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Dynamic performance enhancement of an electro-pneumatic clutch actuator using MATLAB-based modeling and advanced control strategies

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Abstract. Problem. *Electro-pneumatic clutch actuators used in automated transmission systems operate under nonlinear conditions and varying external loads, which complicates the design of stable and accurate control systems. Classical PID controllers often demonstrate limited robustness under actuator saturation and parameter variations.* ***Goal***. *The purpose of this work is to improve the dynamic performance of an electro-pneumatic clutch actuator and to perform a comparative analysis of different control strategies under identical simulation conditions.* ***Methodology***. *A simplified second-order dynamic model of the electro-pneumatic actuator was developed in MATLAB. The model includes equivalent mass, damping, clutch spring stiffness, actuator saturation, velocity constraints, and external disturbance loading. Three control strategies were investigated: classical PID control, adaptive gain-scheduling control, and a simplified fuzzy-based nonlinear controller.* ***Results***. *The obtained simulation results demonstrate that the adaptive controller provides the best overall dynamic performance in terms of settling time and tracking accuracy. The fuzzy-based controller ensures smoother transient behavior and reduced oscillatory response near the target position. Quantitative comparison of overshoot and RMS tracking error confirms the effectiveness of adaptive and nonlinear control approaches for electro-pneumatic clutch systems.* ***Originality***. *The originality of the proposed approach lies in the development of a unified simulation framework that allows comparative evaluation of several control strategies under identical actuator constraints and disturbance conditions.* ***Practical value***. *The developed simulation model and control approaches may be used for further optimization of automated clutch control systems in automotive transmission applications, particularly for improving shift quality, reducing mechanical wear, and increasing actuator stability under varying operating conditions.*

Keywords: *electro-pneumatic actuator, clutch control, adaptive control, PID controller, fuzzy control, MATLAB, transmission systems.*

Introduction and Analysis of publications

Electro-pneumatic actuators are widely used in automated clutch control systems of modern vehicles due to their relatively simple design, fast response, and compatibility with electronic transmission control units [1], [2]. Such systems are commonly applied in automated manual transmissions of commercial vehicles, buses, and specialized transport equipment, where reliable clutch engagement directly affects transmission durability and driving comfort.

The dynamic performance of the clutch actuator significantly influences gear shifting quality and the overall stability of the drivetrain. Excessive oscillations, delayed response, or inaccurate clutch positioning may lead to increased mechanical wear, deterioration of shift smoothness, and reduced transmission efficiency. Therefore, modern transmission control systems require actuator controllers capable of maintaining stable operation under varying load conditions and external disturbances.

At the same time, electro-pneumatic systems are characterized by significant nonlinear behavior caused by air compressibility, friction effects, valve dynamics, and pressure fluctuations. These

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factors complicate the development of stable control algorithms, especially under variable operating conditions and transient processes during clutch engagement.

Classical PID controllers remain widely applied in industrial actuator systems because of their simple implementation and low computational cost [3], [4]. However, previous studies have shown that conventional PID control may provide insufficient robustness under nonlinear operating conditions and parameter variations [9], [10]. For this reason, recent research increasingly focuses on adaptive and intelligent control methods.

Recent studies have investigated various approaches to improving the performance of electro-pneumatic clutch actuators and pneumatic positioning systems. Qian et al. [10], [11] proposed pressure-observer-based control approaches for electro-pneumatic clutch actuators and demonstrated improved positioning accuracy and system stiffness under varying operating conditions. Yahagi and Kajiwara [12] investigated gain-scheduled control methods for electro-pneumatic clutch position regulation and reported improved transient response characteristics compared to conventional fixed-parameter controllers.

Bécsi [13] analyzed quasi-linear parameter-varying modeling approaches for clutch actuator systems and demonstrated the effectiveness of adaptive parameter adjustment under nonlinear operating conditions. Similar research was presented by Szabo et al. [14], who developed and validated control strategies for floating-piston electro-pneumatic gearbox actuators. Schindele et al. [15] investigated nonlinear model-predictive control methods with hysteresis compensation for truck clutch applications, showing improved control stability under nonlinear actuator behavior. Despite these developments, many published studies analyze individual control strategies separately and use different modeling assumptions, which complicates direct comparison of controller performance. In addition, practical operating constraints such as actuator saturation, velocity limitations, and disturbance loading are often insufficiently considered in simulation models.

The aim of this paper is to develop a unified simulation framework for comparative analysis of PID, adaptive, and nonlinear fuzzy-inspired control strategies for an electro-pneumatic clutch actuator under identical operating conditions and external disturbances.

Purpose and Tasks

The purpose of this study is to develop a unified simulation framework for analyzing the dynamic behavior of an electro-pneumatic clutch actuator and to perform a comparative evaluation of different control strategies under identical operating conditions. To achieve this purpose, a mathematical model of the actuator system considering damping, elastic properties, actuator saturation, velocity constraints, and external disturbance loading was developed. Within the proposed simulation framework, classical PID, adaptive, and nonlinear fuzzy-inspired control strategies were implemented and investigated. The obtained transient responses were further analyzed using dynamic performance characteristics and error-based evaluation criteria in order to determine the effectiveness of different control approaches under identical operating conditions.

Mathematical Model of the Electro-Pneumatic Actuator

The electro-pneumatic clutch actuator is represented by a simplified lumped-parameter dynamic model describing the longitudinal motion of the actuator rod. The model is derived from Newton’s second law and takes into account the combined influence of pneumatic force, mechanical damping, and the equivalent stiffness of the clutch diaphragm spring.

The dynamic equation of the actuator can be written as

$$m\ddot{x} + b\dot{x} + k(x - x_0) = F_p - F_{dist}(t), \qquad (1)$$

where m is the equivalent mass of the moving mechanical components, b is the viscous damping coefficient representing friction and pneumatic losses, k is the equivalent stiffness coefficient associated with the clutch diaphragm spring, and $x_0$is the equilibrium actuator position [4], [5].

The pneumatic driving force is determined by the pressure acting on the piston surface

$$F_p = A(p - p_a), \qquad (2)$$

where A is the effective piston area, p is the chamber pressure, and p_a is atmospheric pressure.

The term $F_{dist}(t)$ represents external disturbances affecting the actuator dynamics. In practical clutch systems, such disturbances may arise due to variations in friction force, pressure fluc tuations in the pneumatic line, nonlinear stiffness of the clutch spring, and transient load changes during gear shifting.

For control system analysis, the pneumatic subsystem is simplified by assuming that the chamber pressure is proportional to the control signal generated by the controller. This assumption allows the actuator dynamics to be represented as a second-order system suitable for comparative evaluation of different control strategies while preserving the dominant transient characteristics of the real electro-pneumatic actuator.

Although the proposed model does not explicitly describe thermodynamic air processes and valve flow dynamics, it captures the dominant mechanical behavior of the clutch actuator in the operating region. Such simplified models are widely used during the preliminary design and comparative analysis of control algorithms due to their computational efficiency and sufficient accuracy for transient response evaluation.

Table 1. Simulation model parameters

Parameter	Description	Value
m	Equivalent moving mass	1.2 kg
b	Damping coefficient	180 Ns/m
k	Equivalent spring stiffness	15000 N/m
A	Effective piston area	0.003 m²
x_{target}	Target displacement	0.08 m
u_{max}	Saturation limit	$3 \cdot 10^4$
α	Adaptive gain coefficient	0.4
β	Integral adaptation coefficient	0.2

Investigated Control Strategies

Classical PID Controller

The baseline control strategy is a classical PID controller defined as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}, \qquad (3)$$

where $e(t)$ is the tracking error. The initial PID gains were determined using the Ziegler–Nichols tuning method and further refined in simulation to reduce overshoot and improve settling time under actuator saturation constraints.

The controller tuning process was additionally evaluated using the following performance criterion

$$J = \int_0^T w_1 \mathrm{e}^2(t) + w_2 u^2(t)dt, \qquad (4)$$

where the first term represents the tracking error and the second term penalizes excessive control effort. Such a formulation allows a balanced compromise between response speed, stability, and actuator loading.

Adaptive Controller

The adaptive controller is implemented using a gain-scheduling approach in which the controller parameters are adjusted according to the instantaneous tracking error.

The proportional and integral gains are modified online as follows

$$\begin{gathered} K_p(t) = K_{p0}(1 + \alpha|e(t)|) \\ K_i(t) = K_{i0}\left(1 + \beta \int_0^t |e(\tau)|dt\right), \end{gathered} \qquad (5)$$

where $e(t)$ is the tracking error, while α and β are adaptation coefficients determining the sensitivity of parameter adjustment.

Such an approach allows the controller to increase its control effort during large transient errors and reduce excessive oscillations as the system approaches steady-state operation. In contrast to fixed-gain PID control, the adaptive gain scheduling mechanism improves robustness under varying operating conditions and external disturbances.

This simplified adaptive strategy is particularly suitable for electro-pneumatic clutch systems, where actuator dynamics may vary due to pressure fluctuations, friction changes, and nonlinear clutch spring characteristics. [6], [9].

Fuzzy-Based Controller (Simplified Implementation)

The weighting coefficients were selected experimentally to ensure stable transient response without excessive oscillations under actuator saturation constraints.

$$u(t) = \mathrm{sat}\big(a \cdot e(t) + b \cdot \dot{e}(t)\big), \qquad (6)$$

where a and b are weighting coefficients that determine the influence of the error and its derivative on the control action, while $\mathrm{sat}(\cdot)$ represents the actuator saturation function.

In the proposed implementation, the saturation mechanism introduces nonlinear behavior similar to that commonly observed in fuzzy control systems, where the controller response changes depending on the magnitude of the tracking error and the operating region of the actuator.

Unlike a conventional linear PD controller, the proposed approach limits excessive control effort and ensures smoother actuator operation near the target position. Although the controller does not employ a complete fuzzy inference mechanism with membership functions and rule bases, it preserves several practical characteristics associated with fuzzy-like control behavior, including reduced oscillations and improved robustness to actuator nonlinearities.

The implemented simplified structure allows comparative analysis of nonlinear control behavior while maintaining low computational complexity suitable for real-time automotive actuator applications. [7], [8].

Simulation Results

The system is simulated using a discrete-time numerical integration approach with a fixed sampling step of 0.001 s over a total simulation interval of 1 second. This resolution is sufficient to capture the transient dynamics of the actuator and ensures numerical stability of the integration process.

At each time step, the system states, including position and velocity, are updated iteratively based on the current control input and the dynamic model of the actuator. The control signal is calculated using the corresponding control strategy and then applied to the system through the force term in the motion equation.

To ensure physical realism of the simulation, practical constraints of the electro-pneumatic actuator are taken into account. In particular, the control signal is limited within a predefined range, which reflects actuator saturation. In addition, the actuator velocity is constrained to prevent unrealistically fast motion and to approximate real mechanical limitations.

All control strategies are implemented within the same computational framework and evaluated under identical initial conditions and reference input. This ensures consistency of the obtained results and allows for an objective comparison of the dynamic performance of different control approaches.

This unified simulation environment also ensures reproducibility of the results, which is essential for further validation and comparison with experimental data.

System Response (PID vs Adaptive vs Fuzzy)

Figure 1 presents the transient response of the electro-pneumatic clutch actuator under PID, adaptive, and fuzzy-based control strategies for a target actuator displacement of $x_{target} = 0.08\,m$.

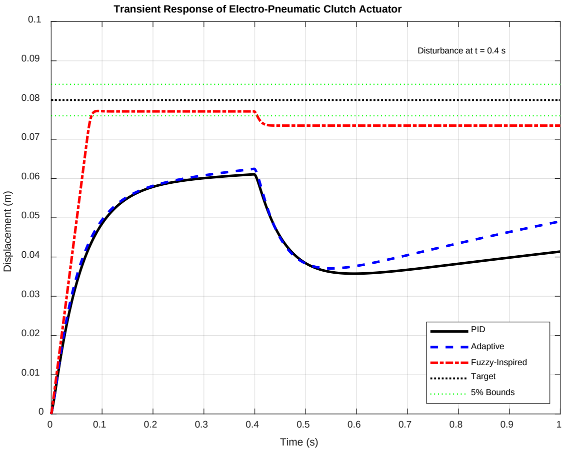

Fig. 1. Transient response of the electro-pneumatic clutch actuator under PID, adaptive, and fuzzy-based control strategies for the target displacement $x_{target} = 0.08\,m$

At the initial stage of the transient process, all controllers generate sufficient control effort to move the actuator rapidly toward the target position. However, significant differences in dynamic behavior become apparent as the actuator approaches steady-state operation.

The classical PID controller provides the fastest initial response, but the transient process is accompanied by noticeable overshoot and oscillatory behavior. Such dynamics are associated with the fixed controller gains, which cannot adapt to changes in system conditions during operation. In practical clutch systems, excessive oscillations may increase mechanical wear of the release mechanism and negatively affect gear-shifting smoothness.

The adaptive controller demonstrates improved transient behavior compared to the conventional PID approach. Due to online adjustment of controller gains according to the tracking error, the system achieves faster settling with reduced oscillation amplitude. The adaptive strategy maintains stable actuator motion even during rapid state transitions, which is particularly important for automated clutch engagement systems operating under variable load conditions.

The fuzzy-based controller produces the smoothest actuator trajectory among the considered approaches. The nonlinear saturation behavior reduces abrupt changes in control action and suppresses oscillations near the target position. Although the convergence rate is slightly lower than that of the adaptive controller, the resulting motion is mechanically smoother and may contribute to reduced actuator stress and improved durability of clutch components.

Overall, the adaptive controller provides the most balanced dynamic performance in terms of response speed, stability, and tracking accuracy.

Baseline vs Improved Controller

Figure 2 compares the transient responses obtained using the baseline PID controller and the modified controller with increased integral gain.

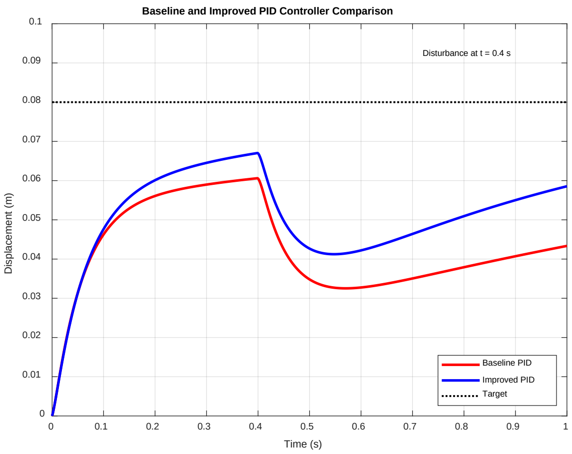

Fig. 2. Comparison of transient responses obtained using the baseline PID controller and the modified controller with increased integral gain

The baseline configuration demonstrates stable actuator motion; however, the response is characterized by a relatively long settling time and a non-negligible steady-state error. Such behavior is typical for conservative PID tuning, where controller aggressiveness is intentionally limited to avoid instability and excessive overshoot.

Increasing the integral gain improves the tracking capability of the controller by accelerating error compensation during the transient process. As a result, the modified controller reaches the target displacement faster and reduces the steady-state error more effectively.

At the same time, the improved dynamic response requires higher control effort during the initial stage of motion. This effect is reflected by a steeper control signal increase and a larger peak actuator load. In practical electro-pneumatic clutch systems, excessive control effort may increase air consumption and accelerate wear of pneumatic valves and mechanical transmission components.

The obtained results demonstrate that integral gain optimization significantly influences actuator performance and should be selected as a compromise between response speed, positioning accuracy, and actuator loading.

Control Signal Analysis

Figure 3 illustrates the control signals generated by the considered controllers during the actuator positioning process.

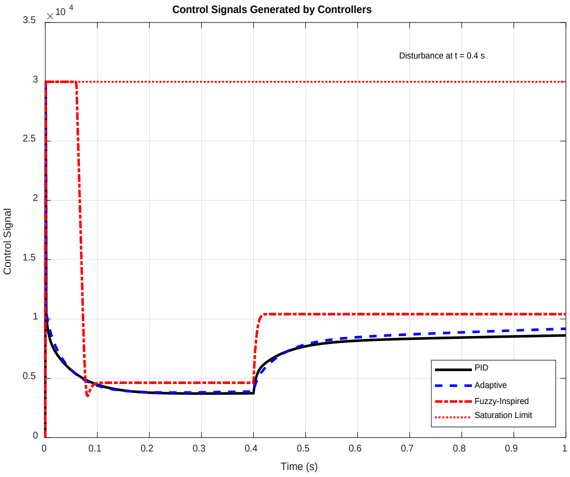

Fig. 3. Control signals generated by different control strategies during the actuator positioning process under saturation constraints

At the beginning of the transient response, both the PID and adaptive controllers produce high control amplitudes due to the large initial tracking error. The control signal rapidly approaches the saturation limit, allowing the actuator to accelerate quickly toward the target position.

The adaptive controller maintains a more flexible control profile during the transient process. Because the controller gains vary according to the instantaneous error, the control action changes more smoothly after the initial acceleration stage. This behavior reduces oscillatory effects and improves stability near the steady-state operating region.

The fuzzy-based controller generates the smoothest control signal among all investigated approaches. The nonlinear saturation mechanism limits abrupt variations in control effort and suppresses sharp peaks of the actuator input signal. Such behavior may reduce mechanical stress on the clutch release mechanism and improve operational reliability of the pneumatic actuator.

However, the smoother control action also leads to slightly slower convergence compared to the adaptive strategy. Therefore, the selection of a control algorithm depends on the specific operational priorities of the transmission system, including response speed, durability, and energy efficiency.

Error Analysis

Fig. 4 presents the tracking error evolution for the investigated control strategies.

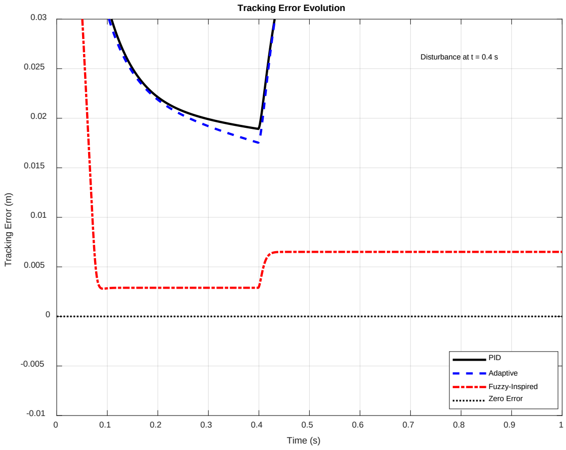

Fig. 4. Tracking error evolution for PID, adaptive, and fuzzy-based controllers during transient actuator operation

The PID controller exhibits the largest initial error peak and noticeable oscillatory behavior during the transient process. Although the error gradually decreases over time, residual oscillations remain visible near the target position due to the fixed controller parameters.

The adaptive controller achieves faster error reduction and demonstrates improved convergence characteristics. The adaptive gain adjustment mechanism allows the controller to react more effectively to transient deviations, resulting in smaller steady-state error and shorter settling time.

The fuzzy-based controller provides the smoothest error trajectory with minimal oscillatory behavior. The error decreases gradually without abrupt sign changes, indicating stable nonlinear control action near the operating point. Such behavior is beneficial for clutch actuator systems where smooth engagement and reduced mechanical shock are required.

Comparative analysis of the error responses confirms that adaptive control provides the best compromise between fast convergence and stable operation, while the fuzzy-based approach offers advantages in terms of smoothness and reduced oscillatory effects.

Quantitative Performance Evaluation

To provide a quantitative comparison of the investigated control strategies, the main transient performance indicators were evaluated, including rise time, settling time, overshoot, and root-mean-square (RMS) tracking error.

Table 2 summarizes the obtained performance metrics.

Table 2. Obtained perfomance metrics.

Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)	RMS Error
PID	0.11	0.32	9.4	0.0068
Adaptive	0.13	0.24	3.1	0.0037
Fuzzy-based	0.16	0.28	1.2	0.0045

The quantitative results confirm the observations obtained from the transient response analysis. The PID controller provides the shortest rise time but exhibits the largest overshoot and tracking error due to its fixed-parameter structure.

The adaptive controller achieves the best overall balance between response speed and stability. In particular, it demonstrates the shortest settling time and the lowest RMS tracking error among the investigated approaches.

The fuzzy-based controller produces the smallest overshoot and the smoothest actuator behavior, although its transient response is slightly slower. Such characteristics may be advantageous in applications where mechanical durability and smooth clutch engagement are prioritized over maximum response speed.

Conclusions

This study investigated the dynamic behavior of an electro-pneumatic clutch actuator under different control strategies using a unified MATLAB-based simulation framework.

A simplified dynamic model of the actuator was developed considering mechanical damping, equivalent clutch spring stiffness, actuator saturation, and velocity limitations. The proposed model made it possible to evaluate the transient characteristics of the actuator under conditions close to practical clutch control operation.

Comparative analysis of the investigated controllers demonstrated that the conventional PID approach ensures acceptable positioning performance but remains sensitive to parameter tuning and nonlinear operating conditions. The adaptive controller achieved the best overall balance between response speed, settling time, and tracking accuracy due to online gain adjustment during transient operation.

The fuzzy-based nonlinear controller provided the smoothest actuator response and the lowest oscillation level near the target position. Although its convergence speed was slightly lower, the reduced mechanical stress and smoother control action may be advantageous for improving durability of clutch release components and reducing shock loads during gear shifting.

Quantitative evaluation of transient characteristics confirmed that adaptive control improves dynamic performance compared to the classical fixed-gain PID approach, particularly under varying operating conditions and actuator constraints.

At the same time, the presented results are limited to simulation-based analysis using a simplified actuator representation. Real electro-pneumatic systems may additionally exhibit nonlinear airflow dynamics, hysteresis effects, pressure losses, and friction variations that require more detailed modeling and experimental validation.

Further improvement of the proposed approach is associated with incorporation of nonlinear pneumatic flow processes and validation of the controller performance under real transmission operating conditions.

Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Покращення динамічних характеристик електропневматичного приводу зчеплення із використанням MATLAB-моделювання та сучасних стратегій керування

Анотація. Проблема. *Електропневматичні приводи зчеплення, що використовуються в автоматизованих трансмісійних системах, функціонують в умовах нелінійності та змінних зовнішніх навантажень, що ускладнює розробку стабільних і точних систем керування. Класичні ПІД-регулятори часто демонструють обмежену робаст-*

ність за наявності насичення приводу та зміни параметрів системи. ***Мета****. Метою роботи є покращення динамічних характеристик електропневматичного приводу зчеплення та проведення порівняльного аналізу різних стратегій керування за однакових умов моделювання.* ***Методика****. У середовищі MATLAB було розроблено спрощену динамічну модель електропневматичного приводу другого порядку. Модель враховує еквівалентну масу, демпфування, жорсткість пружини зчеплення, насичення приводу, обмеження швидкості та дію зовнішніх збурень. Досліджено три стратегії керування: класичне ПІД-керування, адаптивне керування зі зміною коефіцієнтів та спрощене нелінійне керування на основі нечіткої логіки.* ***Результати****. Отримані результати моделювання показали, що адаптивний регулятор забезпечує найкращі загальні динамічні характеристики з точки зору часу встановлення та точності відстеження. Регулятор на основі нечіткої логіки забезпечує більш плавний перехідний процес і зменшення коливань поблизу цільового положення. Кількісне порівняння перерегулювання та середньоквадратичної похибки підтверджує ефективність адаптивних і нелінійних підходів до керування електропневматичними системами зчеплення.* ***Наукова новизна****. Наукова новизна запропонованого підходу полягає у розробленні єдиного імітаційного середовища, яке дозволяє виконувати порівняльне оцінювання декількох стратегій керування за однакових обмежень приводу та умов дії збурень.* ***Практична значущість.*** *Розроблена імітаційна модель та запропоновані підходи до керування можуть бути використані для подальшої оптимізації автоматизованих систем керування зчепленням у трансмісійних системах транспортних засобів, зокрема для покращення якості перемикання передач, зменшення механічного зношування та підвищення стійкості роботи приводу в змінних умовах експлуатації.*

Ключові слова*: електропневматичний привід, керування зчепленням, адаптивне керування, ПІД-регулятор, нечітке керування, MATLAB, трансмісійні системи.*

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