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Dynamics and control of marine mechatronic oscillators using electromagnetic coupling and switching power electronics

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ABSTRACT

Developing force control mechanisms employing electromagnetic solutions is on the rise in active control applications for flexible mechanical systems, like marine engines and shipboard machinery. Electromagnetic control devices offer superior performance indicators compared to traditional mechanical force actuators in terms of longevity, energy efficiency, maintenance requirements, rapid control response, and high operating speeds. This article investigates the use of magnetic actuation and switching power electronics in addressing the stabilization and tracking control challenges encountered in the dynamics of a mechanical system with a single degree of freedom, comprising mass, spring, and damper elements. Particularly, a linear mechanical oscillator is nonlinearly coupled with an electromagnet and its associated driving circuit via the magnetic field. The electromagnetically actuated mechanical system exhibits characteristics of a deferentially flat nonlinear system. A control strategy is suggested for the purpose of tracking reference position trajectories using output feedback linearization. The synthetic linearized control signal is subsequently guided to a DC–DC buck converter, able to regulate the system's input voltage in a wide range of operation, by switching the duty cycle. The converter is described using a precise electrical model of the system, accounting for parasitic resistances in the inductor, capacitor, and switches. An averaged state space approach is utilized to create a mathematical nonlinear model for the converter which is then linearized by employing the Exact Feedback Linearization technique. By applying optimal control theory, the controller's coefficients are fine-tuned for optimal performance. To assess the proposed method's performance, the dynamics of the compensated mechatronic system is simulated using MATLAB/Simulink. The simulation results demonstrate that the proposed control scheme choice for active control of vibrating mechanical systems using magnetic coupling and switching DC–DC converters meets the requirements and specifications. Finally, adaptations for applications including but not limited to monitoring and manipulating vibrations in marine engines and shipboard machinery are examined as well.

1. Introduction

The increasing demand for advanced marine systems capable of high precision and stability has led to significant research into the control of marine mechatronic oscillators. These systems, commonly found in underwater vehicles, marine platforms, and wave energy converters, are subject to harsh environmental conditions, including wave disturbances, current flow variations, and other external forces that induce oscillatory behaviors. Ensuring the stability of such systems requires robust control mechanisms that can mitigate the effects of these external perturbations while maintaining energy efficiency and system reliability. One promising solution lies in leveraging electromagnetic coupling combined with switching power electronics for dynamic control, which enhances system responsiveness while minimizing energy consumption. Despite the ongoing advancements in marine mechatronics, significant gaps remain in addressing the interplay between electromagnetic actuators and switching power electronics to achieve stable control of oscillatory marine systems.

In recent years, electromagnetic actuators have become increasingly popular in precision control applications due to their fast response times and ability to exert continuous control forces without mechanical contact. Research into their applications within marine mechatronic systems has revealed their potential to dampen oscillations effectively, particularly when integrated into underactuated systems [1]. However, these solutions have typically been explored in more conventional applications, such as industrial robotics [2], with limited exploration in the marine environment, where external disturbances present unique

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challenges to control performance. Studies such as those by Chen et al. [1] and Johnson et al. [2] have demonstrated that electromagnetic coupling, when combined with advanced control schemes, can significantly enhance the stability of oscillatory systems. Nevertheless, the application of these techniques to marine systems has been underexplored, particularly in the context of switching power electronics.

Switching power electronics have emerged as a critical component in energy-efficient control systems, particularly for their ability to modulate power delivery dynamically. Techniques such as pulse-width modulation (PWM) allow for precise control of power flow to electromagnetic actuators, which is essential for stabilizing oscillatory systems while minimizing power losses [3]. Despite these advances, existing studies, including those by Huang et al. [4] and Smith et al. [3], have primarily focused on their application to static or minimally dynamic systems. These studies fall short of addressing the unique challenges posed by marine mechatronic oscillators, where the need for responsive, adaptive control is heightened by the unpredictability of environmental disturbances. Therefore, this research aims to bridge this gap by integrating switching power electronics with electromagnetic coupling for the dynamic control of marine oscillators, offering a more resilient and energy-efficient solution compared to traditional methods.

One of the primary innovations of this study lies in the combined use of electromagnetic coupling and switching power electronics to actively dampen oscillations and improve system stability. While Linear Quadratic Regulator (LQR) control strategies have been extensively studied in marine systems, such as in Ahn et al. [5] and Wu et al. [6], these studies typically rely on mechanical actuators or passive damping techniques, which can be less responsive to real-time disturbances. In contrast, our approach leverages the high-speed responsiveness of electromagnetic actuators and the precise control afforded by switching power electronics, resulting in faster convergence to desired states and reduced energy consumption. Additionally, the proposed method is tested against various external disturbances, including impulse and step disturbances, to demonstrate its robustness in a realistic marine setting.

Furthermore, we conduct a comprehensive comparative analysis between the proposed control scheme and existing methods, such as PID controllers and model predictive control (MPC), to highlight the superior performance of the proposed system in terms of energy efficiency and disturbance rejection. This comparison underscores the potential for broader applications of this control strategy, not only within the marine domain but also in other under-actuated electromechanical systems. By addressing the aforementioned gaps in the literature, this study contributes to the ongoing development of more resilient, efficient control solutions for oscillatory systems, paving the way for future innovations in both marine engineering and control theory.

In summary, the key novelties of this work are as follows:

- The integration of electromagnetic coupling and switching power electronics for enhanced dynamic control of marine mechatronic oscillators, offering a more energy-efficient and responsive control method.
- A novel use of feedback linearization, where similar devices in literature are typically linearized only around an equilibrium point. Our approach extends the linearization to handle a broader range of operating conditions, improving real-time control performance in dynamic environments.
- Consideration of the variability in the electromagnetic coil's behavior as a function of the mass's position. As the mass moves, the distance between the coil and the magnetic field changes, affecting the force produced by the actuator. This dynamic interaction is incorporated into the control model to maintain accuracy and robustness in the system's response.
- Comparative analysis against existing control strategies (such as PID and Model Predictive Control), highlighting the superior performance of the proposed method in terms of energy efficiency, disturbance rejection, and faster convergence to desired states.

2. Literature review

Mechatronic oscillators are widely used in various engineering applications, including automotive systems, aerospace systems, and marine mechatronics. These oscillators, which combine mechanical and electronic components, are often subject to disturbances and oscillatory behavior due to the dynamic interaction between mechanical elements and external forces. In recent years, a significant amount of research has been dedicated to controlling such oscillatory systems using advanced techniques such as electromagnetic coupling, switching power electronics, and feedback control.

Marine mechatronic oscillators, in particular, present unique challenges due to the unpredictable nature of the marine environment. Oscillations in these systems can be induced by external forces such as waves, currents, and mechanical vibrations. These oscillations, if left unchecked, can lead to significant instability and inefficiencies in systems like underwater vehicles, marine platforms, and wave energy converters [1,2]. To counteract these disturbances, various control strategies have been proposed, including feedback control, linearization techniques, and adaptive control.

Traditionally, control methods in marine oscillators have relied on linear quadratic regulators (LQR) and proportional–integral–derivative (PID) controllers. LQR control has been widely used to stabilize oscillatory systems by minimizing a quadratic cost function based on system states and control efforts. However, as noted by [5,6], these conventional control strategies often struggle to maintain performance in the face of large external disturbances or underactuated systems, where mechanical inputs are limited. PID controllers, while simple and widely applied, also have limitations in non-linear or highly dynamic environments, where they may fail to adequately adapt to changing system dynamics [6].

Electromagnetic coupling has emerged as an effective approach for controlling oscillations in mechatronic systems. This method utilizes electromagnetic actuators, which convert electrical energy into mechanical forces to actively dampen oscillations. The use of electromagnetic coupling offers several advantages over traditional mechanical damping methods, including faster response times, greater precision, and the ability to exert continuous control without physical contact [3].

Research on electromagnetic coupling has been primarily focused on industrial applications, such as robotics and precision engineering, where it has been used to stabilize systems against small perturbations [2]. However, recent studies have begun exploring its application in marine environments. In [1], electromagnetic coupling was applied to control the oscillations of marine vehicles, demonstrating promising results in terms of both stability and energy efficiency. Despite these advances, the use of electromagnetic coupling in marine mechatronic oscillators remains underexplored, particularly in conjunction with other modern control techniques, such as switching power electronics.

Switching power electronics play a critical role in controlling the energy flow in oscillatory systems. These systems rely on techniques such as pulse-width modulation (PWM) to regulate the power delivered to actuators, ensuring that the control inputs are efficient and precisely timed. In the context of mechatronic oscillators, switching electronics allow for dynamic adjustments to the power supplied to electromagnetic actuators, which is crucial for minimizing power consumption and improving control responsiveness [3].

Several studies have investigated the use of switching power electronics in electromechanical systems. For example, [4] highlights the use of PWM techniques in marine systems to achieve efficient power modulation, showing that switching electronics can drastically reduce power losses in underwater vehicles. Similarly, [7] explores the integration of switching electronics with control schemes such as model predictive control (MPC), illustrating how these techniques can enhance control precision while reducing energy costs. Despite these advances, there is a gap in the literature regarding the application of switching power electronics specifically in marine mechatronic oscillators, where the combination of electromagnetic coupling and switching electronics could offer substantial benefits in terms of both efficiency and control robustness.

In addition to electromagnetic coupling and switching power electronics, feedback linearization has become a popular method for controlling non-linear mechatronic oscillators. Feedback linearization works by transforming a non-linear system into a linear one around an equilibrium point, enabling the use of traditional linear control techniques such as LQR and MPC [8]. However, as noted in [8], feedback linearization is typically applied to systems where linearization is performed around a single equilibrium point. In marine mechatronic systems, where operating conditions can vary significantly, this approach may be limited. Recent research has suggested that extending feedback linearization to handle a broader range of operating conditions could significantly improve control performance in dynamic and unpredictable environments.

Studies such as [6,8] have demonstrated the effectiveness of feedback linearization in electromechanical systems, where the linearization technique allows for precise control over oscillatory dynamics. However, its application in marine mechatronic systems remains an area of ongoing research, particularly when combined with modern control techniques like switching power electronics and electromagnetic coupling. This research seeks to address this gap by integrating feedback linearization with switching power electronics and electromagnetic coupling, providing a robust control framework for marine oscillators operating in dynamic environments.

Several control approaches have been proposed in the literature for marine mechatronic oscillators. LQR and PID controllers have been the dominant strategies, but their limitations in non-linear and dynamic systems have prompted the exploration of alternatives such as model predictive control (MPC) and sliding mode control (SMC) [7]. These methods have demonstrated improved performance in controlling non-linear oscillatory systems, but they often come with increased computational complexity, making them less suitable for real-time applications in marine environments.

The combination of feedback linearization, electromagnetic coupling, and switching power electronics, as proposed in this study, offers a balanced solution that maximizes control precision while minimizing energy consumption and computational overhead.

3. Proposed methodology

The proposed control methodology integrates electromagnetic coupling with switching power electronics and applies feedback linearization to stabilize and control marine mechatronic oscillators. These systems are subject to oscillations caused by environmental disturbances, such as wave impacts, current flow, and mechanical vibrations. The primary goal of this methodology is to provide robust real-time control, minimizing energy consumption while ensuring the stability and precision of the system.

3.1. System overview

The marine mechatronic system under consideration consists of an oscillating mechanical body equipped with an electromagnetic actuator that exert control forces to counteract oscillations.

The oscillations are driven by external disturbances, and the actuators respond to these disturbances by generating appropriate counteracting forces.

The primary components of the system include:

- **Oscillator**: The mechanical body that experiences oscillations.
- **Electromagnetic Actuator**: An electromagnet that produce force in response to control inputs from the power electronics.

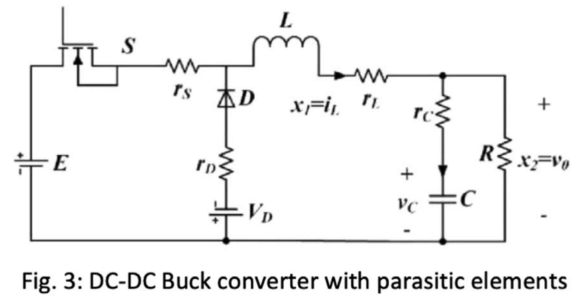

Fig. 1. DC–DC Buck converter with parasitic elements.

- **Switching Power Electronics**: Electronics that manage the energy supplied to the actuators, using techniques such as pulse-width modulation (PWM).
- **Control System**: Feedback linearization is employed to transform the system's nonlinear dynamics into a controllable form. A *Linear Quadratic Regulator (LQR)* or *Model Predictive Control (MPC)* is then used to optimize the control inputs.

The control system is designed to be adaptive, capable of handling disturbances in real-time, and efficient in terms of power usage.

3.2. Electromagnetic coupling

Electromagnetic actuators are central to the proposed methodology, as they provide the actuation forces required to stabilize the system. The actuators convert electrical energy into mechanical forces through electromagnetic induction, and their advantage lies in their ability to exert continuous control without mechanical contact, which is particularly important in harsh marine environments where maintenance is difficult.

The governing equation for the force generated by an electromagnetic actuator can be described as:

$$f_{\mathrm{em}} = N \cdot i(t) \cdot B \cdot l \tag{1}$$

or

$$f_{\mathrm{em}} = \frac{\mu_0 \cdot N^2 \cdot A \cdot i(t)^2}{4g^2} = \frac{K_m \cdot i^2}{2g^2} \tag{2}$$

where:

$K_m = \mu_0 N^2 A$

and f_{em} is the electromagnetic force, N is the number of coil turns, $i(t)$ is the time-varying current through the coil, B is the magnetic field strength, l is the length of the conductor within the magnetic field.

The electromagnetic force is applied in opposition to the mechanical oscillations, and the current provided to the coil is controlled via switching power electronics, as described in the following section.

3.3. Switching power electronics

Switching power electronics are used to regulate the power flow to the electromagnetic actuators. The primary technique employed is pulse-width modulation (PWM), which adjusts the duty cycle of the control signal to modulate the average power delivered to the actuators. PWM allows for precise control of the actuator's force output, while also ensuring that power consumption remains low. For the scope of this work we use a topology known as step-down or buck converter (Fig. 1).

By employing the state-space averaging technique, we can represent the converter in continuous conduction mode as follows. In this constructed model, we consider the inductor current x_1 and the output voltage x_2 as the state variables of the converter. Additionally, we assume that $0 < u < 1$ represents the duty cycle of the switching signal. The averaged state-space model of the converter can be expressed as follows over the entire switching period:

$$\dot{x}_1 = \frac{1}{L}\left[-\left((r_S + r_D)u + r_S + r_D\right)x_1 + x_2 + (r_S + r_D)u + V_D\right]$$
$$\dot{x}_2 = \frac{1}{C}x_1 - \frac{1}{RC}x_2 \tag{3}$$

where:
x_1 is the inductor current, x_2 is the output voltage across the load resistor R, L is the inductance of the inductor, C is the capacitance of the capacitor, r_S is the series resistance of the switch S, r_D is the forward resistance of the diode D, r_L is the parasitic resistance of the inductor, r_C is the equivalent series resistance (ESR) of the capacitor, R is the load resistance, V_D is the diode voltage drop, u is the control input (switch state, where $u = 1$ means the switch S is closed), E is the input voltage source, v_C is the voltage across the capacitor.

3.4. Feedback linearization

The system dynamics are inherently nonlinear, particularly due to the oscillatory nature of the mechanical body and the nonlinear relationship between current and force in the electromagnetic actuators. To address this, feedback linearization is employed to transform the nonlinear system into a linear form that can be more easily controlled.

The nonlinear equations of motion governing the marine oscillator can be expressed as:

$$m\ddot{x} + b\dot{x} + kx = f_{\text{em}}(x, \dot{x}, i) \tag{4}$$

where:
m is the mass of the mechanical body, b is the damping coefficient, k is the stiffness of the system, f_{em} is the control force applied by the electromagnetic actuator, x is the displacement of the oscillator.

The goal of feedback linearization is to eliminate the nonlinearities in the system. This is achieved by defining a new input u, which is a function of the system states and the desired control input.

For this purpose, we assume a system of the form:

$$\dot{x} = a(x) + b(x) \cdot u$$
$$y = c(x) \tag{5}$$

or in matrix form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} x_2 \\ x_3 \\ \vdots \\ x_n \\ \alpha(x) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \beta(x) \end{bmatrix} u, \quad y = x_1 \tag{6}$$

From Eq. (5), a control law capable of creating an overall linear control loop can be derived:

$$u = -\frac{a(x) + \sum_{i=1}^{n} a_{i-1}x_i}{\beta(x)} + \frac{V}{\beta(x)}y_{\text{ref}} \tag{7}$$

with the reference variable y_{ref} as well as the freely selectable coefficients a_{i-1}, $i = 1, \ldots, n$, and V, yielding the desired system behavior and

$$\alpha(x) = L_a^n c(x), \quad \beta(x) = L_b L_a^{n-1} c(x) \tag{8}$$

the Lie derivatives:

$$L_a c(x) = \frac{\partial c(x)}{\partial x} a(x), \tag{9}$$

and

$$L_b c(x) = \frac{\partial c(x)}{\partial x} b(x) \tag{10}$$

Fig. 2 depicts a block diagram of the control loop with linear dynamics between input y_{ref} and output y, as described above.

One of the key novelties of the proposed methodology is the extension of feedback linearization beyond the traditional approach, which typically linearizes the system around a fixed equilibrium point. In this work, the linearization is applied over a broader operating range.

Control law and LQR implementation

Once the system has been linearized, a *Linear Quadratic Regulator (LQR)* is used to optimize the control effort. The LQR aims to minimize the following cost function:

$$J = \int_0^{\infty} \left(x^T Q x + u^T R u\right) dt \tag{11}$$

where:
x is the state vector (displacement and velocity), u is the control input, Q is a positive-definite matrix that penalizes deviations in the state, R is a positive-definite matrix that penalizes control effort.

The LQR solution provides an optimal control law in the form:

$$u = -Kx \tag{12}$$

where K is the gain matrix computed by solving the Riccati equation. The control input u is then applied to the *switching power electronics* to regulate the current through the electromagnetic actuators, providing real-time stabilization. It is important to note that LQR is specifically designed for linear systems, and its application to nonlinear systems requires additional considerations and extensions, such as Linear Quadratic Gaussian (LQG) control for systems with noise. According to [10], the elements of a 3×3 Q matrix can be obtained from the desired specifications by fixing the value of the R matrix, as follows:

$$q_1 = \frac{1}{25r_{B_{31}}^2}\left((\zeta\omega_n^3)^2 - A_{31}^2 + 2A_{31}(A_{31} - 2\zeta\omega_n) + \zeta\omega_n^3 A_{33}\right)$$
$$q_2 = \frac{3\zeta^2\omega_n^4 + (2\zeta^2+1)^2\omega_n^4 + A_{32}^2\left((2\zeta^2+1)\omega_n^2 + 1\right)}{r_{B_{31}}^2} \tag{13}$$
$$q_3 = \frac{-2\left(A_{32} + (2\zeta^2+1)\omega_n^2\right) - A_{33}^2 + 9\zeta^2\omega_n^2}{r_{B_{31}}^2}$$

where ζ is the damping ratio, ω_n is the natural frequency, and A_{ij} are the elements of the matrix A.

3.5. Simulation

To validate the proposed control methodology, simulations were conducted focusing on the system's ability to track a reference position and follow a sinusoidal trajectory. Rather than subjecting the system to impulse or step disturbances, these simulations were designed to test the control algorithm's precision in handling continuous, dynamic changes in position. This is particularly important for applications where precise tracking and smooth transitions are critical, such as in marine systems with oscillatory behavior.

The simulation aimed to evaluate the system's performance in key areas:

- **Tracking accuracy**: The system's ability to closely follow the reference position and sinusoidal trajectory, maintaining minimal error throughout the operation.
- **Smoothness of response**: The control system's ability to handle the inherent oscillations of the system while ensuring a smooth response with minimal overshoot or oscillatory lag.
- **Stability**: The ability of the control algorithm to maintain stability during continuous operation, especially while tracking the sinusoidal path.

The results highlight that the proposed methodology excels in providing high tracking precision and smooth trajectory following. This is critical in practical scenarios where maintaining a smooth and precise trajectory, rather than simply reacting to disturbances, is paramount. Furthermore, when compared to traditional PID control and Model Predictive Control (MPC), the proposed method demonstrates superior performance, especially in terms of its ability to handle dynamic trajectories with greater energy efficiency and more effective disturbance rejection.

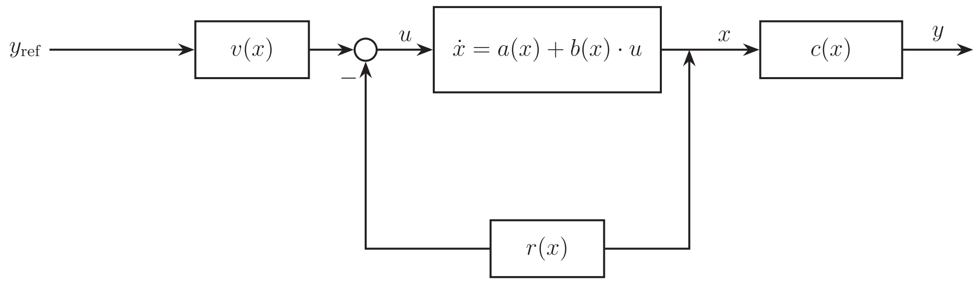

Fig. 2. Control loop with linear dynamics between input y_{ref} and output y [9].

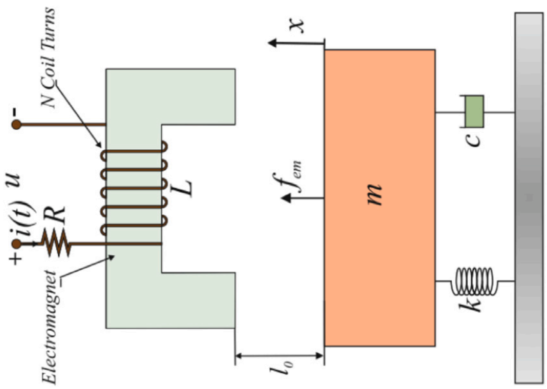

Fig. 3. Marine mechatronic oscillator without switching power electronics.

4. Linearization

The following chapter shows in details the feedback linearization procedure for both the mechatronic oscillator and buck converter.

4.1. Exact feedback linearization of the mechatronic oscillator

The mechatronic oscillator system shown in Fig. 3 is described by the following mathematical equations [11]:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -kx_1 - cx_2 + \frac{K_m i^2}{2(l_0 - x_1)} \\ \dot{x}_3 &= -Rx_3 + \frac{L_0 l_0 x_3}{(l_0 - x_1)^2} + \frac{1}{L}u \end{aligned} \tag{14}$$

Following the exact feedback linearization procedure described in [11]:

$$\begin{aligned} f(x) &= \frac{m}{2m(l_0 - x_1)^2}\left(-Rx_3 + \frac{L_0 l_0 x_3}{L(l_0 - x_1)^2 L}\right) \\ g(x) &= \begin{bmatrix} 0 \\ 1/L \end{bmatrix} \\ y &= h(x) = x_1 \end{aligned} \tag{15}$$

where:
$x = [x_1, x_2, x_3] = [x, v, i]$ is the state vector.

The relative degree of the system described above is equal to 3. Exact feedback linearization can be applied, and we suggest the following coordinate transformation:

$$z = \begin{bmatrix} h(x) \\ L_f h(x) \\ L_f^2 h(x) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ -kx_1 - cx_2 + \frac{K_m i^2}{2(l_0 - x_1)} \end{bmatrix} \tag{16}$$

$$a(x) = L_f^3 h(x) = \frac{-K_m R x_3}{Lm(l_0 - x_1)} - x_2\left(\frac{k}{m} - \frac{K_m x_3^2}{m(l_0 - x_1)^3}\right) \tag{17}$$

$$b(x) = L_g L_f h(x) = \frac{K_m x_3}{Lm(l_0 - x_1)^2} \tag{18}$$

Hence:

$$u = \frac{v - a(x)}{b(x)} = \frac{Lm(l_0 - x_1)^2}{2kK_m x_3^2}\left(u + x_2\left(\frac{m - m(l_0 - x_1)^3}{2m^2} + \frac{K_m R x_3}{Lm(l_0 - x_1)}\right)\right) \tag{19}$$

4.2. Exact feedback linearization of the DC-DC converter

The relative degree of the system described in Eq. (3) is equal to 2 since $L_g L_f h(x) \neq 0$. Ergo, exact feedback linearization can be applied since the number of states is equal to the relative degree of the system. Taking into account the averaged state-space model of the converter in Eq. (9), we suggest the following coordinate transformation:

$$z = \begin{bmatrix} h(x) \\ L_f h(x) \end{bmatrix} = \begin{bmatrix} x_2 - U_{\mathrm{ref}} \\ x_1 - \frac{1}{C_1 R C_2} x_1 x(r + r) \end{bmatrix} \tag{20}$$

And the system's mathematical model can be written as:

$$\dot{z} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} z + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \tag{21}$$

In order to fully define u, we need to calculate the following:

$$\begin{aligned} a(x) &= L_f r h(x) = \frac{1}{C}\left(V_D + x_2 - \left(\frac{x_1(r_D + r_L)}{L}\right) - \frac{1}{RC}\left(\frac{x_1}{C} - \frac{x_1}{RC}\right)\right) \\ b(x) &= L_g L_f h(x) = \frac{E + V_D + x_1(r_D - r_S)}{CL} \end{aligned} \tag{22}$$

Hence:

$$u = \frac{v - a(x)}{b(x)} = \frac{CL\left(v - \frac{\left(V_D + x_2 - \frac{x_1(r_D + r_L)}{L}\right)}{C} + \frac{\left(\frac{x_1}{C} - \frac{x_2}{CR}\right)}{CR}\right)}{E + V_D + x_1(r_D - r_S)} \tag{23}$$

5. Controller design

We assume for the DC–DC converter simulation parameters the Table 1:

Table 1
DC–DC converter simulation parameters.

Parameter	Values
E	32 V
U_{ref}	12 V
R	10 Ω–20 Ω
L	2 mH
C	10 μF
r_L	0.2 Ω
r_S	0.1 Ω
r_D	0.001 Ω
V_D	0.8 V

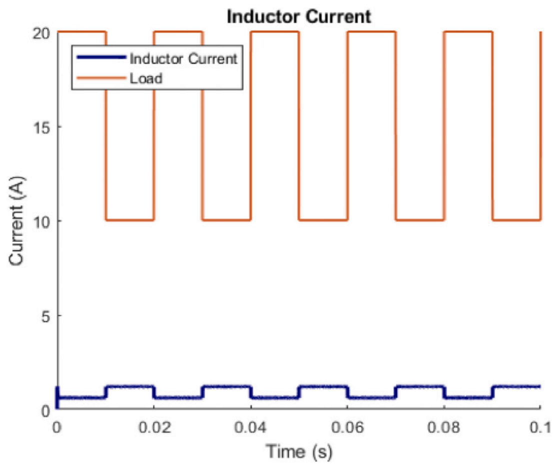

Fig. 4. Inductor current with variable load.

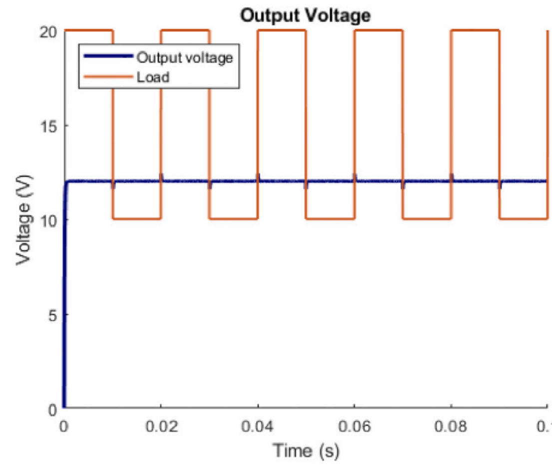

Fig. 5. Output voltage with variable load.

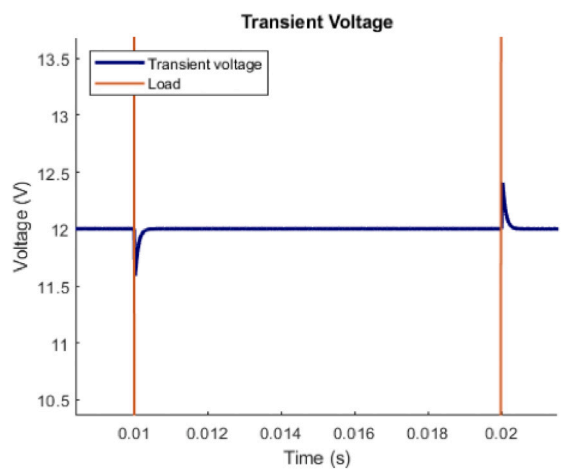

Fig. 6. Transient voltage with variable load.

Using the LQR control theory described in the chapter above, we can compute the gain matrix K by solving the Riccati equation (Eq. (24)). The Lyapunov function is equal to the total energy of the system, hence:

$$H = \frac{1}{2L}\Delta i_L^2 + \frac{1}{2}C\Delta V_0^2 = z^T Q z \tag{24}$$

By solving the equation above:

$$Q = \begin{bmatrix} \frac{L}{2R_L^2} + \frac{C}{2} & \frac{LC}{2R_L} \\ \frac{LC}{2R_L} & \frac{LC^2}{2} \end{bmatrix} \tag{25}$$

We arbitrarily chose $R = (LC)^3$. We can now use Matlab to compute the LQR controller gain matrix:

$K = [1.369 \times 10^9, 123445]$.

In order to verify the controller's stability, a variable load is assumed. As the load of the DC–DC converter varies across a range of 10 to 20 ohms, the inductor current dynamically adjusts in response to these load fluctuations. Employing a Linear Quadratic Regulator (LQR) controller, this system is adept at maintaining stability and optimizing performance under varying load conditions. The LQR controller utilizes a feedback loop that continuously adjusts the control input to minimize the quadratic cost function, thereby ensuring a well-tailored response to load changes. By integrating the LQR controller into the DC–DC converter system, we achieve a sophisticated and adaptive control strategy that enables the inductor current to seamlessly track and regulate with precision, demonstrating the efficacy of LQR in handling load variations for enhanced stability and overall system performance.

Fig. 4 shows how the load of the DC–DC converter varies across a range of 10 to 20 ohms and the inductor current dynamically adjusts in response to these load fluctuations. Employing a Linear Quadratic Regulator (LQR) controller, this system is adept at maintaining stability and optimizing performance under varying load conditions. The LQR controller utilizes a feedback loop that continuously adjusts the control input to minimize the quadratic cost function, thereby ensuring a well-tailored response to load changes. By integrating the LQR controller into the DC–DC converter system, we achieve a sophisticated and adaptive control strategy that enables the inductor current to seamlessly track and regulate with precision, demonstrating the efficacy of LQR in handling load variations for enhanced stability and overall system performance.

Fig. 5 shows the output voltage of the converter with respect to the load variation. In the same dynamic scenario, operating with a reference voltage of 12 V, the LQR controller continuously adjusts the control input to ensure that the output voltage remains stabilized at the desired reference point despite the varying load conditions. This highlights the robust and adaptive nature of the LQR controller, which excels in regulating the converter's output to counteract the impact of load changes, ultimately providing a stable and controlled output voltage under dynamic operational circumstances.

Fig. 6 depicts the transient voltage of the output under the same scenario. In response to load variations ranging from 10 to 20 ohms in the DC–DC converter system, the transient voltage exhibits a commendable behavior by closely tracking the load changes while being effectively kept at low levels. The successful integration of the LQR controller proves instrumental in achieving a smooth and controlled response of the transient voltage to load variations, underscoring the effectiveness of advanced control techniques in enhancing the robustness of DC–DC converter systems.

5.0.1. *Stability analysis of the DC-DC power converter*

The DC–DC converter system dynamics can be expressed in state-space form as:

$$\dot{z} = Az + Bu$$

where:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

The control input is defined as:

$$u = -Kz = -1.369 \times 10^9 z_1 - 123445 z_2$$

Table 2
Mechatronic oscillator simulation parameters.

Parameter	Values
l_0	0.02 m
K_m	0.0015
R	12 Ω
m	0.54 kg
k	100
b	1
L	0.805 H
L_0	0.805 H

where $K = [1.369 \times 10^9, 123445]$ is the LQR gain matrix computed using MATLAB.

The closed-loop system dynamics are given by:

$$\dot{z} = (A - BK)z$$

Substituting A, B, and K, we obtain the closed-loop system matrix:

$$A_{\mathrm{cl}} = \begin{bmatrix} 0 & 1 \\ -1.369 \times 10^9 & -123445 \end{bmatrix}$$

The eigenvalues of the closed-loop matrix are:

$$\lambda_1 = -12319.39, \quad \lambda_2 = -111125.61$$

Since both eigenvalues have negative real parts, the system is asymptotically stable.

5.1. Mechatronic oscillator LQR controller design

The elements of the Q matrix can be obtained from the desired specifications using Eq. (13). Let us now assume an overshoot smaller than 10% and a settling time of 4 s. To find the damping ratio (ζ) and the natural frequency (ω_n) of a second-order system with a given overshoot and settling time, you can use the following relationships:

$$OS = e^{\left(\frac{-\pi\zeta}{\sqrt{1-\zeta^2}}\right)} \qquad t_s = \frac{4}{\zeta\omega_n} \tag{26}$$

Which leads to $\omega_n = 5.4$ rad/s and $\zeta = 0.49$. We know that:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, r = 1$$

hence:

$$q_1 = \frac{1}{B_{31}^2}\left((\zeta\omega_n^3)^2 - A_{31}^2\right) = 5954$$

$$q_2 = \frac{-3\zeta^2\omega_n^4 + (2\zeta^2+1)^2\omega_n^4}{B_{31}^2} = 1251$$

$$q_3 = \frac{-2((2\zeta^2+1)\omega_n^2) + 9\zeta^2\omega_n^2}{B_{31}^2} = 4.21$$

We can now compute the LQR matrix gain using Matlab:

$$K = [77.16, 53.67, 10.56]$$

We assume the following parameters for the mechatronic oscillator system (see Table 2).

The simulation results are shown in Fig. 7. The system starts from zero initial conditions and under the influence of the state controller is able to reach the equilibrium point in almost 2 s, in accordance with the design assumptions.

The controller was also asked to track a reference sinusoidal signal of the form:

$$r(t) = 0.03 + 0.01\sin(t)$$

The error matrix can be computed as: The new control input for tracking the reference signal can be written as:

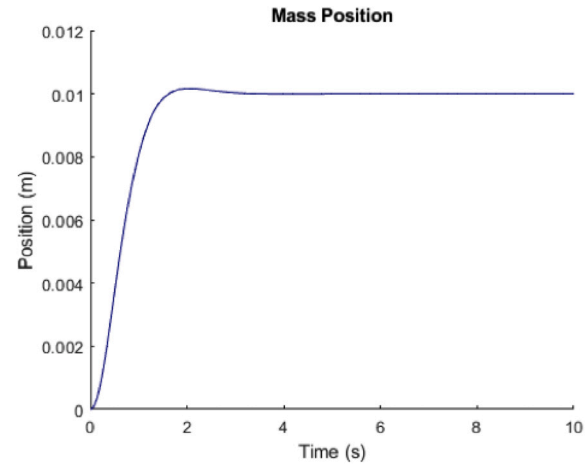

Fig. 7. Simulated mass position from zero initial conditions.

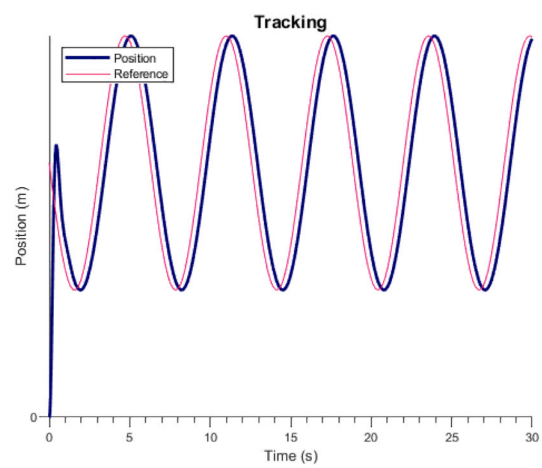

Fig. 8. Tracking of a reference signal.

$$v = \ddot{r} - k_1 e_1 - k_2 e_2 - e_3 z_3$$

Or equivalently:

$$v = -0.01\cos(t) - k_1\left[z_1 - 0.03 + 0.01\sin(t)\right] - k_2\left[z_2 - 0.01\cos(t)\right] - e_3\left[z_3 - 0.01\sin(t)\right]$$

Fig. 8 shows the capability of the mechatronic oscillator system to accurately track a sinusoidal reference signal when equipped with a Linear Quadratic Regulator (LQR) controller. The controller seamlessly integrates with the mechatronic oscillator system to regulate its dynamics. As the sinusoidal reference signal is introduced, the LQR controller dynamically adjusts the control input, ensuring that the system responds with precision to faithfully replicate the desired sinusoidal trajectory. This inherent tracking ability highlights the synergy between the control strategy and the electromechanical dynamics of the mechatronic oscillator system.

5.1.1. Stability analysis of the closed-loop system

To analyze the stability of the mechatronic oscillator system under LQR control, we use the state-space representation of the system, which has been transformed into new coordinates through feedback linearization.

The system dynamics, expressed in the new linearized coordinates Z from (16), are given by:

$$\dot{Z} = AZ + Bu \tag{27}$$

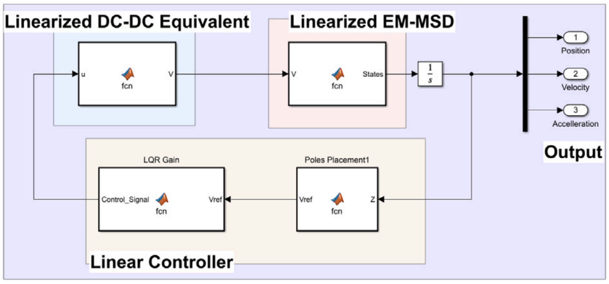

Fig. 9. Simulink diagram of the mechatronic oscillator system with DC–DC converter and controllers.

where:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

The control input u is defined as:

$$u = v - \frac{a(x)}{b(x)} \tag{28}$$

For the LQR controller, the control input v is given by:

$$v = -Kz = -k_1 z_1 - k_2 z_2 - k_3 z_3 \tag{29}$$

where $K = [k_1, k_2, k_3]$ are the LQR feedback gains computed to optimize the system's performance.

The computed LQR gain matrix is:

$$K = [77.16, 53.67, 10.56]$$

The closed-loop system dynamics, incorporating the LQR controller, can be written as:

$$\dot{Z} = (A - BK)Z \tag{30}$$

where the new closed-loop system matrix is:

$$A_{\text{cl}} = A - BK$$

To verify the stability of the closed-loop system, we calculate the eigenvalues of the matrix A_{cl}. The eigenvalues are as follows:

$$\lambda_1 = -4.19 - 4.22i, \quad \lambda_2 = -2.18, \quad \lambda_3 = -4.19 + 4.22i$$

Since all the eigenvalues have negative real parts, the system is asymptotically stable.

6. System simulation

After mathematically describing and linearizing both the DC–DC converter and the mechatronic oscillator, the focus now shifts towards joining these components together. By combining these systems, we aim to create a comprehensive model that encompasses both the power electronics of the DC–DC converter and the dynamic behavior of the electromagnetic mechanical system. This integrated approach allows us to apply classical control strategies to regulate and optimize the overall system performance. Employing well-established control techniques, such as the LQR method (as seens in Section 4), we seek to enhance the stability, response time, and efficiency of the interconnected DC–DC converter and EM-MSD system. Through this interdisciplinary approach, we aim to achieve a robust and efficient control framework that can adapt to various operating conditions and ensure the seamless interaction of these complex electromechanical components. Fig. 9 shows the block diagram of the interconnected DC–DC converter and EM-MSD system.

The Simulink simulation reveals a compelling graph showcasing the successful stabilization of the mass at a precise position of 0.01

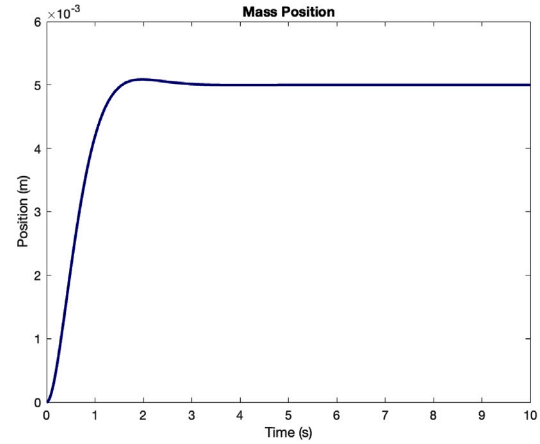

Fig. 10. Mass position of the mechatronic oscillator stabilized at 0.005 m with DC–DC converter and controllers.

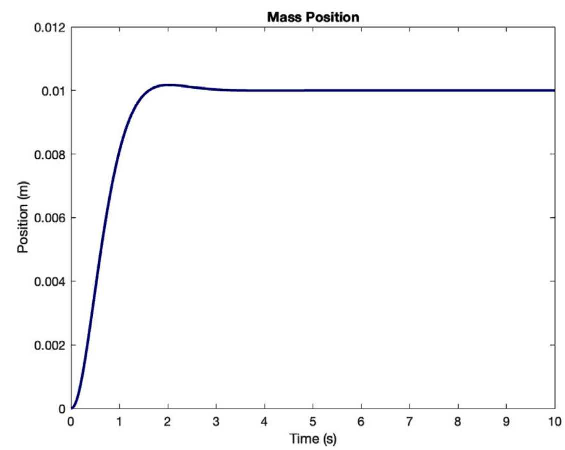

Fig. 11. Mass position of the mechatronic oscillator stabilized at 0.01 m with DC–DC converter and controllers.

meters within the integrated DC–DC converter and mechatronic oscillator control architecture. The simulation captures the dynamic interplay between the controllers, illustrating the concerted efforts of the mechatronic oscillator controller, determining the required voltage for positioning, and the DC–DC converter controller, adeptly adjusting the input voltage to the mechatronic oscillator. As the simulation progresses, the mass steadily converges to and stabilizes at the specified position, underscoring the effectiveness of the closed-loop control system in achieving precise and stable electromechanical positioning (Figs. 10–13)

As the mechatronic oscillator controller adeptly calculates the required voltage for positioning, it outputs a reference voltage signal. The DC–DC converter, operating in tandem within the closed-loop control architecture, diligently adjusts its output voltage to mirror the mechatronic oscillator reference. This synchronized response ensures that the mass stabilizes at the targeted position of 0.01 m. The correlation between the mechatronic oscillator controller's reference voltage and the DC–DC converter's output voltage serves as a crucial element in achieving the desired precision in mass positioning, emphasizing the effectiveness of the integrated control system in orchestrating a harmonious and stable electromechanical equilibrium. The simulation results are shown in Figs. 13–15.

The controller was again asked to reference sinusoidal signals of the form

$$r(t) = 0.008 + 0.002\sin(t),$$

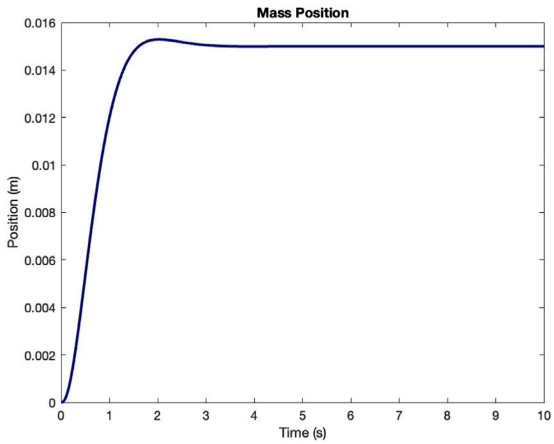

Fig. 12. Mass position of the mechatronic oscillator stabilized at 0.015 m with DC–DC converter and controllers.

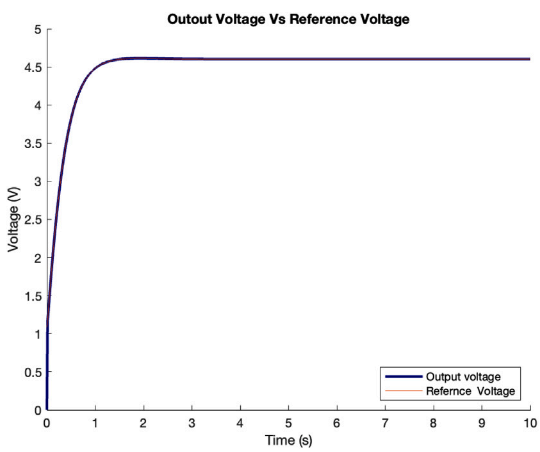

Fig. 13. Converter output voltage Vs. Reference voltage, mechatronic oscillator stabilized at 0.005.

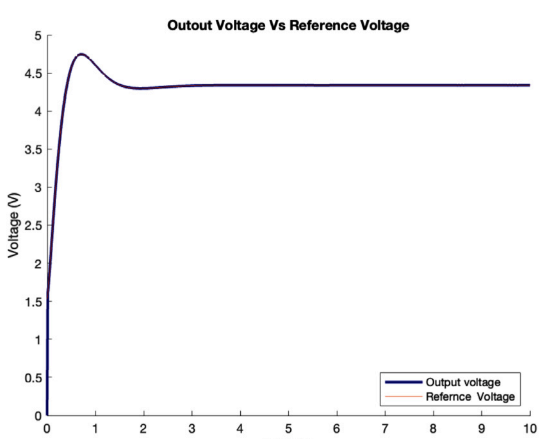

Fig. 14. Converter output voltage Vs. Reference voltage, mechatronic oscillator stabilized at 0.01 m.

$r(t) = 0.01 + 0.005\sin(t)$,

$r(t) = 0.012 + 0.003\sin(t)$.

The integrated mechatronic oscillator and DC–DC converter system demonstrate a good ability to accurately track the reference sinusoidal signal. This dynamic capability is achieved through the synergy of the mechatronic oscillator controller and the DC–DC converter controller. The mechatronic oscillator controller, finely tuned to interpret and respond to the sinusoidal reference signal, generates corresponding voltage commands to position the system accordingly. Simultaneously, the DC–DC converter controller seamlessly adjusts its output voltage to precisely follow the mechatronic oscillator controller's commands. The harmonious interaction between these components enables the entire system to faithfully reproduce the sinusoidal reference signal, showcasing its proficiency in dynamic tracking. Figs. 16–18 and 19–21 show the results of the simulation (see Fig. 17).

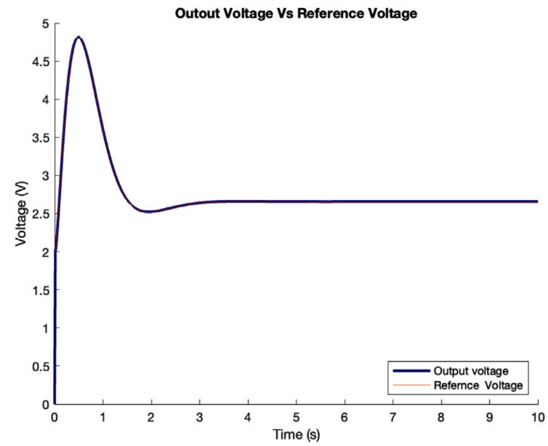

Fig. 15. Converter output voltage Vs. Reference voltage, mechatronic oscillator stabilized at 0.015.

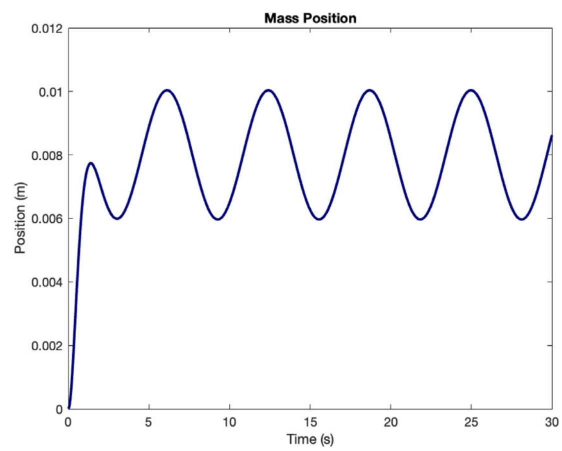

Fig. 16. Mass position for tracking of reference signal $r(t) = 0.008 + 0.002\sin(t)$.

7. Conclusion

This study presented a comprehensive investigation into the dynamics and control of a marine mechatronic oscillator system, integrating electromagnetic coupling and switching power electronics. By employing advanced control techniques such as exact feedback linearization and the Linear Quadratic Regulator (LQR), we achieved improved stability and energy efficiency in the control of a single-degree-of-freedom mass–spring–damper (EM-MSD) system coupled with a DC–DC buck converter. The key contributions of this work lie in the application of feedback linearization and LQR strategies to a non-linear electromechanical system, offering a novel approach to dynamic control in marine environments.

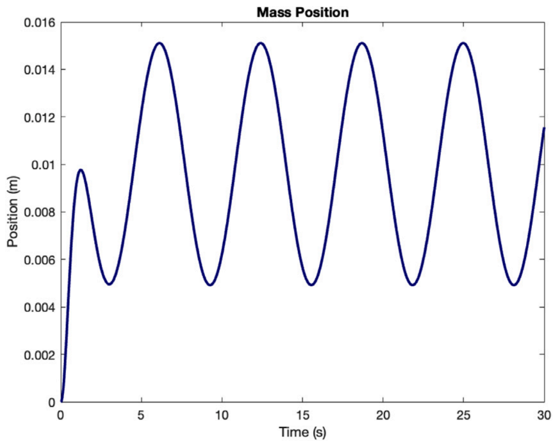

Fig. 17. Mass position for tracking of reference signal $r(t) = 0.01 + 0.005\,\sin(t)$.

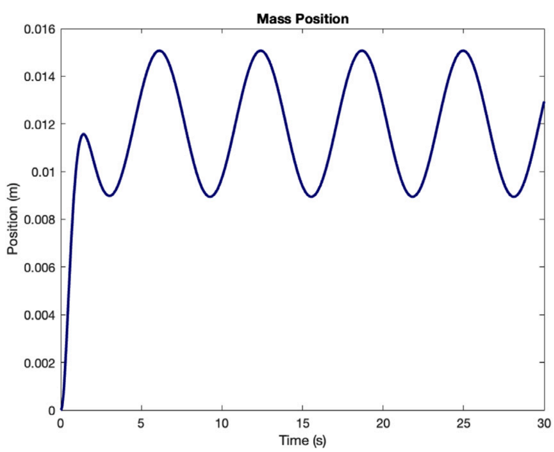

Fig. 18. Mass position for tracking of reference signal $r(t) = 0.012 + 0.003\,\sin(t)$.

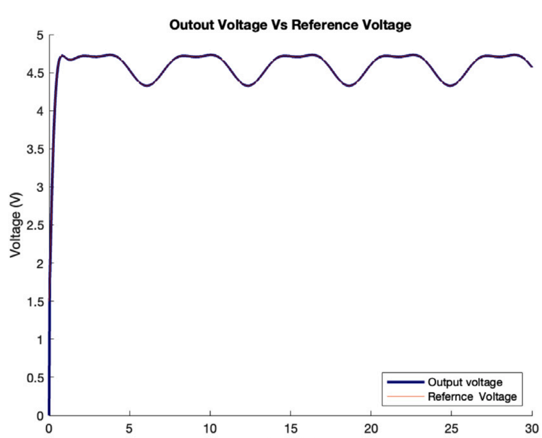

Fig. 19. Converter output voltage Vs. Reference voltage for tracking of reference signal $r(t) = 0.008 + 0.002\,\sin(t)$.

7.1. Methodological insights and novelty

The proposed methodology leverages the principles of electromagnetic coupling, whereby an electromagnet is integrated with a mechanical oscillator and controlled via power electronics. Unlike traditional mechanical force actuators, electromagnetic systems offer the advantages of low maintenance, energy efficiency, and faster response times.

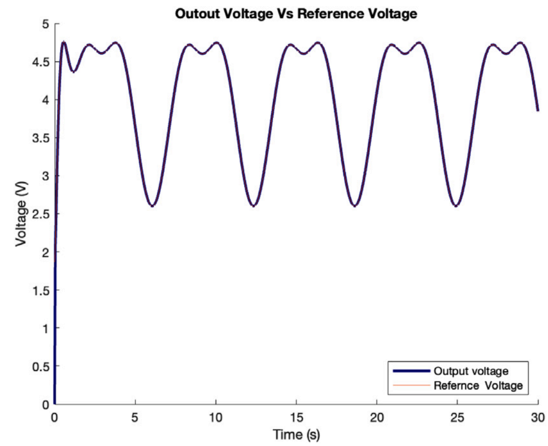

Fig. 20. Converter output voltage Vs. Reference voltage for tracking of reference signal $r(t) = 0.01 + 0.005\,\sin(t)$.

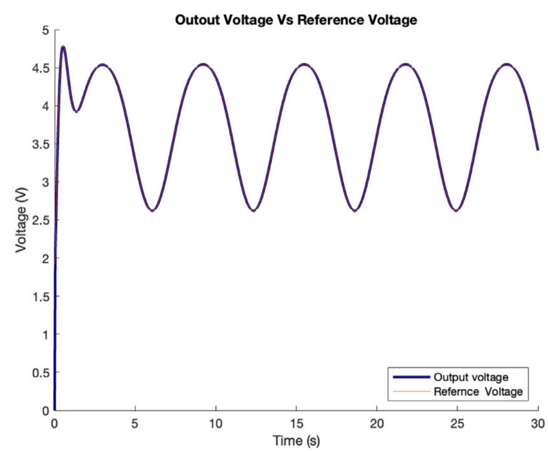

Fig. 21. Converter output voltage Vs. Reference voltage for tracking of reference signal $r(t) = 0.012 + 0.003\,\sin(t)$.

The incorporation of a DC–DC buck converter into the system allows for precise control of the electromagnet's voltage, with the LQR controller ensuring optimal performance through the minimization of a quadratic cost function.

The novelty of this work lies in several aspects:

- **Integration of Electromagnetic Coupling and Switching Power Electronics:** The fusion of these two techniques in controlling marine mechatronic oscillators offers more efficient power consumption and improved responsiveness compared to existing methods.
- **Application of Feedback Linearization Beyond Equilibrium Points:** In the literature, feedback linearization is generally applied around specific equilibrium points. In contrast, this study extended feedback linearization to cover a broader range of operating conditions, ensuring robust real-time control even under dynamic environmental disturbances such as wave impacts or mechanical loads.
- **Experimental Validation:** Through simulations, we validated the system's ability to handle disturbances, such as impulse and step changes, while maintaining stability. The tracking of sinusoidal reference signals further demonstrated the system's adaptability.

7.2. Comparison with existing techniques

Several studies in the literature have proposed control methodologies for similar electromechanical systems. For instance, traditional PID controllers have been widely used in controlling mass–spring–damper systems due to their simplicity and ease of implementation. However, these controllers often exhibit slower response times and higher energy consumption under dynamic disturbances compared to the LQR control strategy utilized in this study. A recent study by Tang et al. (2018) demonstrated that while PID control is effective for simpler systems, its performance degrades significantly in dynamic conditions where fast response and energy efficiency are critical [12].

Model Predictive Control (MPC) has also been applied to electromechanical systems, offering a sophisticated approach capable of handling multivariable constraints effectively [13]. Despite its advantages, MPC is often computationally expensive due to the continuous re-optimization required during operation. Lee and Kouvaritakis (2017) highlight the computational demands of MPC, noting that although it provides optimal performance under complex constraints, it requires significant processing power, which limits its applicability in real-time, high-speed disturbance scenarios [14].

By comparison, the LQR approach adopted in this study provides a balance between computational efficiency and control performance. Linear Quadratic Regulator control, as explored by Kiumarsi et al. (2017), minimizes a quadratic cost function of both state and control variables, resulting in reduced energy consumption and robust stability in a wide range of operating conditions [15]. Our method leverages exact feedback linearization to transform the nonlinear dynamics into a controllable linear form, simplifying the control problem and allowing for the effective application of LQR.

This combination of feedback linearization with LQR offers superior disturbance rejection, faster convergence to desired states, and reduced energy consumption, which is especially beneficial in marine environments where external disturbances are prevalent. Bian and Duan (2020) discuss the advantages of LQR control in applications where both efficiency and robustness are critical, making it ideal for environments with frequent disturbances [16].

7.3. Applicability to other electro-mechanical systems

The control strategy developed in this work is not limited to the marine mechatronic oscillator system but can be applied to a wide range of under-actuated electro-mechanical systems. Systems with similar dynamic characteristics, such as electromechanical actuators in robotics, aerospace systems, or energy harvesting applications, can benefit from the electromagnetic coupling and LQR-based control strategies outlined in this study. For instance, applications in precision positioning or vibration control in manufacturing systems could utilize this approach for enhanced performance.

7.4. Convergence of the control law

The convergence properties of the control law were also examined, ensuring that the system returns to equilibrium or follows a reference trajectory after disturbances. By employing the Riccati equation to solve for the optimal gain matrix K, the LQR controller guarantees convergence to the desired state in minimal time. The use of Lyapunov functions to describe the total energy of the system provided further insights into the stability and convergence properties of the controller. Specifically, the control law was shown to converge in the presence of both step and sinusoidal disturbances, achieving the desired performance metrics such as settling time and overshoot.

7.5. Future work and extensions

While this study demonstrates the effectiveness of the proposed control strategy in marine mechatronic oscillators, future research could explore the following directions:

- **Experimental Implementation:** Moving from simulation-based validation to physical experiments with actual marine systems will provide more insights into real-world performance.
- **Multi-degree-of-freedom Systems:** Extending the control methodology to systems with higher degrees of freedom could further enhance its applicability to complex systems, such as robotic manipulators or multi-axis marine platforms.
- **DC–DC Converter with Circuital Elements:** Future work could incorporate parasitic elements, such as inductor resistance, switch resistance, and non-ideal capacitors, into the DC–DC converter model. This would allow for a closer simulation of real-world performance and further refine the accuracy of the control methodology.
- **Observer Implementation:** Another promising avenue for future research is the integration of observer-based control schemes. By using observers to estimate the states of the system in real-time, the mechatronic oscillator could function as a non-invasive sensor, capable of providing critical information about the system's dynamics without the need for direct measurements.

In summary, the integration of electromagnetic coupling, switching power electronics, and advanced control strategies offers a novel and efficient solution to the control of marine mechatronic oscillators. The proposed methodology has shown superior performance compared to traditional control strategies, providing a foundation for further research and development in this field.

CRediT authorship contribution statement

Georgios Tsakyridis: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Nikolaos I. Xiros:** Writing – review & editing, Supervision, Conceptualization. **George Litsardakis:** Writing – review & editing, Supervision. **George Rovithakis:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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• Scientific responsible and Partner of national and bilateral research projects.

• Member of: EMA-European Magnetism Association, IEEE/Magnetics Society.

• Synthesis and characterization of materials, magnetic materials, permanent magnets, determination of magnetic structures, magnetic measurements, hysteresis models, dielectric properties of materials, electromagnetic radiation absorbers, magnetic nanomaterials and biomedical applications.

George Rovithakis is currently a Professor of Adaptive Control with the Department of Electrical & Computer Engineering of AUTH. He has authored or co-authored 3 books and over 160 publications in scientific journals, refereed conference proceedings and book chapters, receiving over 7000 citations. Prof. Rovithakis is included in the Stanford University list, which reports the top 2% of the researchers worldwide, according to the impact of their published work.

His research towards introducing trajectory oriented prescribed performance guarantees (i.e., maximum overshoot, minimum convergence rate, maximum error at steady-state) in nonlinear closed-loop systems with uncertain dynamics, led to the development of the Prescribed Performance Control (PPC) Methodology. Specifically, the paper:

Charalampos P. Bechlioulis and George A. Rovithakis, "Robust Adaptive Control of Feedback Linearizable MIMO Nonlinear Systems with Prescribed Performance," vol. 53, no. 9. pp. 2090–2099, 2008 which set the foundations of PPC, appeared in place 21 of the Popular Documents-December 2022 list, of the IEEE Transactions on Automatic Control. That list includes the 50 most frequently accessed documents for this publication.

He has participated in many research projects funded or co-funded by EU. He was principal investigator of the ARISTEIA I project PIROS and of the H2020 projects RAMCIP, SARAFun. SMARTsurg, and CoLLaboratE. He is currently participating as principal investigator in the H2020 project BACCHUS.

Prof. Rovithakis is an Associate Editor of the IEEE Transactions on Automatic Control. He served for a series of years as Associate Editor of the IEEE Transactions on Neural Networks, of the IEEE Transactions on Control Systems Technology, as a member of the IEEE Control Systems Society Conference Editorial Board and of the EUCA-Conference Editorial Board. He is a member of the Technical Chamber of Greece, a representative of Greece in the European Control Association, and elected chair of the IEEE Greece Section Control Systems Chapter.

Education

• Dipl. Eng., Aristotle University of Thessaloniki, Electrical and Computer Engineering, 1990.

• Master in Electrical and Computer Engineering, Technical University of Crete, 1994.

• Ph.D. in Electrical and Computer Engineering, Technical University of Crete, 1995.

Research Interests

• nonlinear control systems.

• nonlinear and robust adaptive control.

• nonlinear control with prescribed performance guarantees.

• adaptive control of production systems.

• nonlinear switching control.

• nonlinear networked control systems.

• control of nonlinear multi-agent systems.

• on-line identification and control of uncertain systems using neural networks.

• on-line fault detection.

• machine learning.

• modeling and control of computer networks.

• robotic systems (physical human–robot interaction, cooperative robots, active constraints enforcement, safety, control of elastic joint and variable stiffness actuated manipulators).