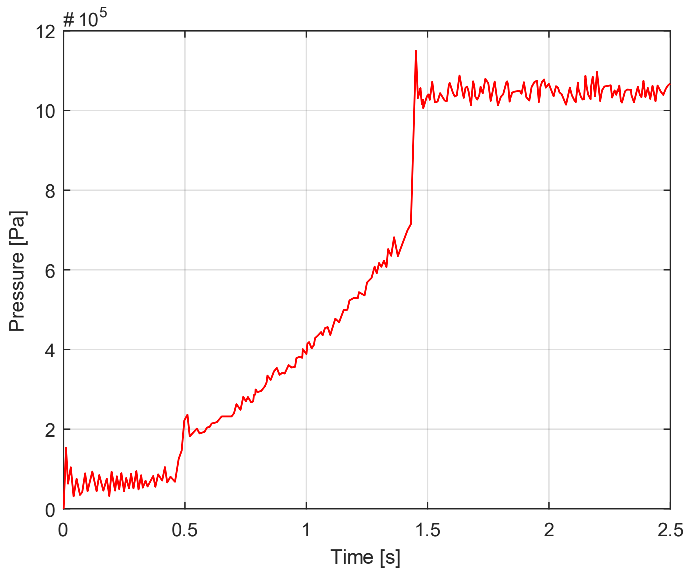

Figure 6 – Results of the experimental test
Рис. 6 – Результаты экспериментального испытания
Слика 6 – Резултати експерименталног испитивања

After the experimental tests, the obtained results were compared with the results obtained by solving equation 14 and by simulating the operation of the hydraulic buffering valve in the MATLAB/Simulink software package. Figure 7 shows the comparative results.

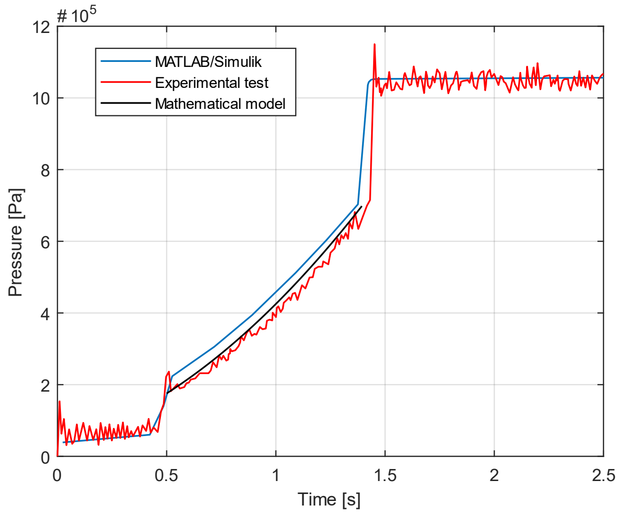

Figure 7 – Comparative presentation of the results obtained
Рис. 7 – Сравнительный обзор полученных результатов
Слика 7 – Упоредни приказ добијених резултата

Figures 8, 9, and 10 show the comparative results obtained by changing certain design parameters of the hydraulic buffering valve.

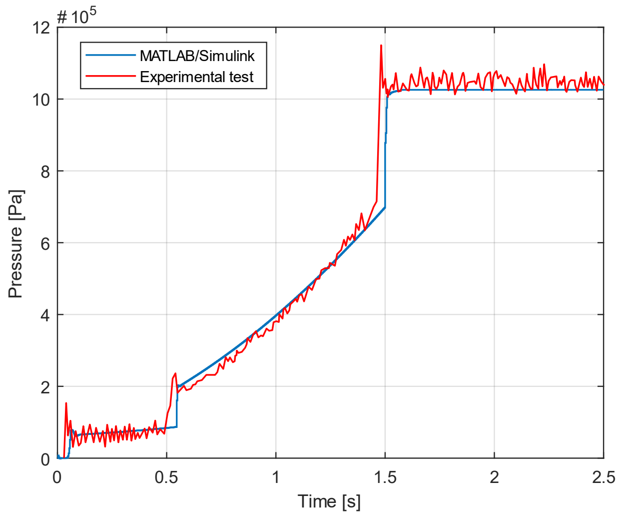

Figure 8 – Comparative presentation of the obtained results - T1
Рис. 8 – Сравнительный обзор полученных результатов – T1
Слика 8 – Упоредни приказ добијених резултата – T1

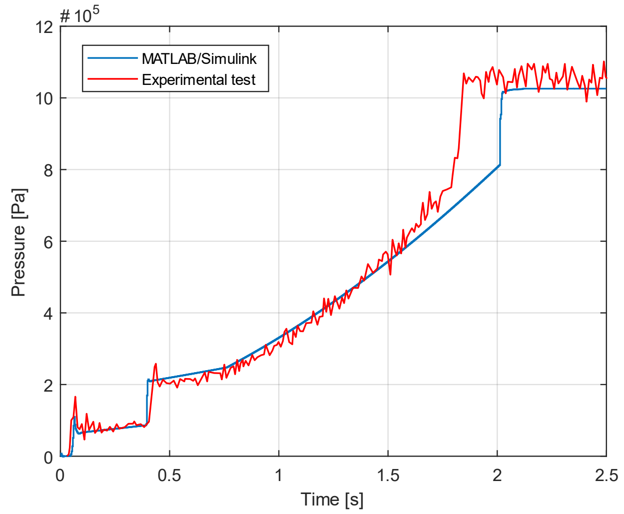

Figure 9 – Comparative presentation of the obtained results – T2
Рис. 9 – Сравнительный обзор полученных результатов – T2
Слика 9 – Упоредни приказ добијених резултата – T2

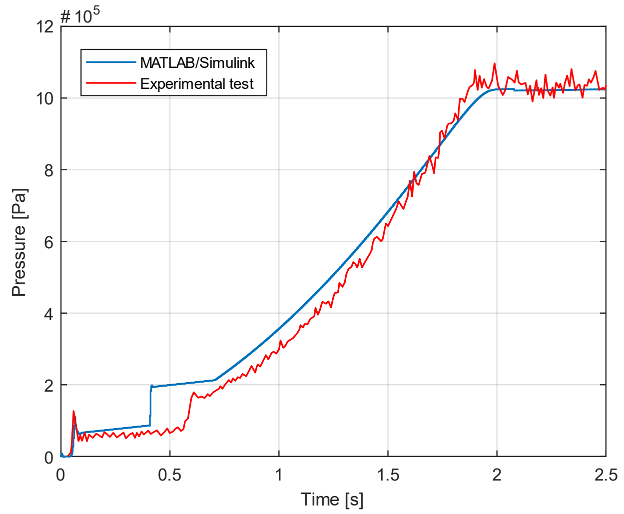

Figure 10 – Comparative presentation of the obtained results – T3
Рис. 10 – Сравнительный обзор полученных результатов – T3
Слика 10 – Упоредни приказ добијених резултата – T3

The values of the design parameters with which the results obtained are shown in Figures 8, 9 and 10 are shown in Table 2.

Table 2 – Hydraulic buffering valve parameters for T1, T2 and T3 results
Таблица 2 – Параметры гидравлического модулятора давления по результатам T1, T2 и T3
Табела 2 – Параметри модулатора притиска за резултате T1, T2 и T3

	T1	**T2**	**T3**	
Surface area of the orifice (A_4)	0.0079	0.0050	0.0095	cm^2
Stiffness of the spring (c)	5.8	5.8	5.8	*N/mm*
Pre-tightening force of the spring (c)	72	70	22	*N*
Stiffness of the spring (i)	14.5	31.5	0	*N/mm*
Distance between the springs (c) and the piston (b) (l_1)	8.5	5.9	0	*mm*
Distance between the piston (a) and (b) (hk)	25	23.5	23.5	*mm*

The analysis of the obtained results shows that the results obtained by simulation sufficiently match the results obtained by experimental measurements. The deviations of the results obtained through simulation from the results obtained experimentally are the consequence of the impossibility of completely accurate determination of the actual values of the design parameters of the hydraulic buffering valve and the friction clutch assembly. The values of the parameters with which the hydraulic buffering valve process was simulated are nominal values and, as it is known, can vary within certain limits (Meng et al, 2016).

When the influence of each of the displayed parameters and the facts presented are taken into account, the matching of the results obtained by simulation and experimental results can be considered completely satisfactory, as well as that the simulation model can be used for further research in terms of investigating the influence of the most important parameters on the pressure modulation process as well as development of a simulation model of power-shift transmission.

Investigating the influence of certain parameters on the pressure modulation process

After the accuracy of the developed hydraulic buffering valve MATLAB/Simulink model being confirmed, the operation of the hydraulic buffering valve can be simulated with a level of certainty at different values of particular parameters that have a significant impact on the pressure modulation process.

The paper analyzed the effects of the following parameters: preload force Fo in the spring (c), stiffness of the spring (c) and the spring (i), distance between the pistons (a) and (b), distance between the piston (b) and the spring (i) and the orifice (d) size.

The results of these simulations are shown in Figures 11, 12, 13, 14, 15, and 16 (Wang et al, 2017).

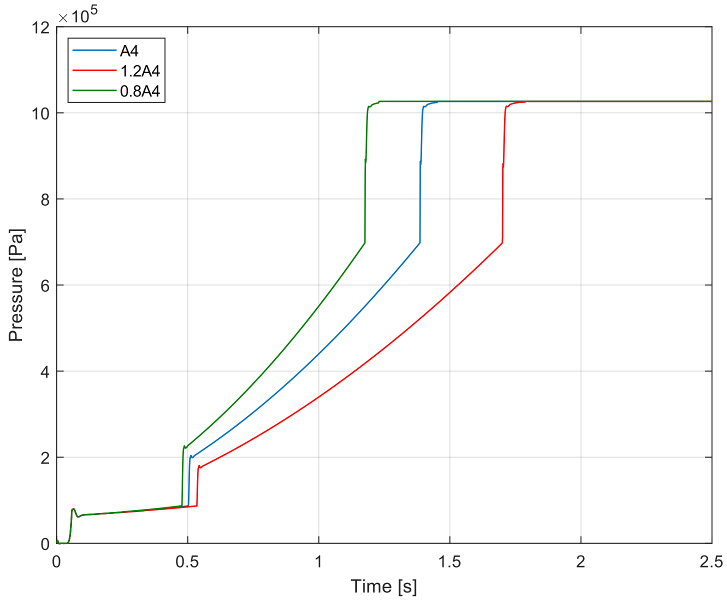

Figure 11 – Influence of the A_4 orifice surface (d) on the pressure modulation process
Рис. 11 – Влияние поверхности отверстия A_4 (d) на процесс модуляции давления
Слика 11 – Утицај површине A_4 прогушнице (d) на процес модулације притиска

The size of the orifice (d) is of particular importance in the pressure modulation process, as its reduction ensures a smaller increase in pressure in the pressure modulation process and increases the total duration of the pressure modulation process.

With an increase in the size of the orifice (d), there is a greater increase in pressure in the modulation process and the duration of the pressure modulation process is reduced.

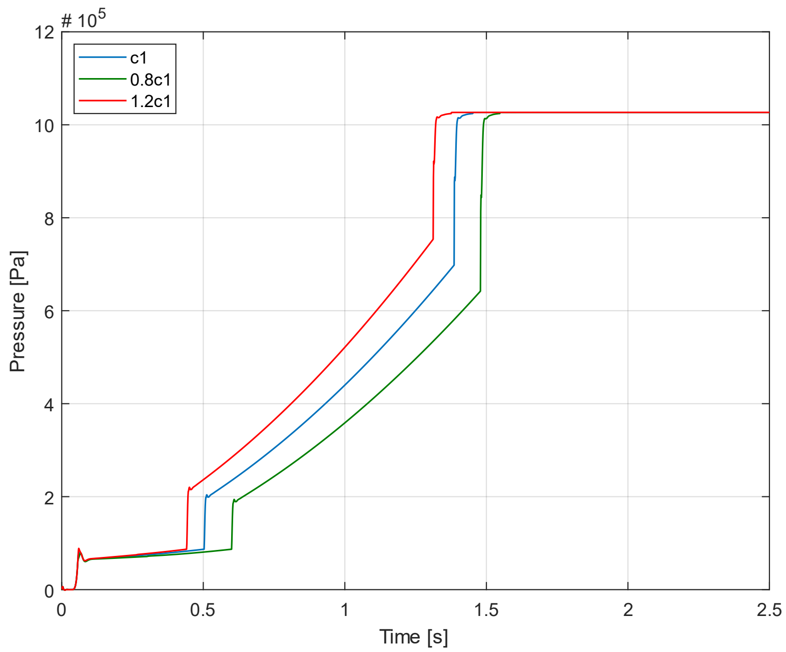

Figure 12 – The influence of the stiffness of the c_1 spring (c) on the pressure modulation process

Рис. 12 – Влияние жесткости пружины c_1 (c) на процесс модуляции давления

Слика 12 – Утицај крутости c_1 опруге (c) на процес модулације притиска

Changing the stiffness of the c_1 spring (c) leads to the increase in the pressure intensity and the pressure modulation time change.

As the stiffness increases, the time of the pressure modulation process decreases.

Also, with an increase in spring stiffness, there is also an increase in pressure at the end of the pressure modulation process (Ren et al, 2014).

The effect of changing the stiffness of the c_2 spring (i) is identical to the effect of changing the stiffness of the c_1 spring (c).

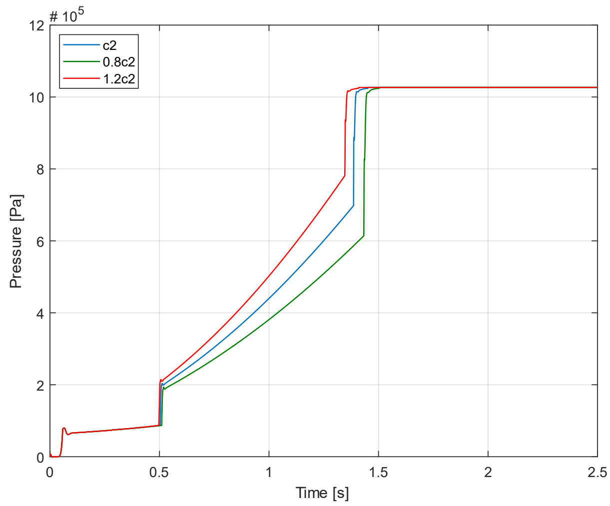

Figure 13 – Influence of the stiffness of the c_2 spring (i) on the pressure modulation process
Рис. 13 – Влияние жесткости пружины c_2 (i) на процесс модуляции давления
Слика 13 – Утицај крутости c_2 опруге (i) на процес модулације притиска

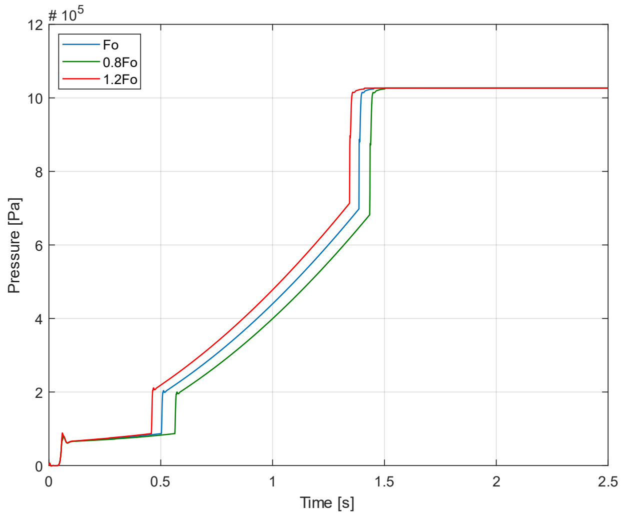

Figure 14 – Influence of the preload force F_o of the spring (c) on the process of pressure modulation
Рис. 14 – Влияние усилия преднатяга F_o пружины (c) на процесс модуляции давления
Слика 14 – Утицај силе преднапрезања F_o опруге (c) на процес модулације притиска

Changing the pre-tightening force Fo in the spring (c) changes the regularity of the increase in pressure in the executive cylinder.

Its increase reduces the time required to move the piston of the friction scope to the end position and increases the initial pressure in the process of pressure modulation in the friction clutch assembly, which can lead to the appearance of shock engagement of the friction clutch assembly.

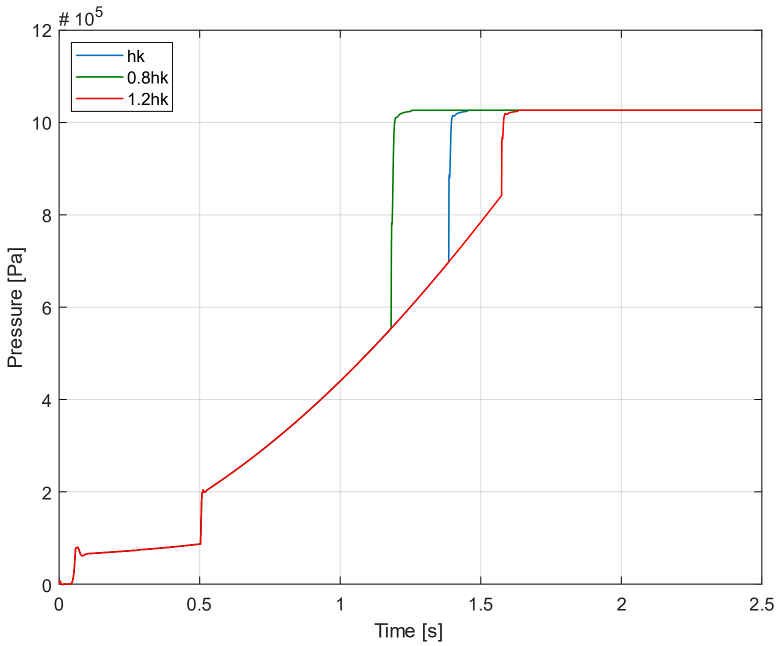

Figure 15 – Influence of the distance between the piston (a) and the piston (b) on the pressure modulation process

Рис. 15 – Влияние расстояния между поршнем (a) и поршнем (b) на процесс модуляции давления

Слика 15 – Утицај растојања између клипа (a) и клипа (b) на процес модулације притиска

Changing the distance between the pistons (a) and (b) can affect the magnitude of the pressure and the duration of the pressure modulation process.

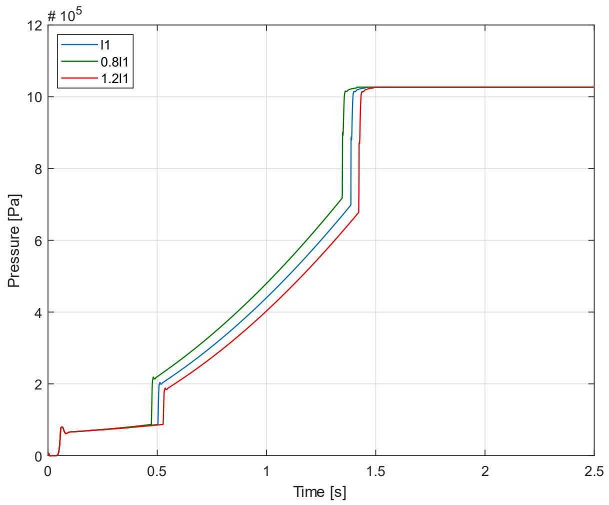

Figure 16 – Influence of the distance between the piston (b) and the spring (i) on the pressure modulation process
Рис. 16 – Влияние расстояния между поршнем (b) и пружиной (i) на процесс модуляции давления
Слика 16 – Утицај растојања између клипа (b) и опруге (i) на процес модулације притиска

Changing the distance between the accumulator piston (b) and the spring (i) can adjust the moment when this spring will come into effect. The pressure modulation takes place first in accordance with the stiffness of the spring (c) and then in accordance with the stiffness of both springs.

Conclusion

A simulation model of the hydraulic buffering valve was developed in the MATLAB/Simulink software package, and the influence of the most important parameters of the pressure modulator on the pressure modulation process was analyzed. The results of the simulation of the operation of the pressure modulator sufficiently match the results obtained by experimental measurements in laboratory conditions. After the comparison of the obtained results, it was determined that the results obtained using the simulink model are within 10% of the relative error compared to the experimental test. The simulation model enables an easy change of parameters. The deviation of the obtained results in relation to the experimental tests can be explained by a large number of variables that affect the process of pressure modulation. Also, certain parameters are variable during the experiment measurement, such as the temperature and viscosity of the fluid. Larger number of simulations of the system operation can be performed in a shorter period of time, in order to observe the behavior of the system and choose the optimal values of the most important parameters.

It is concluded that the developed simulink model met the set requirements, and as such it can be used to evaluate the operation of the hydraulic buffering valve for power-shift transmission. It can be used for both calculation and design. The developed simulink model can be implemented in the simulation model of the transmission, which will represent the simulation model of the powershift transmission during the gear change.

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Имитационное моделирование работы модулятора давления в коробках передач без разрыва потока мощности

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РУБРИКА ГРНТИ: 55.43.00 Автомобилестроение
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: Модулятор давления оказывает наибольшее воздействие на динамические характеристики трансмиссии с переключением передач, не прерывая поток мощности. Модулятор давления — запчасть коробки передач, контролирующая повышение давления в узлах трения в процессе переключения передач. За счет выбора оптимального управления повышением давления при изменении уровня передачи достигается снижение *динамических нагрузок в зубчатых передачах и тепловых нагрузок в узлах трения.*

Методы: В данной статье анализируется принцип работы одного из решений моделятора давления, а также влияние некоторых параметров на управление повышением давления при переключении передач. После анализа принципа работы модулятора давления была разработана имитационная модель в пакете программного обеспечения MATLAB/Simulink.

Результаты: В статье также проведен сравнительный анализ результатов, полученных с помощью имитационной модели, и результатов испытаний выбранного модулятора давления. Результаты моделирования показали удовлетворительное совпадение с экспериментальными результатами. Установлено предельное отклонение в размере 10%.

Выводы: Разработанная имитационная модель обеспечивает относительно простое и быстрое изменение параметров модулятора давления, а также способствует более быстрому и лучшему пониманию, как те или иные параметры влияют на повышение давления в процессе переключения передач.

Ключевые слова: переключение передач без разрыва потока мощности, модулятор давления, моделирование.

Моделирање и симулација рада модулатора притиска код мењачких преносника са променом степена преноса без прекида тока снаге

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ОБЛАСТ: машинство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: Модулатор притиска има највећи утицај на динамичке карактеристике мењачких преносника са променом степена преноса без прекида тока снаге. Представља елемент мењачког преносника који контролише повећање притиска у фрикционим склоповима током процеса промене степена преноса. Избором оптималне контроле прираштаја притиска при промени степена преноса постиже се смањење динамичких оптерећења у зупчастим преносницима и термичких оптерећења у фрикционим склоповима.

Методе: Анализиран је принцип једног од решења моделатора притиска, као и утицај појединих параметара на контролу прираштаја притиска у току промене степена преноса. Након анализе принципа рада модулатора притиска, развијен је симулациони модел у софтверском пакету MATLAB/Simulink.

Резултати: Резултати добијени коришћењем симулационог модела упоређени су са експерименталним резултатима изабраног модулатора притиска. Резултати симулације су показали задовољавајуће поклапање са експерименталним резултатима, у границама до 10% одступања од експерименталних резултата.

Закључак: Развијени симулациони модел омогућава релативно лаку и брзу промену параметара модулатора притиска, као и могућност бржег и бољег разумевања утицаја појединих параметара на повећање притиска током процеса промене степена преноса.

Кључне речи: промена степена преноса без прекида тока снаге, модулатор притиска, симулација.

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