3rd International Conference
″Research & Innovation in Engineering ″
COMAT 2014
16-17 October 2014, Braşov, Romania

ESTIMATING THE TORQUE DISTRIBUTION IN A PLANETARY GEARBOX

Alexa Octavian[1], Ilie Constantin Ovidiu[2], Radu Vilău[3]
[1]Military Technical Academy, Bucharest, Romania, alexa.octavian@gmail.com
[2]Military Technical Academy, Bucharest, Romania, ovidiuilie66@yahoo.com
[3]Military Technical Academy, Bucharest, Romania, radu.vilau@yahoo.com

Abstract: *In the case where one intends to reveal the torque distribution onto the elements of a planetary gearbox, issuing a virtual model is previously needed. This model should replicate both the physical structure and the real working behavior. The torque is transmitted along the gearbox through the intermediary of three simple planetary mechanisms by successively locking different components with the aid of some multi-plate clutches. The simulation of the friction element's engagement is achieved by introducing a physical signal that replaces the pressure of the hydraulic command system. The pressure evolution has been previously experimentally determined, during the vehicle's taking-off procedure. The friction elements are modeled considering their three working stages: fully disengaged, partially engaged and fully engaged. The torque distribution is modeled starting from the energy conservation law as well as the torque balance law.*
Keywords: *simulation, torque, powertrain, planetary gearbox.*

1. INTRODUCTION

The planetary gearbox subjected to the present study consists of a train of planetary mechanisms and a set of multiple-disc clutches and brakes. Different scientists have previously described their working behavior by mathematical modeling and simulation. Jungang Wang [1] proposed a mathematical model able to describe the working process of the planetary mechanisms in transient modes. When issuing the dynamic equations, he has taken into account the losses due to the torsion vibrations within the meshing area of the gears. The loss assessment has been achieved by supplying the model with elasticity and friction coefficients. In another study [2], the authors proposed a theoretical approach to reveal the distribution torque within an automotive driveline. A better model would describe the real working mode if developing virtual simulation models. These models are featured by the fact that the system's elements are treated as physical subsystems, linked together by a net of physical connectors (shafts, flanges etc.). Otter et al. provided such a model in their paper [3]. When developing the model, its creator used a part of the predefined blocks of the Dymola Library to model the physical components of the planetary gears and multiple-disc clutches of the gearbox. All the blocks take advantage of predefined connecting physical ports; thus one can model the rigid linkages of the gearbox. Within the study, the gear shifting simulation was achieved by using a signal that successively locks the multiple-disc clutches.

2. DEVELOPMENT OF THE SIMULATION MODEL

For the present study, the Matlab programming environment was employed to model the planetary gearbox. The effects due to the torsion vibrations, the rotational inertia and the shafts' elasticity were taken into account. The basic components of the virtual simulation model were the three planetary gears and the four friction elements (three clutches and a brake), as it can be noticed in Figure 1. The basic components of the gearbox have been built using the SIMSCAPE module, by imposing the specific conditions of the real working environment. A simple planetary gear consists of three external elements (the sun gear, the crown and the carrier). The working behavior of the planetary gear has been achieved by writing within its source code (Figure 2) the so-called *Willis equation* (kinematic equation), the energy conservation law and the torque balance law [4]. The carrier locking generates these three equations and the gear's ratio K. The physical connection between the external elements is achieved by the (R, S, C) nodes, the „*through*” variables (M_s, M_r, M_c), the „*across*” variables (ω_s, ω_r, ω_c) and by the physical conserving ports. The power running through the three physical ports is directed, by means of the connection lines, towards the other components of the physical net.

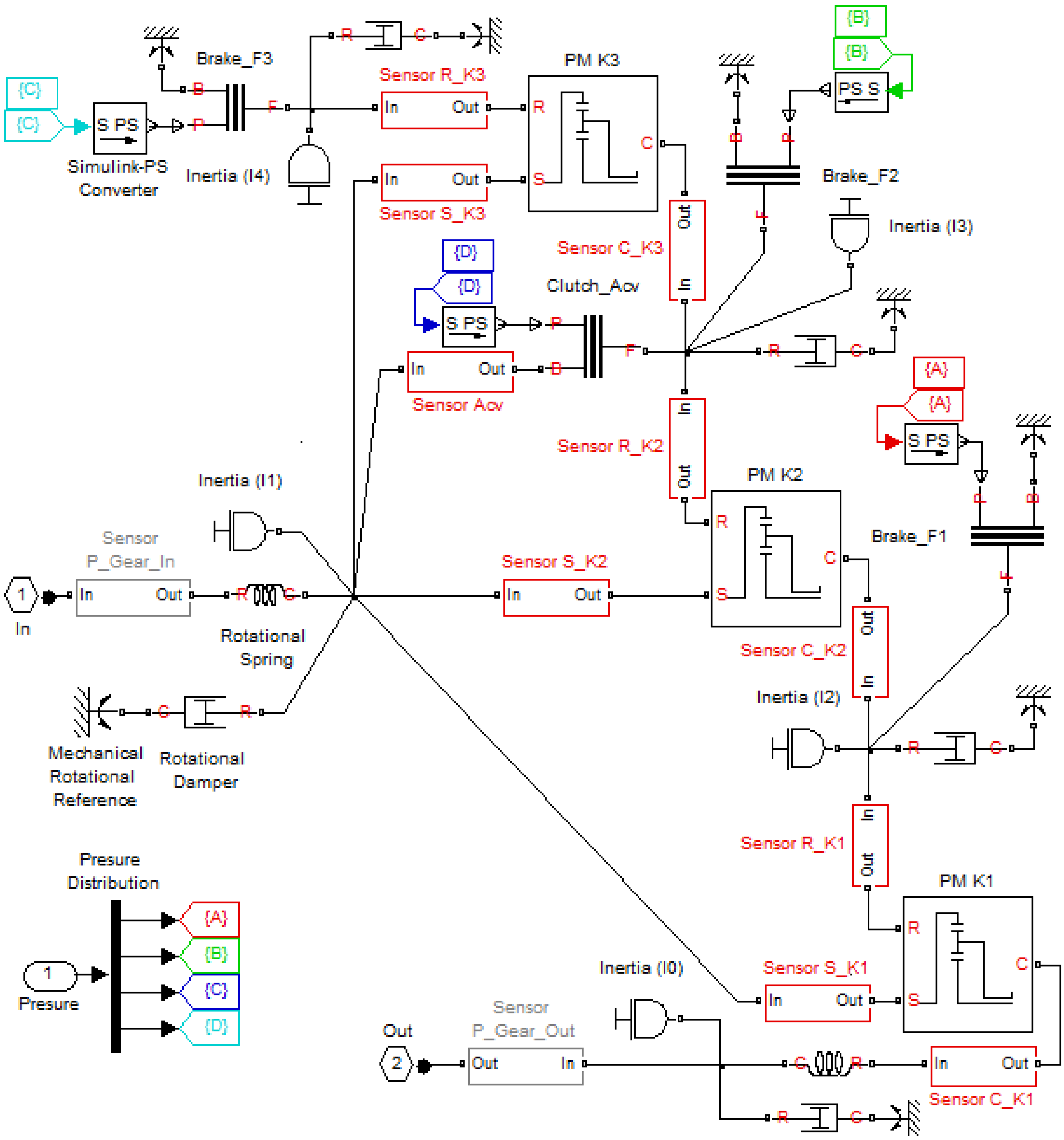

Figure 1: Virtual model to simulate the planetary gearbox

```
equations
  ws + K*wr == (1 + K)*wc; % Willis equation and torque balance law;
  Mr == K*eta*Ms; Ms + Mr + Mc ==0; % eta - efficiency of the planetary mechanisms;
end
```

Figure 2: Source code of a planetary gear

The multiple-disc clutches and brakes block on of the external elements. When using a brake, the element's angular speed drops to null. When using a clutch, the connected elements have the same angular speed. Physically speaking, the friction elements are featured by three working modes: fully disengaged, partially engaged and fully engaged In order to model the work of the friction elements when in partially engaged mode and fully engaged mode we used the *Stribeck model* [5]. Compared to the *classic friction model*, the Stribeck model (Figure 3) changes the variation mode of the friction force. It eliminates the discontinuity that might occur due to the simulating software, within the vicinity of the area where the relative angular speed (ω) between the friction surfaces closes to null. Therefore, the friction force has a single value when the relative angular speed (ω) is null. The friction force is approximated by the gain between the pressing force (F_n) and either the dynamic (cdfr) or the static friction coefficient (csfr).

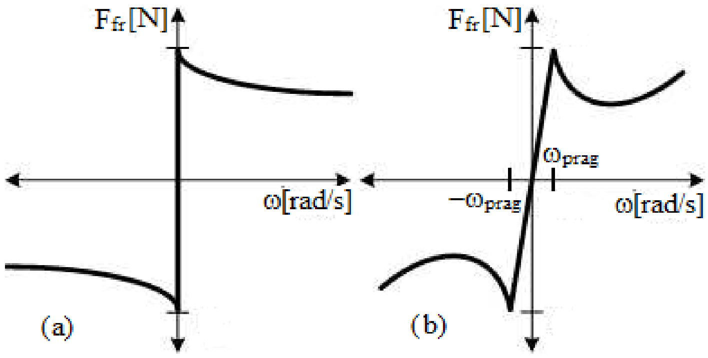

Figure 3: Friction force vs. angular speed: a) classic model; b) Stribeck model

The dynamic friction coefficient is used when slipping. In this situation the relative angular speed isn't null. The static friction coefficient is used when the relative angular speed is very close to null. The equations that estimate the physical behavior of the friction elements both in the slipping and locking stage are written within the source code of the friction element (Figure 4) according to the relative angular speed, for different variation intervals.

```
equations
 if ((w>=w_prag) || (w<=-w_prag))
   M ==2/3*p*A*cdfr*R*sign(w);   % sliding regime;
 elseif ((-w_prag<w<0) || (0<w<w_prag))
   M ==2/3*p*A*csfr*R*sign(w)*(w/w_prag);
 else (w=0)
   B.t ==F.t;  B.w ==F.w;             % locking regime;
 end
```

Figure 4: Part of the friction element's source code

During the slipping stage, when the dynamic friction torque transfers at high rates, the discs' angular speeds are different; hence the relative angular speed has non-null values. It also tends to higher values than its limit value ω_prag. Modeling this situation implied the use of the „if" condition of SIMSCAPE followed by the equivalent equation of the friction torque. During time, the transfer rate of the friction torque is low and the friction element is still within the friction stage. The discs still have different angular speeds, but the relative angular speed rapidly decreases to zero. The situation is described by the „elseif" condition of the simulating environment. In the locking stage, described by „else", the discs of the friction element have the same angular speed and ω is zero.

Besides the basic components, in the virtual simulation model other blocks of the SIMSCAPE library occur. They were used to model the pressing force of the pistons that act inside the clutches of brakes, to visualize the torque distribution throughout the planetary mechanism or to model the inertia moments, elastic or viscous forces, viscous and dry damping forces. The time histories of the hydraulic system's parameters are obtained experimentally [6].

3. RESULTS

The simulation model presented in this paper is able to completely describe the work of the physical components of the analyzed gearbox for various working situations. For this study, we simulated the working conditions and gearbox's behavior during the vehicle's taking-off procedure. The torque diagrams obtained by simulation (Figure 5) underline the distribution of the torque for all the planetary mechanisms elements (K_1, K_2 and K_3).

Analyzing the diagrams, we noticed that the power flow runs only via the planetary mechanism K_1 in the first gear of the gearbox. Moreover, the other planetary mechanisms (K_2 and K_3) are consuming power due to the acceleration process and internal friction, although they do not actively take part in the power flux transit. When engaging the second and the fourth gears of the planetary gearbox, the power runs through K_1 and K_2 planetary gears. When engaging the third gear, the power uses all the three planetary gears to pass through the gearbox.

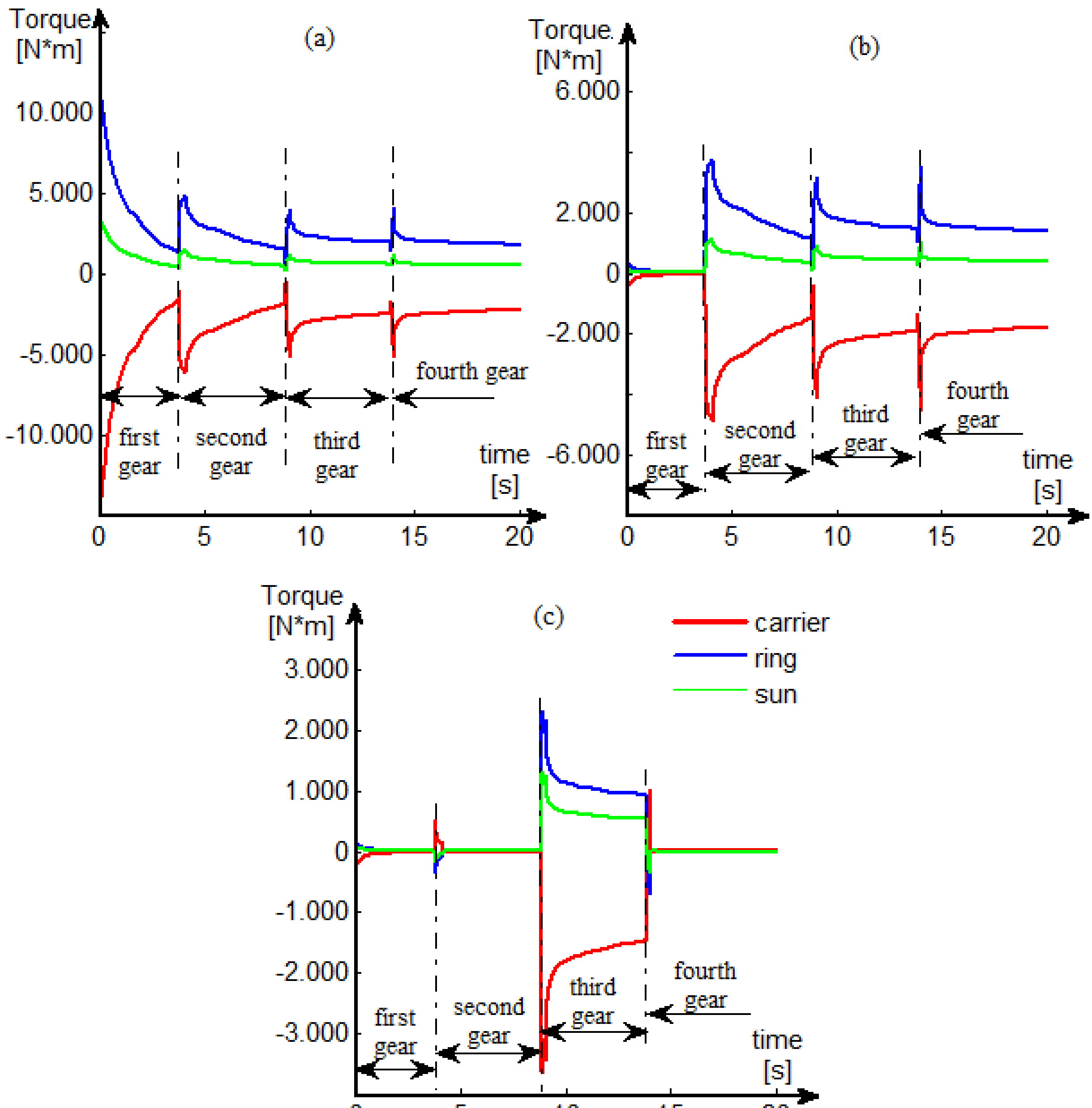

Figure 5: Torque and angular speed distribution:
a) K1 planetary gear; b) K2 planetary gear; c) K3 planetary gear;

4. CONCLUSIONS

The simulation model was conceived to analyze the modes of the power flow for all the four gears of the planetary gearbox. Analyzing the presented data, we noticed that the determination of the time histories of the torque for all the elements of the planetary gears, clutches and brakes are made of is possible. Moreover, the model can be used as a working platform for developing further an automating algorithm to shift the gears of the gearbox. As a result, we were able to draw some major lines in the improvement of the vehicle's working process efficiency that also leads to an improvement in the dynamic features of the vehicle.

Acknowledgements

This paper has been financially supported within the project entitled ***“Horizon 2020 - Doctoral and Postdoctoral Studies: Promoting the National Interest through Excellence, Competitiveness and Responsibility in the Field of Romanian Fundamental and Applied Scientific Research”***, contract number POSDRU/159/1.5/S/140106. This project is co-financed by European Social Fund through Sectoral Operational Programme for Human Resources Development 2007-2013. **Investing in people!**

REFERENCES

[1] J. Wang, Y. Wang and Z. Huo, Analysis of Dynamic Behavior of Multiple-Stage Planetary Gear Train Used in Wind Driven Generator, The Scientific World Journal, vol. 2014, Article ID 627045, 11 pages, 2014.
[2] Truță M., Marinescu M, Vilău R, Alexa O., Ilie C., Self-Generated Torque Induced by the Lockable and Self-Locking Differentials within the 4wd Drivetrain, Applied Mechanics and Materials, Vol. 659 (2014), pp 268-273, ISBN 978-3-03835-272-3.
[3] Otter M., Schlegel C. and Elmqvist H., Modeling and Realtime Simulation of an Automatic Gearbox using Modelica, 9th European Simulation Symposium-ESS’97, pp. 115-121, 1997.
[4] Ciobotaru T., Grigore L., VÎNTURIȘ V. and LOGHIN L., Transmisii planetare pentru autovehicule militare, Publishing House of the Military Technical Academy, Bucharest, 2005.
[5] Samanuhut P., Modeling and control of automatic transmission with planetary gears for shift quality, PhD Thesis, The University of Texas at Arlington, 2011.
[6] Loghin L., Contribuţii privind studiul proceselor ce au loc la schimbarea etajelor în transmisiile hidromecanice ale autovehiculelor militare cu şenile, PhD Thesis, Publishing House of the Military Technical Academy, Bucharest, 2005.