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# DEVELOPMENT AND SIMULATION OF A DYNAMIC MODEL OF A MINI MILLING CENTER USING MATLAB-SIMULINK

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***Abstract:*** *This paper presents a dynamic, axis-level model of a mini milling center implemented in MATLAB/Simulink with Simscape. Each translational axis is modeled as a closed-loop electromechanical drive—motor, coupling, ball-screw, sled, and encoder—regulated by a PID controller. The primary aim is a realistic virtual-commissioning model for controller tuning and scenario testing prior to hardware deployment, rather than a full process-level digital twin. The model captures the dominant electromechanical dynamics and allows disturbance injection via cutting forces. The axes are also represented as a 3D multibody assembly. Several operating modes are simulated to assess positioning accuracy and closed-loop stability. Results indicate that the approach is effective for controller adjustment and virtual testing of control algorithms, supporting open-architecture mini-mill solutions for education, prototyping, and applied research.*

***Key words:*** *Dynamic model, milling equipment, Matlab, Simulink, Digital Twin*

## 1. INTRODUCTION

The development and simulation of a dynamic model of a mini milling center using MATLAB/Simulink serves an important purpose in the analysis and optimization of machining processes [1], [9], [10].

Milling is a very sophisticated machining operation which uses a rotary tool that cuts intermittently. This leads to chip loads and chip thickness which are variable and pose a consideration to the efficiency of the milling operation in terms of its stability and accuracy [2], [4].

It is important to understand the dynamic behavior of the milling center to predict and optimize problems like chatter, tool wear, and degradation of surface finish quality so that the overall efficiency and quality in the machined parts is improved [1], [10], [13].

Without going through a lengthy physical experimentation process, dynamic modeling enables an analysis of how certain parameters like cutting speeds, feed rates, and tool shapes change the course of the machining operations, therefore, saving time and resources [3], [14]. This model allows for examining myriad design specifications, operational conditions, and control variables, thus, making optimal decisions regarding machining strategies [5], [6], [7].

Industries such as aerospace, automotive, and medical devices require dynamic models that are reliable and robust due to an increase in demand for high-efficiency and high-precision machining.

Detailed models of the parts of the milling center and their relations can be built using a powerful simulation tool like MATLAB/Simulink, which allows one to capture the machining processes dynamics intricately [8], [11], [12].

In addition, dynamic models serve as the basis for closed-loop control implementation, whether PID or model-based, allowing for real-time position adjustments and compensating for disturbance factors like cutting forces or backlash.

Integration of the control methods with the simulation framework allows evaluation of the system stability response for different control methods and loading conditions [15].

While simulating multi-axis systems such as the CNC milling machine's three translational axes, it becomes important to add accurate models of the motor elements, transmission systems (like ball screws and couplings), and structural compliance.

The prediction of cross-axis interactions, positioning errors, and vibration modes that are crucial if one is to achieve micron-level precision becomes easier with these details [2], [4], [8].

Preventing self-excited vibrations has been shown to be highly efficient with online and AI-based methods, as self-excitation phenomena, chatter detection, and stability analysis are core [1], [4], [5]. Also, deep learning techniques for predictive modeling of tool wear enhances virtual commissioning and adaptive cutting [3], [6], [7].

The development and validation of dynamic models of mini milling centers using MATLAB/Simulink propels adaptive and digitally integrated manufacturing systems towards more intelligent levels [1], [8], [9]. Models contribute in more ways than just aiding in machine design and virtual commissioning in the context of Industry 4.0.

They also assist in training, diagnostics, and performance monitoring which broadens their utility in adaptive multifunctional systems [6], [8].

## 2. DYNAMIC MODEL

### 2.1 Description of the System

The mini milling center consists of three translational axes (X, Y, Z), each driven by a DC motor coupled through an elastic coupling to a ball screw transmission. A rotary incremental encoder provides positional feedback. The ball screw has a lead (pitch) of 10 mm/revolution, with a maximum travel of 110 mm per axis.

The primary dynamic components for modeling each axis include:

- DC motor dynamics;
- Elastic coupling dynamics;
- Ball screw transmission which converts the rotational motion into a linear motion;
- Sled dynamics (linear inertia, friction, damping);

Assumptions for the mathematical modeling:

- System parameters are constant;
- Friction is approximated as viscous (linear) friction;
- Elastic coupling is modeled as a torsional spring-damper;
- The ball screw transmission is assumed to be rigid except for the elastic coupling.

### 2.2. Dynamic Mathematical Model

The mathematical model for the DC Motor electrical part is:

$$\boldsymbol{V(t) = R \cdot i(t) + L \cdot \frac{di(t)}{dt} + ke \cdot \omega m(t)} \quad (1)$$

The mathematical model for the DC Motor mechanical part is:

$$\boldsymbol{Jm \cdot \frac{d\omega m(t)}{dt} = kt \cdot i(t) - Tload(t) - bm \cdot \omega m(t)} \quad (2)$$

The mechanical equation for ball screw shaft is presented in eq. 3:

$$Js \cdot \frac{d\omega s(t)}{dt} = kc \cdot \big(\theta m(t) - \theta s(t)\big) + bc \cdot \big(\omega m(t) - \omega s(t)\big) - \left(\frac{p}{2\pi}\right) \cdot Fs(t) \quad (3)$$

Elastic coupling mathematical model:

$$Tload(t) = kc \cdot [\theta m(t) - \theta s(t)] + bc \cdot [\omega m(t) - \omega s(t)] \quad (4)$$

The ball screw transmission can be represented as a conversion from rotational to linear motion:

$$x(t) = \left(\frac{p}{2\pi}\right) \cdot \theta s(t)$$
$$v(t) = \left(\frac{p}{2\pi}\right) \cdot \omega s(t) \quad (5)$$

The sled dynamics, the moving mass in linear motion, is expressed by eq. 6.

$$m \cdot \frac{d^2x(t)}{dt^2} = Fs(t) - bl \cdot \frac{dx(t)}{dt}$$
$$Fs(t) = \left(\frac{2\pi}{p}\right) \cdot Ts(t) \quad (6)$$

The complete dynamic model for the linear motion of the sled is expressed as eq. 7.

$$m \cdot \frac{d^2x(t)}{dt^2} = \left(\frac{2\pi}{p}\right) \cdot \left[kc \cdot \left(\theta m(t) - \theta s(t)\right) + bc \cdot \left(\omega m(t) - \omega s(t)\right)\right] - bl \cdot \frac{dx(t)}{dt} \quad (7)$$

The incremental encoder model for position feedback is as follows:

$$x_{enc(t)} = x(t) + e(t) \quad (8)$$

The complete mathematical model of the DC motor's mechanical part is:

$$Jm \cdot \frac{d\omega m(t)}{dt} = kt \cdot i(t) - kc \cdot \left(\theta m(t) - \theta s(t)\right) - bc \cdot \left(\omega m(t) - \omega s(t)\right) - bm \cdot \omega m(t) \quad (9)$$

The final kinematic equation for the ballscrew transmission is:

$$x(t) = \left(\frac{p}{2\pi}\right) \cdot \theta s(t) \quad (10)$$

Considering the technological force, the updated linear dynamic equation becomes:

$$m \cdot \frac{d^2x(t)}{dt^2} = \left(\frac{2\pi}{p}\right) \cdot \left[kc \cdot \left(\theta m(t) - \theta s(t)\right) + bc \cdot \left(\omega m(t) - \omega s(t)\right)\right] - bl \cdot \frac{dx(t)}{dt} - Ft(t) \quad (11)$$

## 2.3 Implementation in MATLAB/Simulink

This dynamic mathematical model can be directly translated into a MATLAB/Simulink simulation by using appropriate blocks such as Embedded Matlab function.

In Figure 1 the block diagram of the dynamic model for a linear kinematic axis is presented.

The two Signal Builder blocks are used to generate the trapezoidal velocity profile for the sled's translational motion and to introduce the technological resistance force that occurs during movement. The corresponding plots are shown in the figures below.

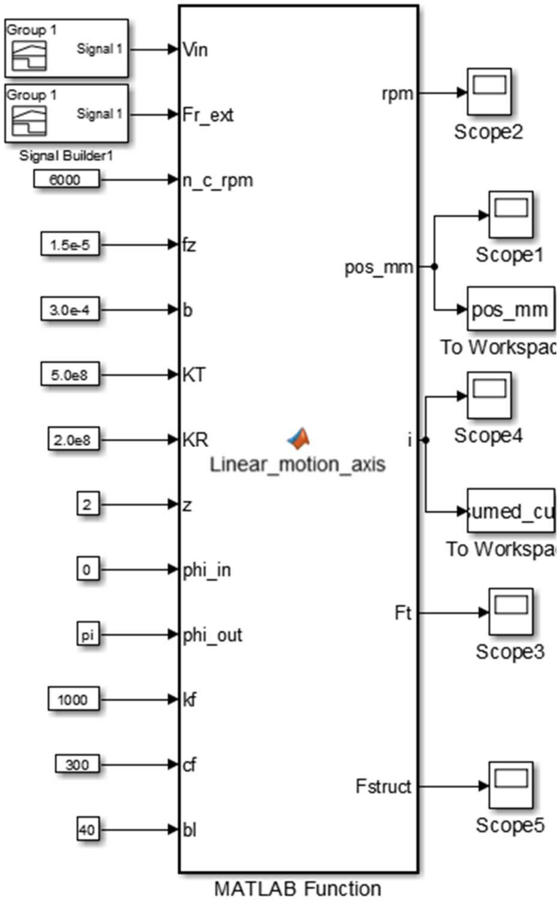

**Fig. 1.** Simulink block diagram used to implement the dynamic model equations.

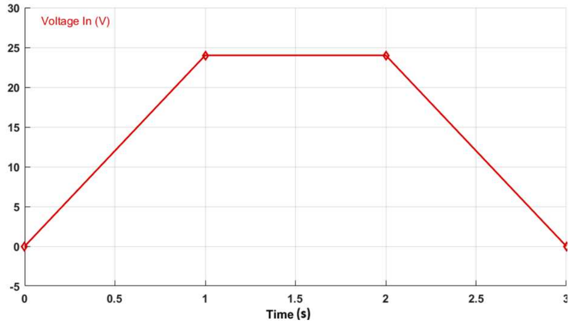

**Fig. 2.** Input Voltage profile

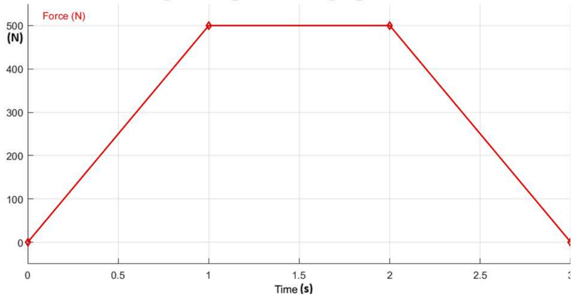

**Fig. 3.** Input technological force

The simulation was carried out using the data provided by the manufacturer for the Dunkermotoren GR63x25 DC motor. The characteristics of this motor are presented below in Table 1.

*Table 1*

| Parameter | Symbol / Unit | Value |
|---|---|---|
| Nominal voltage | VDC | 24 V |
| Nominal current | A | 2.7 A |
| Nominal torque | Nm | 0.14 Nm |
| Nominal speed | rpm | 3300 rpm |
| Stall torque | Nm | 1.08 Nm |
| Maximum torque | Nm | 1.08 Nm |
| No-load speed | rpm | 3600 rpm |
| Nominal output power | W | 48.4 W |
| Maximum output power | W | 101.8 W |
| Torque constant | Nm/A | 0.06 Nm/A |
| Terminal resistance | Ω | 1.33 Ω |
| Terminal inductance | mH | 2.9 mH |
| Starting current | A | 18 A |
| No-load current | A | 0.36 A |
| Demagnetization current | A | ≥ 24 A |
| Rotor inertia | g·cm² | 400 g·cm² |
| Weight of motor | kg | 1.2 kg |

Results obtained after running the dynamic model simulation are presented below.

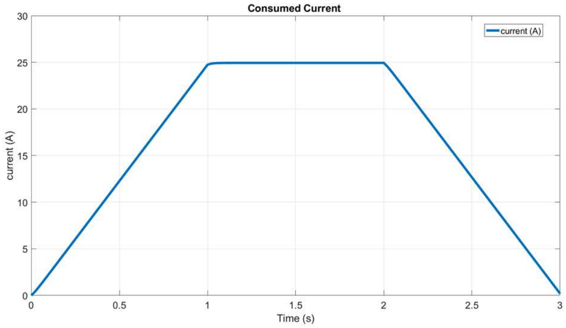

**Fig. 4.** Consumed Current (A)

## 2.4. Dynamic Simscape Model

To validate the mathematical equations a block diagram was realized in Simulink Simscape.

In the figure 5 below the Simscape-Multybody is presented.

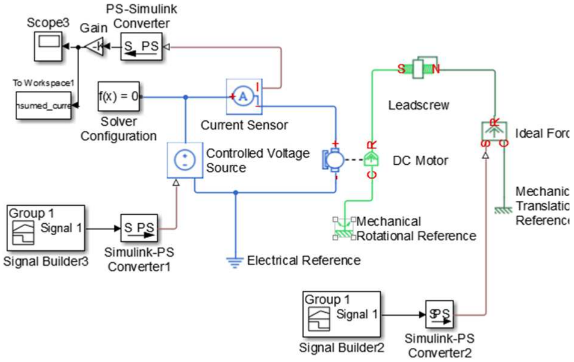

**Fig. 5.** Block diagram in Simulink Simscape used for dynamic model validation

## 2.5 Cutting Force & Regenerative Effects

We complement the baseline where the technological force *Ft*(*t*) acts as a disturbance by computing *Ft* mechanistically. For a slotting cut with axial depth *b* and feed per tooth *fz*, the tooth-level force components are commonly expressed as:

$$F_{T(\varphi,t)} = K_T \cdot b \cdot h(\varphi,t), \quad F_{R(\varphi,t)} = K_R \cdot b \cdot h(\varphi,t) \qquad (12)$$

where $K_T$ and $K_R$ are material- and tool-dependent coefficients, $\varphi$ is the instantaneous immersion angle, and *h(φ,t)* is the uncut chip thickness. The resultant projected along the axis gives *Ft*(*t*) used in the axis dynamics.

Dynamic chip thickness with regeneration closes the loop between deflection and force:

$$h(\varphi,t) = f_z \cdot \sin\varphi + [\,x(t) - x(t-T)] \cdot \sin\varphi \qquad (13)$$

with $T = 2\pi / \Omega c$, where *Ωc* is the cutter angular speed. Substituting this *Ft*(*t*) into the axis equation enables stability (chatter) and surface-quality studies at the axis level.

## 2.6 Structural Compliance

To relax the rigid-frame assumption, augment the slide DOF with a parallel spring–damper (*kf*, *cf*) capturing the dominant structural mode along the axis:

$$m \cdot \ddot{x}(t) + \left(b_l + c_f\right) \cdot \dot{x}(t) + k_f \cdot x(t) = \left(\frac{2\pi}{p}\right) \cdot \left[\,k_{c(\theta_m - \theta_s)} + b_{c(\omega_m - \omega_s)}\right] - Ft(t). \qquad (14)$$

This lumped representation recovers the principal resonance that constrains servo tuning and disturbance rejection on mini mills.

## 3. PID INTEGRATION

The integration of a PID controller into the system's dynamic response is shown in Figure 6.

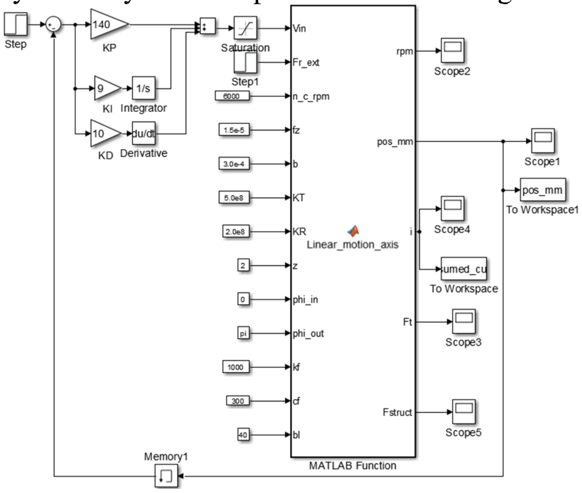

**Fig. 6.** PID integration into the dynamic response of the system

The response of the system with the calibrated KP=140, KI=9, KD=10 is presented in Figure 7.

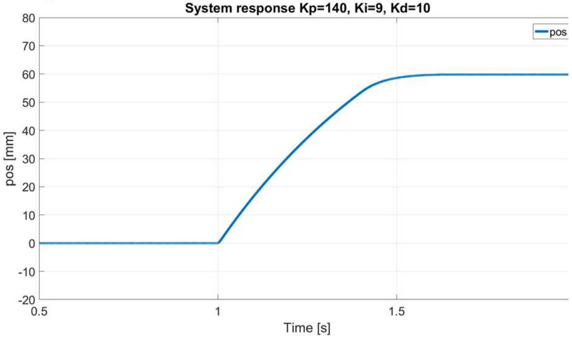

**Fig. 7.** Step response of the System

## 4. CONCLUSIONS

This work presented a dynamic, axis-level model of a mini milling center implemented in MATLAB/Simulink with Simscape. Each translational axis was modeled as a closed-loop electromechanical drive (DC motor–coupling–ball screw–sled–encoder) regulated by a PID controller. The simulations showed accurate positioning and well-damped responses over representative operating modes, indicating that the model is effective as a **virtual-commissioning** environment for controller tuning and scenario testing prior to hardware deployment.

We also outline modular upgrades that increase fidelity and keep the workflow reproducible: a mechanistic cutting-force module with regenerative effects for basic chatter/stability studies, and a lumped structural-compliance element to capture the dominant frame mode. These additions, together with the PID design notes, make the framework useful for education, prototyping, and open-architecture research on mini mills.

**Limitations and future work.** The present baseline treats cutting force as an external disturbance and assumes a rigid frame; therefore, it cannot predict chatter or surface finish without the proposed extensions. Future work will focus on parameter identification and experimental validation on a physical mini mill, implementation and testing of the mechanistic force/regeneration and compliance modules, and—separately—evaluating actuator variants (e.g., stepper/BLDC) on the same mechanical load.

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## Dezvoltarea și simularea unui model dinamic al unui centru de frezare miniaturizat utilizând Matlab-Simulink

Această lucrare prezintă etapele parcurse în procesul de dezvoltare a unui model virtual dinamic pentru axele cinematice ale unui centru de frezare miniaturizat. Pentru atingerea acestui obiectiv, a fost utilizat mediul de lucru matlab/simulink și biblioteca simscape. Scopul principal este realizarea unui model realist al centrului de frezare miniaturizat – un digital twin – care să permită analiza comportamentului dinamic al sistemului de frezare încă din faza de proiectare, înainte de implementarea fizică. Fiecare axă cinematică a fost modelată tridimensional și este prezentată ca un sistem de acționare în buclă închisă, compus dintr-un motor electric de curent continuu, un mecanism de transmisie cu șurub cu bile și un encoder incremental montat pe axul motorului. Modelarea a fost realizată în simscape, pentru a evidenția fenomenele fizice implicate, iar comanda mișcării a fost implementată printr-un regulator pid. Au fost simulate diferite regimuri de funcționare relevante. Analizele s-au concentrat pe precizia de poziționare și stabilitatea sistemului. Rezultatele confirmă că metoda propusă este eficientă și oferă un instrument util pentru reglarea controlerelor și testarea virtuală a algoritmilor de comandă. Lucrarea contribuie la dezvoltarea de soluții flexibile pentru echipamente de frezare cu arhitectură deschisă, adresând nevoile din domeniul educației, prototipării și cercetării aplicate.

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