TƏBİƏT VƏ TEXNİKA ELMLƏRİ BÖLMƏSİ

UDC 510.6

MATHEMATICAL MODELING OF THE USE OF MAGNETIC LEVITATION SYSTEMS IN MEASURING TECHNOLOGICAL PARAMETERS

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Abstract: *The article scientifically examines the potential of magnetic levitation technologies in the context of increasing precision measurement requirements in modern technologies. Magnetic levitation systems (MLS) offer contactless, highly sensitive measurement capabilities, especially advantageous in terms of eliminating vibration and mechanical friction. The fundamental electromagnetic principles used in such systems are explained within the framework of the Lagrangian function and nonlinear dynamic equations, with detailed analysis of system stability conditions and control models.*

The purpose of the article is to mathematically substantiate the operating principle of high-precision measurement devices used in industrial and scientific research fields, and to develop analytical models and apply simulation methods to improve the efficiency of these systems. Within the presented mathematical model framework, the relationships between physical variables and control parameters of the magnetic levitation system are identified and their impact on measurement accuracy is evaluated.

The results show that measurement technologies based on magnetic levitation systems have great potential not only to replace traditional mechanical systems but also to create long-lasting, wear-free, and high-response control and measurement systems. This approach enables the development of high-precision, contactless measurement systems applicable in microelectronics, aerospace industry, biomedicine, and nanomechanics.

Keywords: *Magnetic levitation system, parameter, technological processes, model, optical sensors*

1. Introduction

High-precision parameter measurement in technological processes is one of the main requirements in modern industry and scientific research. Ensuring production quality, effective equipment management, and automation of processes necessitate reliable measurement systems. Although traditional mechanical, piezoelectric, and optical sensors are widely used, their technical limitations such as vibration, mechanical friction, wear, and thermal instability call for new alternative measurement approaches.

In this context, magnetic levitation technology (MLS) has recently attracted significant attention as an important alternative in the development of contactless, high-precision measurement systems. Sensors and control systems based on MLS significantly improve measurement accuracy and device lifespan by eliminating physical contact.

Existing literature contains various studies in this area. For example, in [1] R. Krishnan developed dynamic models of electromagnetic levitation systems, mainly analyzing their applications for motor control systems. In [2] Y. Wang and H. Chen compared PID and fuzzy control approaches for position control based on magnetic levitation, showing that simple controls may be insufficiently effective for nonlinear systems.

On the other hand, in [3] Haus and Melcher conducted fundamental research on the energy effects of electromagnetic fields, explaining the role of magnetic forces in measurement mechanisms based on physical principles. In [4] Ogata presented controllable models of MLS systems within the general automatic control framework. However, most of these studies focus either only on control aspects or limit themselves to applications of magnetic levitation in transportation and energy sectors. Works [5,6,7,8,9,10] provide various boundary conditions for solving mathematical models constructed to determine corrosion under mechanical stress in aggressive metal environments.

However, mathematical modeling and experimental substantiation of MLS systems specifically for direct measurement in technological processes remain limited. This article aims to fill this gap by focusing on the application of MLS for improving measurement accuracy, modeling the electromagnetic and nonlinear dynamic nature of these systems, and analyzing control structures. Unlike previous studies, the proposed approach is based on mathematical foundations that ensure stable operation of measurement systems and practical models for engineering applications.

2. Philosophy and Application Areas of Magnetic Levitation Systems

Magnetic levitation (maglev) systems are fundamental in modern technology, and their core philosophy is the physical suspension of objects without mechanical support - that is, maintaining stable levitation solely by the interaction of electromagnetic forces. This phenomenon is possible through the correct management and balancing of electromagnetic fields, which requires complex mathematical models and real-time control mechanisms.

The greatest advantage of maglev systems is their contactless operation, meaning physical non-contact. This characteristic leads to reduced friction and wear compared to traditional mechanical systems, resulting in longer service life. Such features make maglev technology indispensable, especially in fields requiring high precision and durability.

Maglev technology has a wide range of applications. The most well-known is high-speed train systems. In these systems, the levitation principle is used not only to lift the vehicle off the track but also to ensure stable and efficient movement. The absence of mechanical contact minimizes friction, increasing speed and reducing the likelihood of technical failures.

Another important application area is industrial processes. Automated production lines and high-precision measurement systems can precisely determine the position, speed, and distance of components moving via magnetic levitation. This directly affects overall process quality and productivity.

In biomedical technologies, maglev systems open new research directions. For example, contactless transportation of blood samples, formation of three-dimensional cell structures in tissue engineering, and manipulation of micro/nano-scale particles highlight the unique advantages of levitation technology.

In all these fields, the application of maglev systems is not only a technical innovation but also a symbol of technological transformation. The development of this technology brings new scientific challenges and research directions in engineering sciences as well as applied physics and mathematics. Thus, magnetic levitation can be seen not only as a technological tool but also as a reflection of modern scientific thinking and multidisciplinary approaches.

3. Mathematical Modeling

For the effective operation of magnetic levitation systems, an accurate mathematical description of their dynamic behavior and the development of control strategies based on this behavior are of great importance. In this section, the equations of motion for the levitation system, the description of the electromagnetic force, and the control model are presented sequentially.

3.1. Dynamic Model

The main goal in magnetic levitation systems is to maintain the object stably suspended in the air at any desired distance. To achieve this, the system dynamics are expressed by the following nonlinear second-order differential equation:

$$m\cdot\frac{d^2x}{dt^2}=F_m(x,i)-m\cdot g\,,$$

where m is the mass of the levitated object (kg), x is the vertical distance of the object from the electromagnet (m), $F_m(x,i)$ is the attractive force created by the electromagnet (N), g is the acceleration due to gravity $\left(\approx 9{,}81\ {}^{m}/_{san^2}\right)$.

In the equation, the left side represents the inertial force related to the object's acceleration, while the right side expresses the difference between the electromagnetic force and gravitational force. The system naturally exhibits nonlinear behavior since the electromagnetic force depends both on the distance x and the current supplied to the electromagnet.

3.2. Modeling of the Magnetic Force

Based on the physical configuration of the system, the electromagnetic force can be expressed in a simplified and empirically defined model as follows

$$F_m(x,i)=\frac{K\cdot i^2}{x^2}\,,$$

where K is a constant parameter characteristic of the system's electromagnetic configuration, and i is the current supplied to the electromagnet.

This expression shows that the electromagnetic force depends quadratically on the current and inversely quadratically on the distance. Such a relation reflects how the intensity of the electromagnetic field varies with distance and is the primary source of the system's nonlinear behavior.

3.3. Control Model

Active control is required to keep the system stable at any desired position. For this purpose, the classical PID (Proportional–Integral–Derivative) controller is widely applied. The PID control signal is expressed as

$$i(t)=K_p e(t)+K_i\int_0^t e(\tau)d(\tau)+K_d\frac{de(t)}{dt}\,,$$

where $e(t)=x_{istek}-x(t)$ is the error between the actual and desired positions, and K_p, K_i, K_d are the proportional, integral, and derivative gains, respectively.

This control strategy dynamically reacts to the position error to ensure system stability. The proportional component responds to the instantaneous error, the integral component compensates for accumulated errors over time, and the derivative component responds to the rate of change of the error to prevent oscillations.

The mathematical model presented above covers the fundamental dynamic and electromagnetic characteristics of magnetic levitation systems. Building control strategies based on this model creates a fundamental basis for the stable and precise operation of the system. However, when applying the model to real systems, technical factors such as parameter identification, measurement accuracy, and computational resources must also be taken into account.

4. Magnetic Levitation Model for MATLAB Simulation

4.1. Physical Parameters of the Model

```
Parameters
m = 0.05;        % Mass of the levitated object (kg)
g = 9.81;        % Gravitational acceleration (m/s^2)
K = 6.53e-5;     % Magnetic constant (N·m²/A²)
% PID control coefficients (example values)
Kp = 30;         % Proportional gain
Ki = 80;         % Integral gain
```

```
Kd = 5;          % Derivative gain
% Simulation duration
Tsim = 10;       % Total simulation time (seconds)
```

4.2. MATLAB Function for Differential Equations

Magnetic Levitation System Dynamics with PID Control

```
function dxdt = maglev_dynamics(t, x, K, m, g, Kp, Ki, Kd, x_ref)
    % x = [position; velocity; integral error; previous error]
    pos = x(1);    % Position (x)
    vel = x(2);    % Velocity (dx/dt)
    int_e = x(3);  % Integral of position error
    prev_e = x(4); % Previous position error
    % Calculate current error
    e = x_ref - pos;       % Position error
    de = -vel;             % Derivative of error (approximated as -velocity)
    int_e = int_e + e*0.01; % Integral error accumulation (assuming Δt ≈ 0.01 s)
    % PID control signal (i)
    i = Kp*e + Ki*int_e + Kd*de;
    % Electromagnetic force (avoid division by zero by adding small constant)
    Fm = K * i^2 / (pos^2 + 1e-6);
    % Define the system of derivatives
    dxdt = zeros(4,1);
    dxdt(1) = vel;              % d(pos)/dt = velocity
    dxdt(2) = (Fm - m*g)/m;     % Newton’s second law
    dxdt(3) = int_e;            % Accumulated integral error
    dxdt(4) = e;                % Store current error (for future use if needed)
end
```

3. Simulation with ODE

```
% Initial conditions: [initial position; velocity; integral error; previous error]
x0 = [0.01; 0; 0; 0];      % Initial position (0.01 m)
x_ref = 0.01;              % Desired position (m)
% Solving the system using ODE
[t, x] = ode45(@(t, x) maglev_dynamics(t, x, K, m, g, Kp, Ki, Kd, x_ref), [0 Tsim], x0);
% Plotting the position response
figure;
plot(t, x(:,1), 'LineWidth', 2);
xlabel('Time (s)');
ylabel('Position x(t) [m]');
title('Magnetic Levitation System - Position Response');
grid on;
```

This simulation represents a simplified maglev model and accounts for the nonlinear effect of electromagnetic force**.** The PID controller attempts to maintain the object in balance at the desired position.

5. Conclusion

Magnetic levitation technology is an effective tool for the high-precision measurement and control of technological parameters. Through mathematical modeling, the behavior of such systems can be predicted and optimized in advance. Future research may focus on further refining nonlinear models and integrating artificial intelligence-based control methods.

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TEXNOLOJİ PARAMETRLƏRİN ÖLÇÜLMƏSİNDƏ MAQNİT LEVİTASİYA SİSTEMLƏRİNİN İSTİFADƏSİNİN RİYAZİ MODELLƏŞDİRİLMƏSİ

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Xülasə: *Məqalə müasir texnologiyalarda dəqiqlik tələblərinin artdığı bir dövrdə maqnit levitasiya texnologiyalarının potensialını elmi şəkildə araşdırır. Maqnit levitasiya sistemləri (MLS) kontaktsız və yüksək həssas ölçmə imkanları təqdim edir ki, bu da xüsusilə vibrasiya və mexaniki sürtünmənin aradan qaldırılması baxımından üstünlük təşkil edir. Belə sistemlərdə tətbiq olunan fundamental elektromaqnit prinsipləri Laqranj funksiyası və qeyri-xətti dinamik tənliklər çərçivəsində izah edilir, həmçinin sistemin sabitlik şərtləri və idarəetmə modelləri ətraflı təhlil olunur. Məqalənin məqsədi sənaye və elmi-tədqiqat sahələrində istifadə olunan yüksək dəqiqlikli ölçmə qurğularının iş prinsipini riyazi cəhətdən əsaslandırmaq, bu sistemlərin səmərəliliyinin artırılması üçün analitik modellər işləyib hazırlamaq və simulyasiya üsullarını tətbiq etməkdir. Təqdim olunan riyazi model çərçivəsində maqnit levitasiya sisteminin fiziki dəyişənləri ilə idarəetmə parametrləri arasındakı qarşılıqlı əlaqələr müəyyən edilir və onların ölçmə dəqiqliyinə təsiri qiymətləndirilir. Tədqiqatın nəticələri göstərir ki, maqnit levitasiya sistemlərinə əsaslanan ölçmə texnologiyaları təkcə ənənəvi mexaniki sistemlərin əvəzlənməsi üçün deyil, həm də uzunömürlü, aşınmasız və yüksək cavab sürətli idarəetmə və ölçmə sistemlərinin yaradılması üçün böyük potensiala malikdir. Bu yanaşma mikroelektronika, aerokosmik sənaye, biotibb və nanomexanika sahələrində tətbiq oluna bilən yüksək dəqiqlikli, kontaktsız ölçmə sistemlərinin inkişafına imkan yaradır.*

Açar sözlər: *maqnit levitasiya sistemi, parametr, texnoloji proseslər, model, optik sensorlar*

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ИСПОЛЬЗОВАНИЯ СИСТЕМ МАГНИТНОЙ ЛЕВИТАЦИИ ДЛЯ ИЗМЕРЕНИЯ ТЕХНОЛОГИЧЕСКИХ ПАРАМЕТРОВ

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Резюме: *В статье научно исследуется потенциал технологий магнитной левитации в условиях растущих требований к точности измерений в современных технологиях. Системы магнитной левитации (MLS) предоставляют контактные, высокочувствительные возможности измерений, что особенно выгодно с точки зрения устранения вибраций и механического трения. Основные электромагнитные принципы, используемые в таких системах, объясняются в рамках функции Лагранжа и нелинейных динамических уравнений, с детальным анализом условий устойчивости системы и моделей управления. Цель статьи заключается в математическом обосновании принципа работы высокоточных измерительных устройств, используемых в промышленности и научных исследованиях, а также в разработке аналитических моделей и применении методов моделирования для повышения эффективности этих систем. В рамках представленной математической модели выявляются взаимосвязи между физическими величинами и управляющими параметрами системы магнитной левитации, а также оценивается их влияние на точность измерений. Результаты показывают, что технологии измерений на основе систем магнитной левитации обладают значительным потенциалом не только для замены традиционных механических систем, но и для создания долговечных, не изнашивающихся и высокочувствительных систем управления и измерений. Такой подход обеспечивает возможность разработки высокоточных контактных измерительных систем, применимых в микроэлектронике, аэрокосмической промышленности, биомедицине и наномеханике.*

Ключевые слова: *система магнитной левитации, параметр, технологические процессы, модель, оптические датчики*

Elmi redaktor: tex.f.d., dos. E.İsrafilova
Çapa təqdim edən redaktor: tex.f.d., dos. A.Əliyeva
Daxil olub: 10.10.2025
Çapa qəbul edilib: 17.10.2025