Closing Scientific Report
- for the **NKFIH project** no. PD 128398 -

The mechanical constructions of the test equipment, which were designed and built during a previous grant activity (National Excellence Program of the Ministry of Human Capacities of Hungary under grant no. NTP-NFT-17-B-0498), were available for this research period. For these devices, a printed circuit board was designed. With these electronics, it is possible to handle the signals of two types of encoders that perform the signal conditioning of the TTL signals of the encoders too. The electronics also have an ammeter IC with analog signal output and an operational amplifier-based circuit. Thus, the measured signals are already available for microcontroller-based data acquisition and signal processing resulting in the measured state variables of the experimental setup.

A microcontroller-based measurement software was developed to perform the parameter identification measurements and the control tests. This system is capable of hard real-time signal processing and control (preparing the unit for the later work stage). Moreover, the necessary parameters (e.g., sampling time, control parameters, etc.) can be directly changed during the operation via high-level software implemented in the Simulink Desktop Real-Time environment. The applied Simulink environment avoids the need for instantaneous microcontroller programming during measurements.

Simultaneously with the developments mentioned earlier, using the mathematical model of the experimental device, various simulations were established assuming different friction models, e.g., the Coulomb model or the Stribeck model, etc. Three possible identification methods were carried out by simulation to obtain the mathematical model parameters connected to the experimental device.

These methods were summarized in the paper: *Z. Hajdu, C. Budai: Egyenáramú motorok súrlódási viszonyainak identifikációja (Identification of friction conditions for DC motors) in Proc. of Tavaszi Szél Konferencia, 3-5 May, 2019, Debrecen, Hungary, pp. 56-66. (in Hungarian).*

Based on the investigations, it can be concluded that to perform the parameter identification, it is advisable to examine the accelerating and the decelerating motions at different input voltages. It can also be supposed that it is advisable to perform the deceleration measurements by disconnecting the DC motor from the circuit, thereby avoiding the braking effect of the induced voltage.

In addition to manual parameter tuning, the Parameter Identification Toolbox of Simulink built-in gradient-based identification method was used to evaluate the measurement results and determine the parameters. It is noted that genetic algorithms and swarm-intelligence-based methods were also attempted to use. As a conclusion of the parameter identification, it can be summarized that the primary source of dissipation connected to these devices can be modeled as Coulomb and viscous terms. Dominantly, the viscous damping comes from the back EMF of the DC motor.

A fully automated measurement software has been developed to test the system stability experimentally. At the beginning of each experiment, control gains, sampling time, and initial angular position values were set. The system stability was decided on the basis of the motion induced by the discrete-time controller. A practical solution for finding the stability limit was the multi-dimensional extension of the interval halving algorithm, which made it possible to find the stability limit by performing fewer measurement cycles.

First, the application of a discrete-time proportional controller was studied among fixed initial conditions. With this parallel, simultaneous numerical simulation was made on the mathematical model of the already described measurement equipment. If the experimental data and the simulation results are compared, it can be concluded that the measured and simulated curves overlap well. Thus, the stabilizing effect of dry friction and the sensitivity of the system to the initial angular deviation - as an initial condition - were validated experimentally.

These results were presented in the following conference: *T. Haba, C. Budai: Stability analysis of sampled-data nonlinear systems In proc.: 28th International Conference on Mechanical Engineering (OGÉT 2020), April 25, 2020, Online, pp. 301-304 (in Hungarian).*

It is noted that further experimental studies on system stability were also carried out using different controllers. The effect of the additional virtual damping or integral term on system stability was examined.

Simultaneously with the experimental study, an analysis of the fundamental effects of dissipation mechanisms on the controlled and uncontrolled systems was carried out. Thus, the investigated systems generally have either real or virtual stiffness. The study aims to get a possible classification of the dissipative effects based on the dynamic response characteristics. These response properties can have various practical applications, determining the dominant dissipation sources in mechatronic systems.

These results were summarized in the following conference abstract: *C. Budai, J. Kovecses and G. Stepan: Dissipation Effects in Mechanical Systems, 10th European Nonlinear Dynamics Conference (ENOC 2020), July 5-10, 2020, Lyon, France (Due to the COVID-19 pandemic, the conference is postponed to 11-16 July 2021 first, and later to 17-22 July 2022)*

The previously presented results highlighted some interesting non-trivial characteristics that enter when an otherwise unstable system is stabilized by the dissipative effects resulting in the so-called concave amplitude decay. The mentioned instability due to sampling can be modeled as a negative effective viscous damping. This kind of effective negative damping is also included in the Stribeck friction model.

Thus, extended the research connected to the so-called concave envelope vibrations that form the initial idea of the research. An oscillator was analyzed where the moving body is in frictional contact with two rough surfaces moving with different velocities. This system models the stick-slip phenomenon in the presence of other bodies in connection. Because of the combined effects of the effective negative damping of the Stribeck force at one of the contacts and the frictional damping of another contact, the system exhibits various oscillations. It is shown that the stable oscillations decay with a concave envelope, which behavior was previously found in digital position control problems, too.

These results were presented in the following conference: *C. Budai, M. Antali and G. Stepan: Analysis of a friction oscillator with two frictional contacts, Second International Nonlinear Dynamics Conference (NODYCON 2021) on February 16-19, 2021 (online).*

Based on the results obtained by the analysis of the previously mentioned extended model of the stick-slip oscillator, the model of the sampled-data sliding oscillator was further investigated. For the study of the sampled-data system with dry friction, an effective continuous-time model was derived. It is shown that in these systems, the destabilizing effect of sampling can still be compensated to some extent by the presence of dry friction resulted in an unstable limit cycle. The domain of attraction of the zero reference position as the fixed point was determined in the case when initial velocity is also taken into account.

These results were summarized in the following conference abstract: *C. Budai: On the stability of sampled-data systems with dry friction, 16th International Conference "Dynamical Systems – Theory and Applications" (DSTA 2021), December 6-9, 2021 (online).*

In this research period, the model of the sampled-data sliding oscillator was extended with virtual damping. It was demonstrated that even a single degrees-of-freedom mechanical system could have multi-frequency vibrations when a discrete-time controller positions it. The higher harmonics can explain the observed oscillations, which correspond to the periodicity of the eigenvalues of the transition matrix. It was also shown when the effect of dry friction is also taken into account, position-controlled systems with state-feedback can become sensitive to the initial conditions, and limit cycles develop around the desired position.

These results were presented during the First International Nonlinear Dynamics Conference (NODYCON) on February 17-20, 2019, Rome, Italy (*C. Budai, L. L. Kovács. J. Kövecses and G. Stépán: Combined Effect of Sampling and Dry Friction on Positioning. In: NODYCON Book of abstracts, pp. 53-54, 2019*). Furthermore, these results were published in the journal paper: *C. Budai, L. L. Kovács. J. Kövecses and G. Stépán: Combined effects of sampling and dry friction on position control, Nonlinear Dynamics, 98(1), pp. 3001-3007, 2019.*

As it was highlighted, even a single degrees-of-freedom system could have unexpected multi-frequency vibrations due to the periodicity of the characteristic multipliers. But, for a deeper understanding, the phenomenon of multi-frequency vibrations has been further investigated. In summary, in the case where the characteristic multipliers are positive real numbers or complex conjugate pairs with positive real-part, the higher harmonics become omitted. In all other cases, they must be taken into account. In addition, it can be formulated as a condition for deciding whether it is necessary to consider higher harmonics.

These results were published in the journal paper: *C. Budai: Vibrations in single-degrees-of-freedom sampled-data linear mechanical systems, Periodica Polytechnica Mechanical Engineering, 2021 (Status: Accepted).*

It is noted that it has been shown experimentally that multi-frequency vibrations are generated in systems in which, in addition to the virtual stiffness created by the discrete ideal controller, there is also physical (viscous) damping.