ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1217304

TEST BENCH AND SIMULATION RESEARCH ON HYDRODYNAMIC TORQUE CONVERTER FOR DIFFERENT INPUT SIGNALS

Marek Wozniak, Krzysztof Siczek, Zbigniew Pawelski

Lodz University of Technology
Department of Vehicles and Fundamentals of Machine Design
Zeromskiego Street 116, 90-924 Lodz, Poland
tel.:+48 42 6362265, +48 42 6312250, fax: +48 42 6312398, +48 42 6312255
e-mail: marek.wozniak.1@p.lodz.pl, ks670907@p.lodz.pl
zbigmirw.pawelski@p.lodz.pl

Abstract

This paper presents the experimental research and simulating results of a ZM130 hydrodynamic torque converter under steady and unsteady working conditions with an external step signal and sinus on turbine's shaft on a modified test bench. The mathematical model of torque converter was described by the one-dimensional flow theory with variable loss coefficients. The character of received equations from test bend showed by linearized transmittance functions with variable coefficients. For test bend object identification researches will be used an Identification Toolbox from a mathematical code in Matlab, which enables to create transfer functions as a linear model from measurements data as they got the highest correctness level with input signal (as they get the best correction level with input signal on the pump´s shaft). This mathematical model for dynamic loads will be verified by experimental tests. The aim of the carried out studies was determination the effect of sampling time decreasing on the quality of measured parameters. Results of present investigations were compared with those obtained earlier, but for the same input signals .It is possible to affirm that proposed theoretical model imitates the change of dynamic parameters, and the same the property of the torque converter. Researches led on the test bend with extortion input torque sinus signal on the turbine's shaft confirmed correctness of this model.

Keywords: *torque converter, torque, Matlab/Simulink, linearization, nonlinear model, ARX, OE*

1. Introduction

As mentioned in [1, 8-10, 12] torque converters are mounted on different machines in power transmissions, where continuous variable speed ratio is demanded, both kinetic and dynamic, which depends often on changing external loads. Undertaking research is justified because of need of analysing power transmission systems with torque converters working at unsteady conditions. Working machines, city buses and passenger cars are examples of such uses. The results allow building controllers for steering of power transmissions equipped with torque converters.

Researches were carried out in the test bench, shown on Fig. 1. The presented test bench allows to lead investigations using a microcomputer measurement system, thanks to it, European standard in this field was achieved and had been described in earlier publications [5, 11].

The main change on the test bench was a change of state in the control program. The previous version of the Citec programme allowed saving the data points with minimum sample time of 0.5 second, however the presented version makes now possible a level of 0.1 second. This allows the exact the simulation curve set and received, which was very visible near harmonic signal.

2. Test bench researches

Automatic control accepts the basic signals applied to the theory of system identification in research. It gives the possibility to obtain an opinion to qualities and quantitative behavior of the power transmission system for any shape of signal disturbances (being only a function of time).

Fig. 1. ZM130 transmission test bench [8]

The properties of the hydrodynamic torque converter can be described by four parameters, which can be obtained through measurements: torque at the pump shaft, torque at the turbine shaft, the pump angular velocity and turbine angular velocity. According to the transient transmission state caused by changes of the engine moment and load torque, it was decided to consider the described power train with the transmission as object of automatic control with two input signals (Fig. 2): engine moment M1 and load moment M2 and also two output signals: angular velocity of the pump's shaft ω2 and the angular velocity of the turbine's shaft ω2. The input variables pass through the boundary of the torque converter and will be used to analyse the dynamic characteristics of the unit.

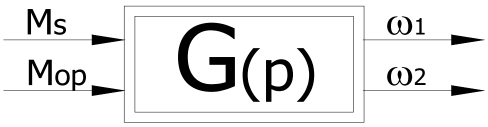

Fig. 2. Input and output signals from the transmission

The Block diagram on Fig. 2 represents the object of control and relationships between input and output signals of the system in linearized of under special boundary conditions, which can be mathematically modeled through the following system of equations:

$$\begin{vmatrix} \omega_1 \\ \omega_2 \end{vmatrix} = \begin{vmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{vmatrix} \times \begin{vmatrix} M_S \\ M_{op} \end{vmatrix}. \tag{1}$$

The above mentioned matrix equation should be recognized as relationship with changing equations transmittance and variable coefficients, during the test bench research it was decided to accept on saving time on the level 0.1 second

Continuous state measurements investigated for the same starting states, which were represented in earlier publications [6-8, 10], both for step and sinus signal on the turbine shaft (M_{op}) and pump shaft (M_s).

For example the Fig. 3 shows the course from the state of researches during the sinusoidal signal, Fig. 4 for step signal. They are following values:

– torque on the turbine's shaft (M_{op}) changing sinusoidally near the value 130 [Nm] with amplitude 20 [Nm] and period of 10 seconds (input signal, Fig. 3),
– rotational speed of turbine's shaft (ω_2) changing sinusoidally near the value 580 [rpm] (output signal, Fig. 3),
– torque on turbine's shaft (M_{op}) changing steeply in the range (80-220 Nm), (input signal, Fig. 4),
– rotational speed of the turbine's shaft (ω_2) changing steeply, answering the temporary values of torque extorting (output signal, Fig. 4).

It was also shown here:

– the speed of the pump (ω_1) stays constant at 1300 [rpm] for harmonic signal, 1400 [rpm] for step signal,
– constant pump torque (M_{srzecz}) – 94 [Nm] for sinus signal, 99 [Nm] for step signal,

theoretical torque on the turbine's shaft (M_{opteor}) (changing sinusoidally or steeply) and theoretically constant speed of the pump (ω_{1teor}), given by the control unit.

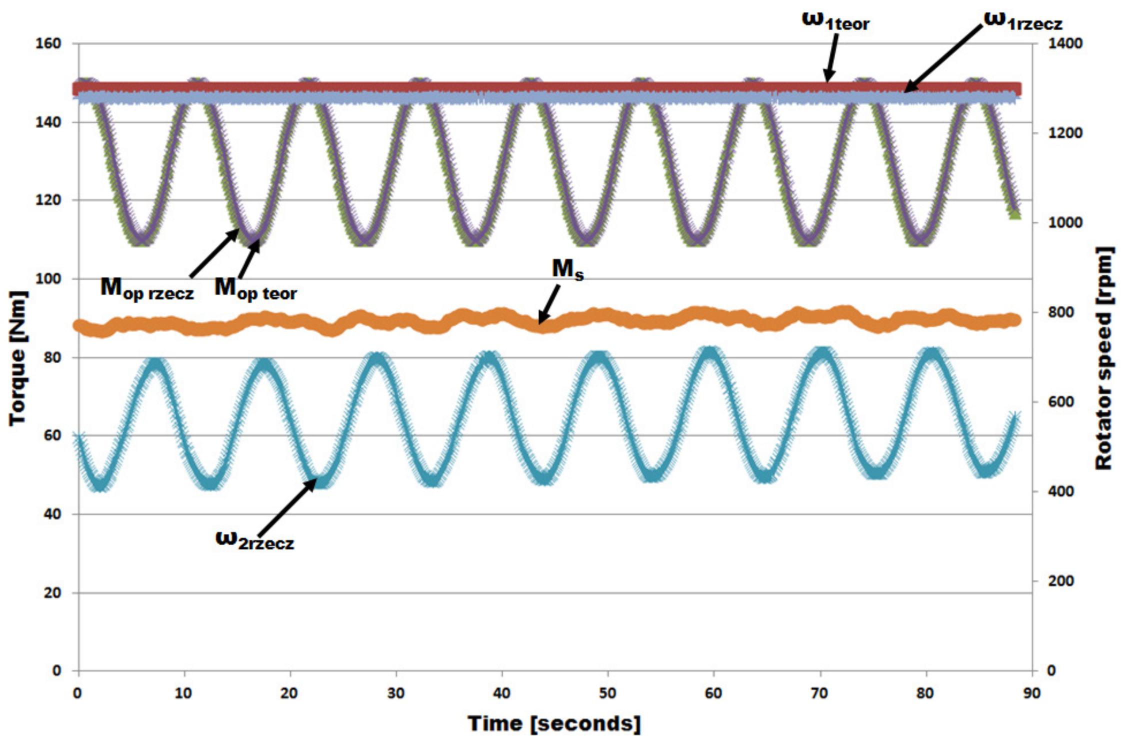

Fig. 3. Course of input and output signals for sinus signal on turbine's shaft

The transmittance character was determined using of the software Matlab with library Identification Toolbox, aimed at the building of models on the basis of measurement data [2, 3].

In the aim to obtain the equations three identification models were used (ARX,OE,ARMAX). For each equation was calculated the percentage filling of the graph (the higher this coefficient is, the more it covers with the real curve), damping coefficient (c), natural frequency (ω_0). The methodology of calculations and computational models as well as their description are presented in the previous paper [11].

3. Test bench results

The Tab. 1 shows the example transmittance equations, values of percentage filling the graph factor, damping coefficient (c), natural frequency (ω_0) during step signal up and down with value 30 [Nm] for constant speed of pump 1400 [rpm].

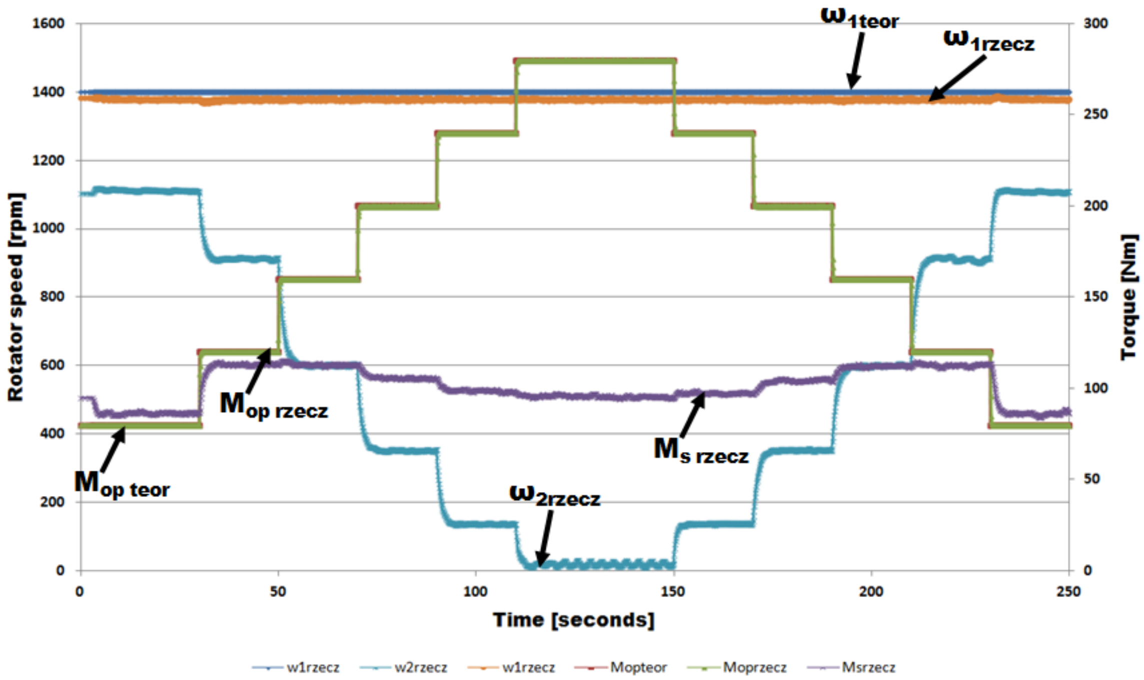

Fig. 4. Course of input and output signals for step signal on turbine's shaf

Tab. 1. Table with transfer functions for step signal

Step M_2 [Nm]	Model ARX					Model OE	Model ARMAX	
	1 1 1	1 1 0	2 1 1	2 2 1	1 2 0	2 2 1	2 2 1 1	2 2 2 1
80 - 110	0.1685 ---------- s + 0.1652 92.12%	0.1495 s + 0.1617 ---------------- s + 0.1584 93.11%	0.113 s + 0.453 ------------------ s^2 + 0.995 s + 0.276 ω_0=0.525 c=0.946 92.09%	-0.2216 s + 0.512 ------------------ s^2 + 1.119 s + 0.2992 ω_0=0.546 c=1.022 93.33%	0.2061 s + 0.143 ---------------- s + 0.1386 93.44%	0.04553 s + 0.03933 ------------------ s^2 + 0.678 s + 0.08883 ω_0=0.298 c=1.137 96.67%	0.2338 s + 0.0906 ------------------ s^2 + 0.8109 s + 0.08741 ω_0=0.295 c=1.171 95.98%	0.1415 s + 0.06337 ------------------ s^2 + 0.6736 s + 0.06116 ω_0=0.247 c=1.161 96.36%
110 - 140	-0.236 ---------- s + 0.07618 91.02%	-0.2423 s - 0.2523 ---------------- s + 0.08117 92.88%	0.102 s + 0.4881 ------------------ s^2 + 1.009 s + 0.222 ω_0=0.471 c=1.071 91.09%	0.04999 s + 0.1303 ------------------ s^2 + 0.791 s + 0.1301 ω_0=0.361 c=1.172 95.66%	-0.0773 s - 0.2415 ---------------- s + 0.07787 94.69%	0.05333 s + 0.04683 ------------------ s^2 + 0.533 s + 0.04633 ω_0=0.215 c=1.129 96.67	-0.6654 s - 0.2064 ------------------ s^2 + 0.6455 s + 0.06628 ω_0=0.257 c=1.255 96.33	-0.6659 s - 0.1771 ------------------ s^2 + 0.6248 s + 0.05684 ω_0=0.238 c=1.112 96.54
140 - 170	0.1286 ---------- s + 0.07409 89.11%	0.1305 s + 0.1357 ---------------- s + 0.07798 93.07%	0.145 s + 0.5263 ------------------ s^2 + 1.175 s + 0.299 ω_0=0.546 c=1.074 90.08%	-0.3416 s + 0.5345 ------------------ s^2 + 1.389 s + 0.3042 ω_0=0.551 c=1.259 93.72%	0.03984 s + 0.1308 ---------------- s + 0.07532 95.33%	0.02933 s + 0.01909 ------------------ s^2 + 0.3106 s + 0.01916 ω_0=0.138 c=1.121 94.18	-0.003 s + 0.3371 ------------------ s^2 + 1.051 s + 0.1914 ω_0=0.437 c=1.202 95.21	0.2457 s + 0.3614 ------------------ s^2 + 1.119 s + 0.205 ω_0=0.452 c=1.235 95.38
170 - 200	0.08292 ---------- s + 0.08453 88.58%	0.08481 s + 0.08874 ---------------- s + 0.09122 92.38%	-0.03077 s + 0.01314 ------------------ s^2 + 0.6626 s + 0.06619 ω_0=0.257 c=1.287 95.22%	-0.03077 s + 0.01314 ------------------ s^2 + 0.5526 s + 0.06319 ω_0=0.251 c=1.099 92.28%	0.152 s + 0.07589 ---------------- s + 0.07676 95.36%	-0.03077 s + 0.01314 ------------------ s^2 + 0.2526 s + 0.01319 ω_0=0.114 c=1.099 94.43	-0.03077 s + 0.01314 ------------------ s^2 + 0.2526 s + 0.01319 ω_0=0.114 c=1.099 95.33%	-0.03077 s + 0.01314 ------------------ s^2 + 0.5526 s + 0.05319 ω_0=0.231 c=1.196 95.22
200 - 230	0.1113 ---------- s + 0.06221 92.61%	0.1124 s + 0.1161 ---------------- s + 0.06509 94.57%	0.08465 s + 0.2324 ------------------ s^2 + 1.153 s + 0.1315 ω_0=0.362 c=1.592 93.44%	-0.6935 s + 0.2101 ------------------ s^2 + 0.843 s + 0.1181 ω_0=0.343 c=1.228 94.59%	0.05656 s + 0.1138 ---------------- s + 0.06369 94.56%	0.1333 s + 0.06498 ------------------ s^2 + 0.5687 s + 0.05717 ω_0=0.239 c=1.292 94.59	-0.06174 s + 0.1405 ------------------ s^2 + 0.63 s + 0.07973 ω_0=0.282 c=1.223 94.58%	-0.8209 s + 0.2135 ------------------ s^2 + 0.707 s + 0.1203 ω_0=0.346 c=1.021 94.88
230 - 200	0.1971 ---------- s + 0.06281 88.76%	0.2072 s + 0.2143 ---------------- s + 0.06849 92.03%	0.1978 s + 0.6368 ------------------ s^2 + 1.259 s + 0.2048 ω_0=0.491 c=1.282 88.23%	-0.02031 s + 0.6309 ------------------ s^2 + 1.211 s + 0.2028 ω_0=0.451 c=1.345 93.38%	0.1463 s + 0.2095 ---------------- s + 0.06689 94.11%	-0.1041 s + 0.02348 ------------------ s^2 + 0.5941 s + 0.07524 ω_0=0.274 c=1.084 94.08	0.1581 s + 0.5352 ------------------ s^2 + 1.153 s + 0.1722 ω_0=0.414 c=1.389 94.09%	0.1115 s + 1.431 ------------------ s^2 + 1.495 s + 0.4603 ω_0=0.678 c=1.081 94.12%
200 - 170	0.2497 ---------- s + 0.04506 91.17%	0.2732 s + 0.2802 ---------------- s + 0.05088 93.68%	0.1007 s + 0.225 ------------------ s^2 + 0.6524 s + 0.0414 ω_0=0.203 c=1.603 90.48%	-0.4005 s + 0.1482 ------------------ s^2 + 0.5496 s + 0.06708 ω_0=0.258 c=1.061 96.61%	1.546 s + 0.3939 ---------------- s + 0.07244 94.52%	0.1376 s + 0.01895 ------------------ s^2 + 0.4724 s + 0.04839 ω_0=0.209 c=1.127 96.64%	0.3188 s + 0.1485 ------------------ s^2 + 1.032 s + 0.1456 ω_0=0.381 c=1.352 94.24%	-0.2412 s + 0.1731 ------------------ s^2 + 0.528 s + 0.08187 ω_0=0.286 c=0.922 95.03%

The Tab. 2 shows Laplace equations and calculated coefficients for the harmonic signal. Damping coefficient and natural frequency were calculated on the basis of the traditional dependences of automatic bases.

Analysing the results from Tab. 1 it is possible to formulate the following conclusions:

– together with the increase of coefficients defining the given model, the degree of meter and nominative of polynomial grows up, and the physical sense of equation is difficult to interpret,
– the higher the coefficients for the given model then the percentage filling graph grows up,
– transmittances, for which first the parameter describes the degree (111, 110, 120), of equation is expressed by unity, have the shape module I rank, remaining equations have response at least module II rank,

– equations II rank describes very approximate dynamics to I rank, which confirm values of percentage filling graph factor and close up values of coefficients after reduction to equations I rank.

Analysing the results from Tab. 2 it is possible to formulate following conclusions:

– for a harmonic signal with a growing up number of calculated periods, the increase in the percentage filling graph factor and coefficients in equations change negligibly, what testifies the test bench class,

it is possible to describe II rank equations in the product form and then a reduction to transmittance I rank. This is in agreement with the simulation results, which show a similar relationship. The shape of those equations is easier to interpret in the equation of higher ranks. Equations for both types of input signals can be reduced.

Tab. 2. Table with transfer functions for sinus signal

SIN M_2 [Nm]	Model OE	Model ARMAX	
	2 2 1	2 2 1 1	2 2 2 1
2 periods	0.6883 s - 0.002508 -------------------------- s^2 + 0.09765 s + 0.006045 ω_0=0.077 c=0.672 93.27%	0.3259 s - 0.02065 -------------------------- s^2 + 0.07144 s + 0.004745 ω_0=0.068 c=0.782 92.99%	0.5949 s - 0.006069 -------------------------- s^2 + 0.08195 s + 0.001373 ω_0=0.037 c=1.105 92.01%
3 periods	0.3482 s - 0.01959 -------------------------- s^2 + 0.0938 s + 0.004505 ω_0=0.067 c=0.745 92.79%	0.3925 s - 0.01721 -------------------------- s^2 + 0.08388 s + 0.003954 ω_0=0.062 c=0.786 93.63%	0.703 s - 0.0008453 -------------------------- s^2 + 0.1017 s + 0.001922 ω_0=0.043 c=1.159 93.31%
4 periods	0.6677 s - 0.003403 -------------------------- s^2 + 0.09948 s + 0.007849 ω_0=0.088 c=0.621 92.54%	0.5748 s - 0.008363 -------------------------- s^2 + 0.08252 s + 0.003923 ω_0=0.062 c=0.665 93.56%	0.4903 s - 0.0128 -------------------------- s^2 + 0.08421 s + 0.002939 ω_0=0.054 c=0.899 93.87%
5 periods	0.6831 s - 0.001645 -------------------------- s^2 + 0.09444 s + 0.003812 ω_0=0.061 c=0.763 92.49%	0.7251 s - 0.0002604 -------------------------- s^2 + 0.1024 s + 0.007064 ω_0=0.084 c=0.609 93.53%	0.722 s - 0.0005469 -------------------------- s^2 + 0.1023 s + 0.003398 ω_0=0.058 c=0.877 93.91%
6 periods	0.6781 s - 0.001263 -------------------------- s^2 + 0.08715 s + 0.002943 ω_0=0.052 c=0.803 93.01%	0.7287 s - 5.365e-005 -------------------------- s^2 + 0.1011 s + 0.001935 ω_0=0.044 c=1.143 94.08%	0.7273 s - 0.0002165 -------------------------- s^2 + 0.1116 s + 0.005956 ω_0=0.077 c=0.789 95.16%
7 periods	0.676 s - 0.001131 -------------------------- s^2 + 0.08513 s + 0.002629 ω_0=0.051 c=0.834 94.14%	0.7249 s - 0.0001712 -------------------------- s^2 + 0.09871 s + 0.004689 ω_0=0.068 c=0.721 94.98%	0.725 s - 0.0002698 -------------------------- s^2 + 0.15967 s + 0.007212 ω_0=0.084 c=0.951 96.81%

4. Comparison of calculated results

Research was carried out and compared with earlier test bench measurements and research done in another simulation model [10]. The non-linear model of the hydrodynamic torque converter was elaborated at the Institute of Vehicles of Technical University of Lodz (Fig. 5) and presented in the previous publication [5].

Equations from the simulation model are calculated as the result of local linearization in every point of established work in Taylor row and then reduced to II rank transmittances. From the calculated equations from the theoretical model, like for the test bench researches, two coefficients – natural frequency and damping factor – are calculated.

Figure 6 shows the comparison of the natural frequency for the test bench researches with hold time 0.5 and 0.1-second and theoretical researches. Fig. 7 presents the comparison of the damping factor. In both types, the input signal was the step signal on the turbines shaft M_{op} which change was 30 [Nm].

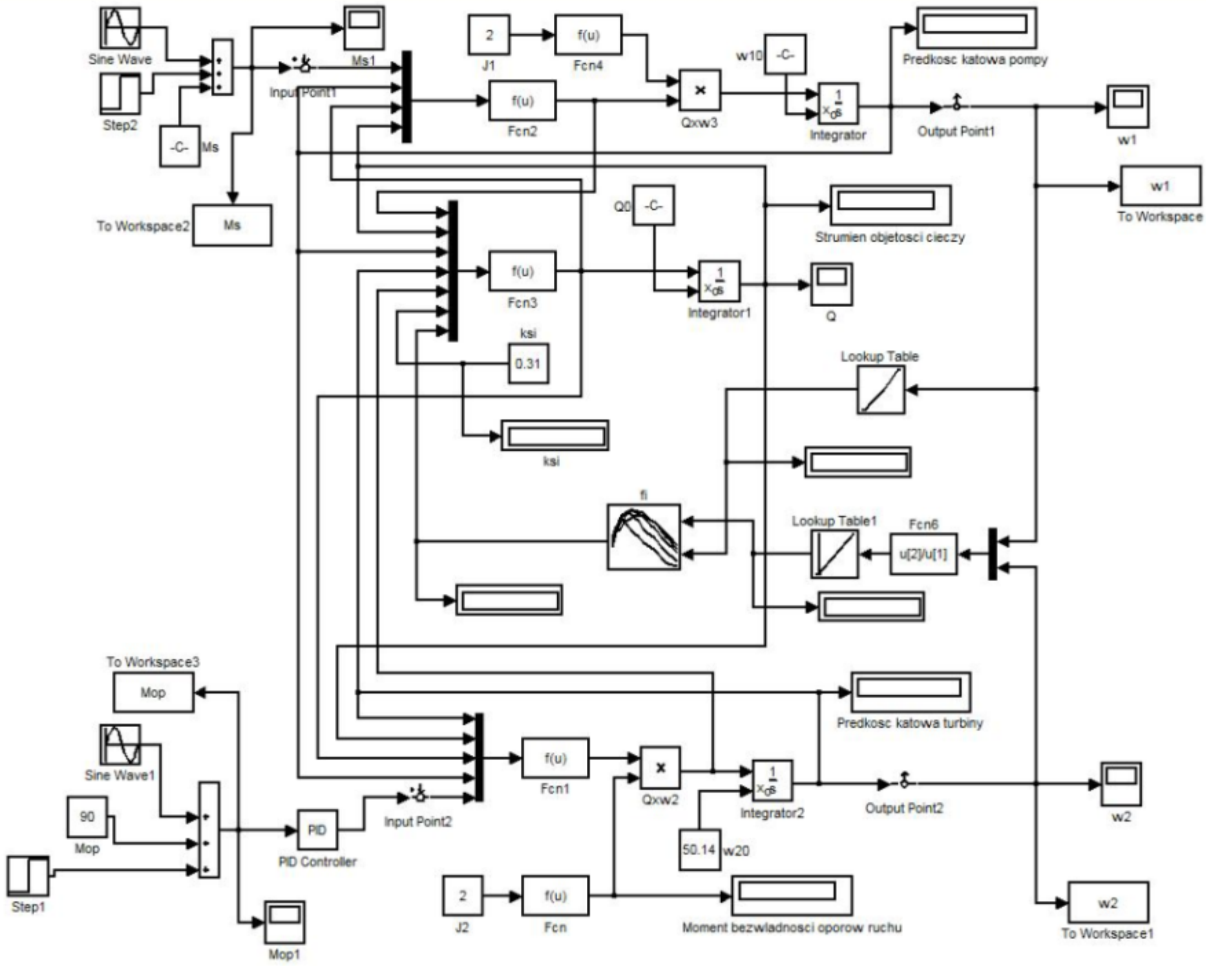

Fig. 5. Torque converter ZM130 model AT Simulink environment [12]

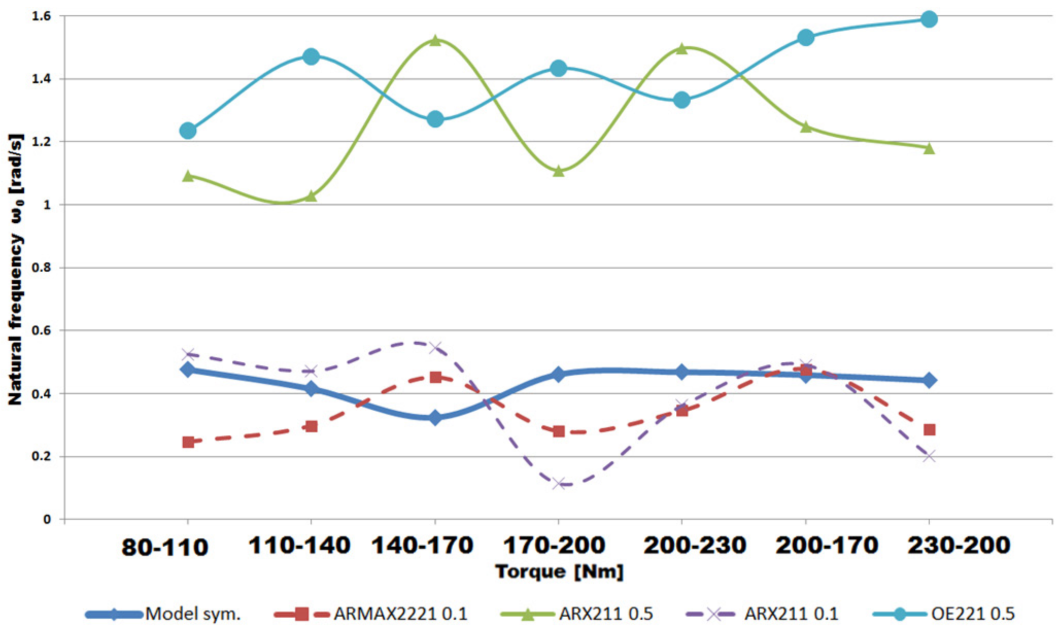

Fig. 6. Comparison of the natural frequency for selected identification models with theoretical results for the step signal

Figure 8 shows the comparison of the damping factor for three types of earlier describes researches for changing sinus signal on the turbine's shaft with amplitude 20 [Nm] and period 10 seconds.

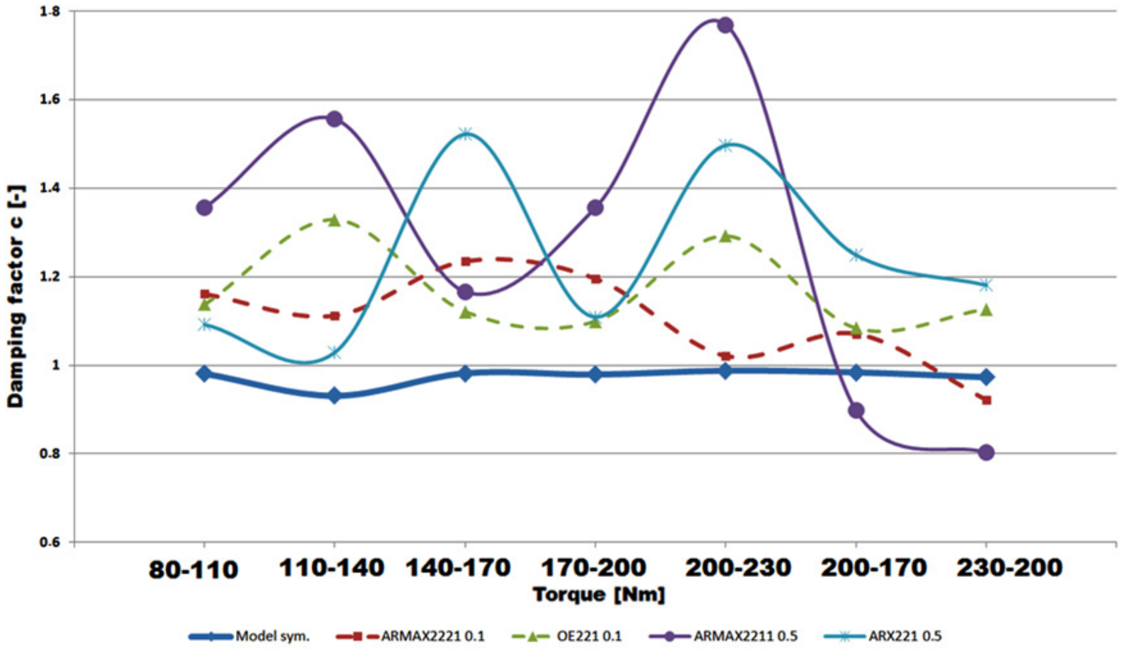

Fig. 7. Comparison of the damping factor for selected identification models with theoretical results for the step signal

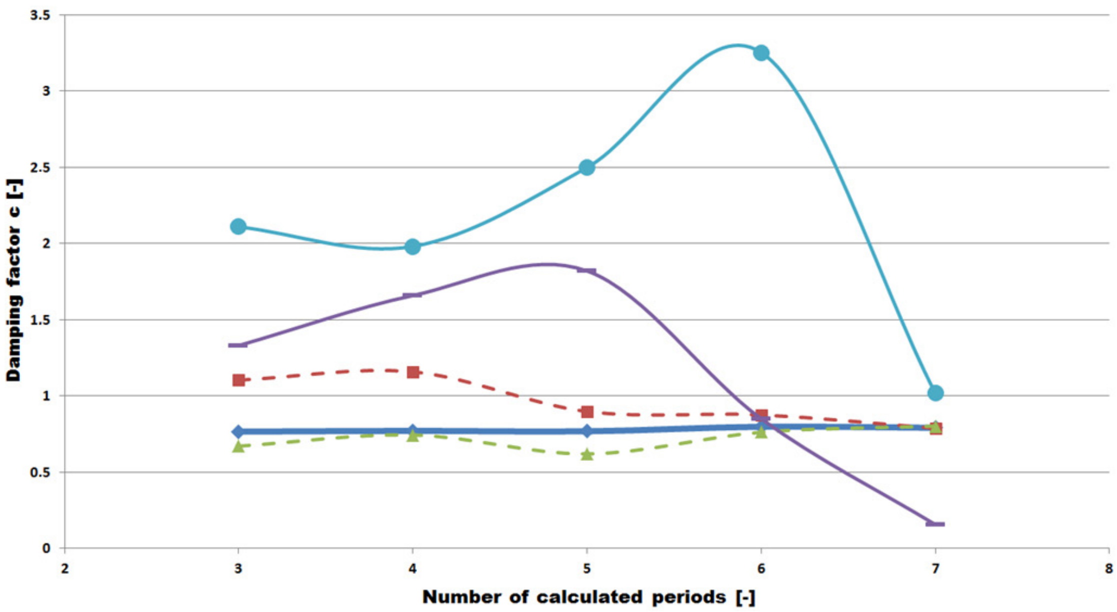

Fig. 8. Comparison of the damping factor for selected identification models with theoretical results for a sinus signal

Comparing results from Fig. 6-8 it is possible to affirm, that:

– Calculated results received on the theoretical way for both types of signals are satisfactory,
– Results with higher acquired frequency are more exact in relation to theoretical values than the results with low frequency. Course of damping factor and natural frequency coefficient for save 0.1 second was marked missing curves and for save constant curve whereas for simulation model constant thicken curve. It can be clearly be seen, that missing curves for both type of signal are more complaint with theoretical values than thicken curves, it testifies about this ”closer” position on graph. Additionally for the results with save 0.5 second, was not always possible to calculated coefficients because the form of the equation did not let for it. Higher number of data points have also better influence for percentage filling graph factor, his increase for step signal was about 3-4% and for sinus signal 6-10% (10% was for periods under 5 second) for everyone identification models.

– According to differences (equations received on stationary researches way are weighted down because of occidental mistakes such how: noises and mistakes from approximated the curve) should underline qualitative agreement and quantitative introduced parameters with theoretical model presented coefficients.

5. Conclusions

Summing up it is possible to conclude that the recognized number of data points grows up the accuracy-received results and confirm that the proposed theoretical model represents the change of dynamic parameter and the same properties of the torque converter. The state researches with step and harmonic signal confirm the correctness of simulation model. Test bench and simulation researches with different hydrodynamic torque converter will be the next stage of work. Investigation will be the next stage of work with different hydrodynamic torque converter, as well as its verification based on the simulating model.

References

[1] De la Fuente, P., Stoff, H., Volgmann, W., Wozniak, M., *Numerical analysis into the effects of the unsteady flow in an automotive hydrodynamic torque converter*, Lecture Notes in Engineering and Computer Science. World Congress on Engineering 2011, ICME, Vol. 3, pp. 2405-2410, London 2011.

[2] Ljung, L., *System Identification Toolbox 7 – User's Guide,* MathWorks, 2008.

[3] Mrozek, B., Mrozek, Z., *Matlab i Simulnik – Poradnik użytkownika*, Wyd. II, HELION 2004.

[4] Pawelski, Z., *Badania charakterystyki przekladni hydrokinetycznej przy wybranych nieustalonych stanach obciazen*, Lodz 1980.

[5] Pawelski, Z., *Własnosci przekladni hydrokinetycznej ZM130 przy skokowej zmianie predkosci katowej walu turbiny*, Archiwum Motoryzacji, Vol 4/2007, pp. 375-388, PIMOT, 2007.

[6] Pawelski, Z., Wozniak, M., Pałczynski, T., *Badania stanowiskowe i symulacyjne wlasciwosci dynamicznych przekladni hydrokinetycznej,* XVIII Miedzynarodowa Konferencja Naukowo-Techniczna Napedy i sterowania hydrauliczne i pneumatyczne 2007, pp.193-204, Wroclaw 2007.

[7] Pawelski, Z., Wozniak, M., Pałczynski, T., *Stationary and simulating researches with input sinus signal on turbine's shaft of hydrokinetic torque converter ZM130*, FISITA 2010 World Automotive Congress – Automobiles and Sustainable Mobility, Budapest 2010.

[8] Pawelski, Z., Pałczynski, T., Wozniak, M., *Wlasnosci nieliniowego modelu przekladni hydrokinetycznej ZM130*, Teka Komisji Motoryzacji PAN, Oddzial w Krakowie, Zeszyt Nr 33-34, pp. 313-324, Krakow 2008.

[9] Pawelski, Z., Wozniak, M., *Badania stanowiskowe i symulacyjne przy wejściowym sygnale sinusoidalnym na wale turbiny przekładni*, Archiwum Motoryzacji, Vol. 2/2009, pp. 163-177, PIMOT, 2009.

[10] Szydelski, Z., *Sprzęgła i przekładnie hydrokinetyczne*, WNT, Warszawa 1973.

[11] Wozniak, M., *Badania stanowiskowe i symulacyjne własności dynamicznych przekładni hydrokinetycznej*, Lodz 2010.

[12] Wozniak, M., De la Fuente, P., *Test bend and unsteady state calculations of a hydrodynamic torque converter*, 4th International Interdisciplinary Technical Conference of Young Scientists, pp. 55-61, Poznan 2011.