Dynamic Emulation of Mechanical Loads with Backlash Based on Rapid Control Prototyping

Karol Kyslan, Emil Kušnír, Viliam Fedák, Milan Lacko and František Đurovský
Department of Electrical Engineering and Mechatronics
Technical University of Košice
Košice, Slovak Republic
karol.kyslan@tuke.sk, emil.kusnir@gmail.com, viliam.fedak@tuke.sk, milan.lacko@tuke.sk, frantisek.durovsky@tuke.sk

Abstract—The paper discusses advanced control of a dynamometer performing dynamic emulation of mechanical loads. Assumed is certain class of nonlinear load with backlash. Paper presents and describes the basic control structure, which can be used for validation of speed algorithms and its practical implementation with rapid control prototyping. Validation of experimental results against the simulations has been performed with experimental test bench containing permanent magnet DC machines and DC-DC converters with high sampling times in current control loops.

Keywords—dynamometer; dynamic emulation; mechanical load; backlash; rapid control prototyping

I. INTRODUCTION

Electrical dynamometers can be found in many applications. In [1] a 2.2 MW dynamometer has been used for cyclic testing of motors in emulation of digging operations. An elevator, as an example of a multi-mass mechanical load, has been emulated with good accuracy by a dynamometer, as shown in [2]. Open source low-cost electric dynamometer has been presented in [3] in order to enable testing of DC machines in robotic applications. Design and control strategy of an absorbing dynamometer with two quadrant DC-DC chopper supplying a drive can be found in [4].

Recent research in dynamometer control algorithms leads to the so called dynamic emulation of mechanical loads (DEML) strategy. It is assumed that electrical dynamometer is on a common shaft with the drive under test (DUT) and the connection is stiff. Speed or position controller of the DUT is tested using a programmable electrical dynamometer that is able to emulate behaviour of any desired mechanical load set by the user. In other words, the dynamometer loads the DUT in such a way that it emulates behaviour of any mechanical load whose mathematical model is known and implemented in the dynamometer control structure - [5], [8], [10]. In this sense the emulation presents an imitation of the system (mechanical load) by another technical device (dynamometer) so that the imitating system behaves in the same way as the imitated system would do.

Several approaches of DEML have been presented in the literature. A fundamental contribution to the DEML is in [5] where closed loop control structure of a dynamometer and its digital implementation has been introduced for the DUT speed control. It is based on speed tracking with implicit feedforward of inverse dynamics and a compensator is used to ensure desired closed loop transfer function. There is no need for inverse dynamics of emulated load and thus the drawbacks of the previous approaches are eliminated. In addition, limitations of previously used inverse model based control strategies [12], [13] are further outlined in [5]. Extension to the position control of the DUT and another class of nonlinear loads were studied in [6] and [7]. Control strategies described in [5]-[7] were developed for the idealized, nearly linear test bench dynamics. A compensation of non-linear friction was introduced in [8] and [9]. Nonlinear control methods were applied for speed and position testing of the DUT in order to improve emulation performance. PI controller and PI estimator were analysed and the latter one was extended to the position control approach [9]. Furthermore, an electric pump mechanism and simplified vehicle mechanics were emulated successfully. Industrial converters as a part of hardware-in-the-loop (HIL) emulator were presented in [10] and [11]. Here, also a novel control structure based on per-normal inertia was studied. It was shown, that this control strategy preserves pole-zero structure of emulated load. Satisfactory experimental results were obtained there, but only for the class of linear mechanical loads.

Our paper is focused on the DEML for the case, where the load presents a dynamic function of the speed and emulation of a certain class of mechanical load with backlash is applied. For emulation of the loads within position control loops an extended control structure has to be used as reported in [7] and [9]. Obviously, in our system is modified an approach analysed in [5] with slight differences. We have used control hardware which is able to reach very fast sampling rates and thus able to emulate nonlinear mechanical loads with backlash. Out contribution do not lie in the development of new emulation strategy; but in our opinion this combination of existing emulation strategy and powerful hardware haven’t been reported before. The dynamometer control structure is presented in Section II. The model of mechanical load with backlash as a target system (for comparison) is presented in Section II. Implementation of algorithm with rapid control prototyping technique (RCP) into the experimental system is discussed in Section IV. The experimental results for the backlash system and its comparison with simulations are in Section V. Finally, conclusions and remarks are presented in Section VI.
II. EMULATION CONTROL SCHEME

Dynamometer control strategy is illustrated in Fig. 1. Derivation of the control strategy can be found in [5]. In this section calculations of the basic elements are presented. In all experiments a simple discrete PI controller with anti-windup connection was used for the speed control of the DUT. Its parameters were not changed during experiments in order to observe only influence of the variable parameters of the emulated load. Mechanical and electrical parameters of both drives were identified and their values can be found in Appendix. Identified torque constant \( J_{DUT} \) is used for estimation of the reference torque \( \hat{\tau}_{DUT} \). The external torque applied on the model of the emulated load \( \tau_{ext} \) was set to zero.

In preliminary verification of dynamometer performance, the external torque was set to a constant value for basic closed-loop testing. Model of the emulated load \( G_{em} \) is described in detail in Section IV. The compensator block \( G_{comp} \) is used to ensure desired closed-loop transfer function. Its model is given as:

\[
G_{comp}(z) = \frac{a_2 z^2 + a_1 z + a_0}{b_2 z^2 + b_1 z + b_0}
\]  
(1)

\[
b_2 = 1; \quad b_1 = -A; \quad b_0 = 0
\]  
(2)

\[
a_2 = \frac{J_{DUT}}{TK_i}; \quad a_1 = 1 - \frac{J_{DUT}(1+A)}{TK_i}; \quad a_0 = \frac{J_{DUT} A}{TK_i} - A
\]  
(3)

In (2) and (3) \( T \) is sampling time, the parameter \( A \) is given by:

\[
A = 1 - \frac{1}{J_{DUT}} \frac{B_{DUT} T}{J_{DUT}}
\]  
(4)

\( J_{DUT} \) is the identified moment of inertia (kgm²) and \( B_{DUT} \) is the identified viscous friction coefficient (Nms/rad) of the DUT.

Now, we look for a discrete PI controller \( G_i(z) \) for the linear dynamics of the DUT (see Fig. 2):

\[
\frac{1}{J_{DUT}s + B_{DUT}} = \frac{K_i}{1 + sT_i} \quad K_i = \frac{1}{B_{DUT}} \quad T_i = \frac{J_{DUT}}{B_{DUT}}
\]  
(5)

It can be easily shown that desired coefficients of the PI controller are:

\[
T_{ss} = T_i \frac{T}{2}; \quad K_{ss} = \frac{2T_i}{K_i(2T + T)}
\]  
(6)

where \( T \) is a user defined time constant of desired 1st order transfer function. Finally, the speed tracking loop controller \( G_t \) (Fig. 1), is given by:

\[
G_t(z) = K_k \frac{z - A}{z - 1}; \quad K_k = K_{ss} \frac{T_{ss} + T}{T_{ss}}; \quad A = \frac{T_{ss}}{T_{ss} + T}
\]  
(7)

Derivation of the equation (5) can be found in [5]. The controller has to ensure high tracking bandwidth, but its performance is limited by sampling period for calculation of the speed value. The reference current value of the dynamometer is calculated with identified dynamometer torque constant \( K_k \).

Fig. 2. Compensated system for emulation, [6]
III. IMPLEMENTATION WITH RCP TECHNIQUE

The experimental system used to verify the emulation strategy is shown in Fig. 1. Permanent magnet DC machines (PMDC) are supplied with DC-DC converter (H-bridge) switching at 10 kHz. Bipolar control strategy of H-bridge is applied with a relationship of a reference voltage to the duty cycle:

\[
z = \frac{U^*}{2U_{DC}} + 0.5 \quad (8)
\]

where \(z\) is the desired duty cycle, \(U^*\) is output of a PI current controller and \(U_{DC}\) is voltage of the battery. With this “converter-machine” arrangement very high sampling times of current loops can be reached. An acid lead battery (12.5 V) is used as a DC supply for the converters as it enables absorption of energy when the drive operates in different torque-speed regions. The actual current of both drives is measured with Hall-effect based linear current sensors Allegro ACS712 and actual rotor speed is measured with the low-cost LARM TTL incremental encoder giving 1000 pulses per revolution.

For both control and signal processing the digital RT-LAB based simulator OP5600 has been used. Measurements and computation of the algorithm were executed in 10 µs time interval so the current loops were sampled at 100 kHz. The rotor speed was calculated from the measured position difference within the fixed sampling interval of 2 ms.

The common configuration with Command Station PC for development within MATLAB/Simulink environment and Target (OP5600) for the C-code execution enables rapid control prototyping (RCP) of the DEML control algorithm. The simulator OP5600 contained powerful target computer and user programmable FPGA powered by Xilinx Spartan 3 [18]. The FPGA was not programmed directly, but a pre-programmed Opal-RT configuration file (bitstream) was involved. With the bitstream, the I/O’s of FPGA were directly mapped into the I/O’s of OP5600 hardware and therefore it was not necessary to program the FPGA, even if it was physically incorporated in the RCP. The drawback of that approach was that the fastest sampling time was only 10 µs. Another possibility is to program FPGA directly with RT-XSG toolbox. Thus, sampling times even below 1 µs could be reached.

IV. TARGET SYSTEM FOR VALIDATION OF DYNAMOMETER PERFORMANCE

In this section, validation of obtained results is discussed. Note that if DUT is driving a mechanical load, the load is rotating at the emulated speed. If the mechanical load is replaced by the DEML performing dynamometer, its actual speed has to be equal to the emulated one.

In laboratory facilities scarcely all kinds of mechanical loads are available. Therefore, the dynamometer speed is compared only to the model, so called a target system (Fig. 3). This is the main drawback of DEML approaches. According to authors’ opinion, this validation is only satisfactory. In Section V the actual speed of DUT is compared with the emulated speed from Fig. 3.

It is assumed that the bandwidth of the current-loop subsystems (Fig. 3) is much higher than bandwidth of superimposed speed loop subsystems [5], [7]. If the dynamics of the current-loop is neglected, a difference between real DUT and target system occurs. It should be noted though, that dynamics of the current loop has only a small influence on the DEML performance [6].

\[G_c(s)\] is a transfer function of the controller for mechanical load and \(G_{em}(s)\) is a system of linear or nonlinear equations that represents mathematical model of analysed mechanical load. Linear emulated mechanical load is given by:

\[T_e = J_{em}\ddot{\omega}_{em} + B_{em}\omega_{em} \quad (9)\]

where \(T_e\) is the electrical driving torque [Nm], \(J_{em}\) is the emulated inertia mass [kgm²], \(B_{em}\) is emulated viscous-friction coefficient [Nms], and \(\omega_{em}\) is emulated angular velocity [rad.s⁻¹]. The transfer function for the emulated load is than:

\[G_{em}(s) = \frac{\omega_{em}}{T_e} = \frac{1}{J_{em}s^2 + B_{em}} \quad (10)\]

From (8) it is obvious that by applying electrical-driving torque \(T_e\) on the load with parameters \(J_{em}\) and \(B_{em}\) the load starts to rotate with angular velocity \(\omega_{em}\). A linear load (9) is used only for the preliminary testing of the dynamometer’s closed-loop performance.

The main goal of this work is to emulate a system with backlash. At presence of backlash, a hard nonlinearity is introduced into the control loop for generation of torque, [17]. When the drive shaft is traversing the backlash, no torque is transmitted through the shaft. When the shaft comes out of the nonlinearity zone and starts to press the load, it results in large surges of torque. This makes the system difficult to control. Several backlash models can be found in the references [14] - [17]. For purposes of the DEML, the simplest model was chosen [16], as shown in Fig. 4 with MATLAB implementation in Fig. 5 that is described by the equations:

\[J_{em}\dot{\omega}_{em} + \omega_{em} = T_e - B_{em}\omega_{em} \quad (11)\]

\[\omega_{em} = \omega_{eq} - \omega_{eq2} \quad (12)\]

\[\omega_{em} = \omega_{eq} - \omega_{eq2} \quad (13)\]
Defining difference angle $\varphi_j$ as:

$$\dot{\varphi}_j = \omega_j$$  \hfill (14)

The equation for the shaft torque is given:

$$T_s = k_i D_s(\varphi_j)$$  \hfill (15)

and the dead zone function is:

$$D_s(x) = \begin{cases} 
  x - \alpha & x > \alpha \\
  0 & |x| < \alpha \\
  x + \alpha & x < -\alpha 
\end{cases}$$  \hfill (16)

In the eqs. (9)-(14) $J_{\text{DUT}}$ and $J_{\text{em}}$ are the DUT and the load moment of inertia, respectively; $T_{\text{DUT}}$ is the DUT torque; $T_{\text{ext}}$ is an external torque applied on the load, typically equals to zero; $T_s$ is transmitted shaft torque; $B_{\text{DUT}}$ and $B_{\text{em}}$ are the DUT and the load viscous frictions, respectively; $k_i$ is the shaft elasticity.

Note that shaft damping is zero, so shaft is modelled as a pure spring. This is necessary condition for this backlash model to be valid [16].

V. EXPERIMENTAL RESULTS

Presented in this section are experimental responses of the dynamometer controlled under DEML. The same structure of results is maintained in each figure. At the top of each figure, the reference speed $n_{\text{REF}}$, measured actual speed $n_{\text{DUT}}$ and emulated speed $n_{\text{EM}}$, obtained by simulation of the target system (Fig. 3), are shown. In middle of each figure, there are measured actual current $I_{\text{DUT}}$ and emulated current $I_{\text{EM}}$, obtained by simulation of the target system. Finally, at bottom of each figure, the measured current of dynamometer $I_L$, is shown. Both target system and DUT have the same PI speed controller and PI current controller with reference current limit of $\pm 5$ A and necessary anti-windup for I-component of both controllers. To the model there was not applied any external load torque in order to better observe the unmodelled friction torque. It is assumed that torque linearly depends on the current, so its behaviour is practically the same.

In the following text emulation of the linear load will be presented, followed by emulation of the two-mass system with backlash. The dynamics of a linear load are presented in (10). Experimental results of its emulation are presented in Fig. 6 and Fig. 7. In both cases, the emulated viscous friction $B_{\text{em}}$ is equal to its estimated value $B$ and only change of inertia $J_{\text{em}}$ is observed. In Fig. 6 the emulated inertia $J_{\text{em}}$ is equal to the identified value $J$. As it can be observed from Fig. 6, the friction torque is covered by dynamometer. Occasional peaks of the load current are undesirable, showing some unmodelled dynamics in the test bench. In Fig. 7, the emulated inertia was increased to the value of $J_{\text{em}} = 5J$. The load current acts in opposite to the DUT current, and thus acceleration becomes lower, resulting in the longer acceleration and deceleration times in comparison with Fig. 6.

Experimental results of emulation the dynamics of the two-mass system with backlash based on the mathematical model described by eqs. (11)-(16) are shown in Fig. 8 to Fig. 13.
In order to demonstrate the backlash effect, parameters $J_{em}$, $B_{em}$, and $k_S$ were unchanged during experiments and only comparison of three angles of backlash for $\alpha = 15^\circ$, $\alpha = 5$, and $\alpha = 1^\circ$ was obtained. Note that change rate of current for both machines were limited by constant DC link voltage constant of the non-controlled H-bridges. Therefore, current limiters must be set very carefully. In order to make dynamometer's dynamics faster than the DUT, current limit of the DUT was set to $\pm 5$ A and dynamometer current limit was set to $\pm 13$ A.

Now we examine detailed response in Fig. 9. During acceleration within time $0.2 - 0.23$ s; the load torque covers only friction torque, DUT is traversing backlash and no torque should be on the shaft. But an acceleration torque is observed, because DUT is accelerating. Within time $0.23 - 0.26$ s the DUT comes out of the backlash zone, what is emulated by significantly increased load torque. Thus, because of DUT is accelerating to its torque limit, its speed is reduced.
Within the time period of 0.26 – 0.28 s the DUT is again traversing backlash and accelerating. Approximately in 0.28 s DUT starts to decelerate, because it is approaching the reference speed. Once again, in 0.3 s DUT it comes out of the backlash zone, thus its torque gets back to its limit and the speed control is deteriorated.

Experiments in Fig. 10 (detailed in Fig. 11) and Fig. 12 (detailed in Fig. 13) presents the same experiment, but only the backlash coefficients have been changed. It can be observed from the speed responses that actual speed tracks emulated speed with satisfactory precision. Dynamic behaviour of two-mass load with backlash is well emulated, which validates emulation strategy.

Note that the responses are valid only for the type of two-mass system with backlash, presented in Section IV with zero damping coefficients.

VI. CONCLUSION

The paper presents a satisfactory emulation of a certain class of nonlinear load with backlash based on existing DEML control strategy. The experimental results on a test bench with cascade-controlled permanent magnet DC machines supplied by DC-DC converters were compared with the simulation results. These were obtained by simulation of the target system – an ideal model of drive under test. The comparisons have shown promising results. Good agreement between experiments and simulation exists and so the emulation of this class of mechanical load is possible.

Main focus of the paper is not in the field of the DUT speed control design, thus its setting and calculation is not presented here. Obviously, the performance of the DEML algorithm depends on the sampling time of the control loops. Even if it enables a high sampling time of the current loops, performance of the proposed test bench is deteriorated by the use of low-cost encoder with only 1000 impulses per revolution. With the sampling time of 2 ms for the speed control loop, the resolution of the encoder is 7.5 rpm for quadrature encoding. The use of the shorter sampling time for actual speed will increase quantification noise (1ms of sampling time equals 15 rpm resolution) so we do not expect the DEML performance will be increased. To resolve this problem, either sophisticated actual speed processing [19] or the encoder with more impulses per revolution should be used.

The paper novelty lies in the fact that the use of fast current loops widens the control bandwidth of emulator enabling the emulation of the mechanical loads with fast dynamics. The conclusions were also proven by experimentation.

One of the main drawback remains, that validation of the results was done only against a model, which represents a real mechanical load with certain precision only. Our future research will focus on the validation the emulator against real mechanical loads.
ACKNOWLEDGMENT

The work was supported by Slovak Cultural and Educational Agency of the Ministry of Education of Slovak Republic under the contract KEGA 042TUKE-4/2012 “Teaching Innovation in Control of Mechatronic Systems”.

This paper was developed with support of Research and development operating program for the project “University Science Park Technicom for innovative applications with support of knowledge technologies”, code ITMS: 2622020182, cofinanced from European funds.

APPENDIX

TABLE 1. ELECTRICAL MACHINE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DUT</th>
<th>Dynamometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>rated power</td>
<td>250</td>
<td>250 [W]</td>
</tr>
<tr>
<td>rated current</td>
<td>6</td>
<td>6 [A]</td>
</tr>
<tr>
<td>rated speed</td>
<td>4000</td>
<td>4000 [rpm]</td>
</tr>
<tr>
<td>resistance</td>
<td>0.85</td>
<td>0.67 [Ω]</td>
</tr>
<tr>
<td>induction</td>
<td>0.0023</td>
<td>0.002 [H]</td>
</tr>
<tr>
<td>inertia</td>
<td>0.00038</td>
<td>0.00043 [kg.m²]</td>
</tr>
<tr>
<td>viscous friction</td>
<td>0.00093</td>
<td>0.00059 [N.m.s]</td>
</tr>
<tr>
<td>voltage constant</td>
<td>0.0724</td>
<td>0.0728 [Vs/rad]</td>
</tr>
</tbody>
</table>

REFERENCES


