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# Recent Advances in Nonlinear Dynamics Applied in Electromechanical Systems

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**Abstract**

Electromechanical equipment is indispensable in the modernization. The motions of electromechanical systems are becoming increasingly complex, which inevitably involves nonlinearity. The recent advances in design, analysis and control are to improve dynamic performance, steady-state stability, and anti-interference ability to meet modern industry upgrading requirements. In recent years, with the increasing complexity of application scenarios, one has higher anticipation for the nonlinear dynamic performance, intelligence, and automation of electromechanical systems, which also brings new challenges to the research, design, and control of electromechanical systems. Therefore, how to combine nonlinear dynamics, artificial intelligence, and automation with the research, design, and control of the electromechanical system has become a hot issue. The advanced analysis, design and control methods contribute to develop and improve nonlinear electromechanical systems with high stability and dynamic performance. We gather the recent advances on nonlinear dynamics and control of electromechanical systems to provide new perspectives to the research and design of the future products.

**Keywords:** nonlinear dynamics; stability; control; electromechanical systems

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## 1. Introduction

This decade, the 2020s of the 21st century, witnesses technological development at an unprecedented pace. The industry is developing toward higher level of speed, intelligence, output power, energy consumption etc. Electromechanical equipment is indispensable in this modernization process. To meet the upgrading requirements, the design, analysis and control methods have been upgrading beyond traditional linearization techniques which often fail to capture the full dynamic behaviors. And the field of electromechanical systems is turned to focus on the inherent and complex nonlinearities. The advanced analysis, design and control methods contribute to develop and improve nonlinear electromechanical systems with weight reduction, high specific strength, enhanced performance, improved efficiency, superior durability, multi-function integration, etc.

Back in 1968, Stephen and Crandall [1] wrote a book about electromechanical systems that emphasized the utilization of mechanical approaches. Hamilton's principle was subsequently introduced to the electrical networks that contain flux linkages and voltage. Later in 1990, Melcher and Woodson [2] publish their book focusing in on the discipline of electromechanical systems. They broaden the field of electromechanical systems and scenarios to include lumped-parameter electromechanics, rotor machines, and incompressible and inviscid fluids.

The rapid evolution of technology globally can be profoundly attributed to foundational research in the field of microelectromechanics. Petersen [3] proposed new fabrication procedures for the construction of deflectable $SiO_2$ (Silicon Dioxide) electrostatic silicon membranes for control relays. These active membranes were designed by insulating amorphous films, which extended their lifetimes. The anticipated compatibility with conventional silicon IC technology helped their potential applicability on integrated devices. Dynamic silicon micromechanics would provide the "ideal" functions which could be invaluable in future—MEMSs (microelectromechanical systems) are among the most common technical applications. Shi et al. [4] applied boundary element and finite element methods to achieve dynamic deformation, and numerical techniques were proposed for the nonlinear responses of MEMSs subjected to DC and AC signals. The responses of their physical analog model of tweezers under AC were concluded as a Mathieu equation for comprehensive analysis.

Another common application of electromechanical systems lies in mechanical transducers. The combination of mechanical movement and electrical conduction is the ideal way to transfer motions into voltage signals. Tilmans [5] designed electrostatic, electromagnetic, and electrodynamic lumped-parameter transducers—equivalent circuits of static and dynamic electromechanical coupling were designed to transfer movements into voltage signals. Abadal [6] proposed a nanocantilever-based sensor for high-resolution and high-sensitivity mass detection. An equivalent model of the cantilever-driver system with current/voltage conversion and a feedback circuit equationwas derived to calculate the voltage collapse and deflection of the cantilever, as well as the current flow and mass resolution. Preumont [7] analyzed the mechatronic dynamics of electromechanical and piezoelectric transducers in which the damping performances could be tuned by the designed circuits. The active damping was considered to be a discrete piezoelectric transducer and integral force feedback was added for guaranteed stability; passive control with inductive shunting was analyzed in the capacitive piezoelectric transducer.

The utilization of energy harvester facilitates the conservation of work to which the electromechanical device also contributes. Erturk [8] proposed distributed-parameter electromechanical models for the study of the dynamics of piezoelectric energy harvesters. The multi-mode frequency responses were studied analytically and reduced to single-mode for modal vibrations. The electromechanically coupled voltages and vibrations were obtained and validated by experiments. To make better use of mechanical energy and to achieve the maximum electromechanical transduction, Masana and Daqaq [9] established a tunable clamped- energy harvester with static axial loads and transversal excitations. Following configuration, the harvester could be tuned over a wide range of frequencies by the axial load, and the bandwidth could be improved by the electromechanical coupling and effective nonlinearity.

The other eletromechanical systems include actuators, resonators, electromechanical transmission systems, etc. Bottauscio et al. [10] aimed to produce an electromagnetic actuator and proposed two advanced finite element-based models to study the corresponding dynamics. The motions of the armature were studied by the overlapping mesh method and with a combination of the finite element method and boundary element methods. Postma et al. [11] studied the strongly nonlinear response of nanomechanical resonators and simulated their nonlinear motions using governing equations that took into consideration high levels of thermomechanical noise. The nonlinear domains at the nanoscale helped in terms of noise reduction and signal enhancement. Liu et al. [12] studied a cutting electromechanical transmission system. They established a dynamic model that encompassed an electric motor, gear transmission, and shearer drum. The meshing shocks came from both the time-varying meshing stiffness and the meshing shock load. The coupling stiff-

ness and damping of the electric motor and gear transmission were derived, and optimal parameters were obtained to reduce the meshing shocks. Neyman L. and Neyman V. [13] studied the dynamics of an electromagnetic converter, with coupling equations describing the circuits and deriving translating masses. The transient, stationary, and resonant modes were analyzed through the models with mobility degrees. Xu and Luo [14] introduced a generalized harmonic balance method to the nonlinear electronic circuits for the analytical solutions. The technique transformed the differential nonlinear circuit equations to the dynamic systems of coefficients of the Fourier series. With the transformation completed, the stability and bifurcations of the nonlinear circuits were obtained, and the nonlinearity, complexity, and singularity of the nonlinear electronic circuits were analyzed analytically.

## 2. The Collections

This Special Issue aimed to collect the recent research on electromechanical systems with a focus on system modeling, nonlinear dynamics, data-driven methods, and machine learning. Wang et al. [15] studied the fault identification of bearings in electric motors. The recurrence quantities are extracted for the hidden properties of the data. various activation functions in the activation layer were discussed for improved fault diagnosis algorithms. Lu et al. [16] considered the contact dynamics of a rotor-stator system. They focused on the analytical solutions of the whirling vibrations and the corresponding bifurcations. Continuous crossing and grazing–sliding motions were captured. Analytical formulations were derived for the self-excited backward whirling vibration of stick–slip nonlinear motions. Xu et al. [17] considered the uncertainties inherence in rotor systems. An innovative sparse-grid integration method was proposed for the high-dimensional integration of the nonlinear vibrations. They found that the combination of the Chebyshev interval method with the sparse grid numerical integration technique enhanced the computational efficiency and robustness during calculation. Liu et al. [18] focused on the semi-analytical computational methods. A close-loop computational matrix ring was constructed for approaching the nonlinear motions. The high dimensional discrete polynomial system was transformed into milli-times smaller size Jacobian matrices for stability and bifurcations. Based on this computational technique, the bifurcation trees was captured with clean and clear stable and unstable periodic motions. They found that a few bifurcation trees were independent of each other. The saddle-node bifurcation triggered the bifurcation trees in the double-well van der Pol system. Zhang et al. [19] designed an H∞ controller to improve the accuracy and reliability of an active–passive integrated six-dimensional orthogonal vibration isolation (APIVI) with parameter uncertainties. The nonlinear model considering the electromechanical coupling effects was established to reflect the frequency dependence of the isolation system.

## 3. Open Problems

The application of nonlinear dynamics in electromechanical systems has achieved significant success. Yet theoretical application and real-word engineering practice retain numerous unresolved problems. These challenges can be categorized into three levels: theoretical modeling, nonlinear analysis and control, and engineering implementation. A comprehensive introduction to these levels is shown below.

### *3.1. Challenges in Modeling and Characterization*

Nonlinearities in electromechanical systems are inevitable. Yet accurate modeling remains the primary challenge that researchers can confront and should overcome.

(1) High-fidelity coupled multi-physics modeling [20,21]

Electromechanical systems are usually coupled by electricity, mechanics, magnetics, thermals, fluids, etc. For instance, the core saturation and eddy current losses where electromagnetic nonlinearities arise in electric motors cause temperatures to rise, which in turn affects the material and mechanical properties, consequently influencing vibrations where mechanical nonlinearities will emerge. A universal model capable of accurately and uniformly describing such complex coupled nonlinear dynamics is still needed.

The balance between model complexity and computational efficiency comes with additional challenges. High-fidelity models (e.g., finite element models) are computationally intensive and difficult to implement for real-time control or system optimization.

(2) Parameter identification and state prediction [22,23]

The parameters of nonlinear models such as the Coulomb friction coefficient, Stribeck velocity in friction models, hysteresis loops, etc., are often difficult to measure accurately in conventional experiments. Simultaneously, key internal state variables, such as internal contact forces, magnetic flux, local stress, etc., are also challenging to measure.

Developing robust algorithms capable of simultaneously predicting system states and identifying key nonlinear parameters in real time continues to be challenging since these algorithms require high levels of insensitivity to model errors and measurement noise.

(3) Time-delayed and magnetic hysteresis modeling [24,25]

Smart materials like piezoelectric ceramics, shape memory alloys, and magnetic materials are widely utilized in electromechanical actuators, and exhibit non-smooth hysteretic phenomena. Existing models are able to describe static hysteresis reasonably well, but accurately modeling dynamic hysteresis remains a challenge.

The practical requirement is the establishment of dynamic hysteresis models that achieve both accuracy, in terms of fitting experimental data, and structural simplicity sufficient for controller design.

### *3.2. Challenges in Analysis and Control Design*

Controller design based on nonlinear models is critical, but is also particularly challenging.

(1) Analysis and control of non-smooth and discontinuous systems [26,27]

Nonlinearities in non-smooth systems, such as impact, backlash, and dry friction, are prevalent in electromechanical systems. These characteristics lead to complex dynamic behaviors like bifurcations and chaos. The existed nonlinearities usual cause traditional control theories based on linear or smooth nonlinear assumptions to fail.

How to define and prove global stability or uniform ultimate boundedness for such non-smooth systems remain challenges. Applying Lyapunov stability theory to the systems is challenging. How to design controllers that can achieve high-precision tracking while also suppressing or even utilizing these nonlinear dynamics (e.g., chaos anti-control) calls for greater efforts.

(2) Model-based robust and adaptive control [28,29]

Nonlinear models always contain unsolved dynamics and parametric uncertainties (e.g., friction coefficients changing with wear). Therefore, the main issues are designing controllers that maintain the desired performance under these uncertainties, quantitatively determining the uncertainty bounds of nonlinear dynamics, and designing robust controllers that are not overly conservative.

For systems with rapidly varying parameters (e.g., parameter drift due to thermal deformation), traditional parameter adaptation laws may not track changes swiftly enough. Consequently, developing faster adaptive algorithms guaranteeing global stability remains an open problem.

(3) Chaos detection, control, and utilization [30,31]

Under certain conditions, electromechanical systems can enter chaotic states that manifest as performance degradation and increased vibration/noise. How to detect chaotic states in real-time and apply effective control to return the system to periodic orbits or fixed points is an area that demands greater attention.

Furthermore, can the system be actively and purposefully guided into a chaotic state for specific applications like mixing or vibrational grinding? This would require a deep understanding and more precise manipulation of chaotic dynamics.

### *3.3. Challenges in Engineering Implementation*

Theory should ultimately be implemented in practice.

(1) Computational complexity and real-time performance [32,33]

Advanced nonlinear control algorithms (e.g., nonlinear model predictive control (NMPC) or real-time optimization-based control) require complex optimization problems or differential equations to be solved, which places high demands on the computational capability of the processor.

How to achieve real-time execution of the complex algorithms on the systems when resource is limited (e.g., DSP or FPGA). This requires synergistic innovation in algorithm simplification, hardware acceleration, and dedicated chip design.

(2) Sensor and actuator limitations [34,35]

High-performance nonlinear control often relies on full-state feedback, yet many critical states cannot be measured using cost-effective and reliable sensors. Simultaneously, actuators (e.g., motors and hydraulic cylinders) themselves have limitations like bandwidth and saturation.

Developing low-cost, highly reliable soft sensors, and proactively considering the real-time actuator dynamics and saturation nonlinearities in controller design is imperative.

(3) Verification and reliability [36,37]

Nonlinear systems are more complex than linear systems, which may cause traditional verification methods based on frequency domain or linear time-invariant assumptions to be inadequate. How to comprehensively verify the stability and reliability of nonlinear systems and the control, especially over a broad range of operating conditions and failure modes remains concern

Developing verification approaches based on nonlinear methods and hybrid theories, and establishing high-fidelity simulation platforms based on hardware, makes it possible to reproduce as many extreme scenarios as possible.

## 4. Conclusions and Acknowledgments

The application of nonlinear dynamics in electromechanical systems is evolving from "passive compensation" towards "active design and utilization." Future breakthroughs will likely involve the following:

(1) Integration of data and models: combining machine learning with nonlinear dynamics theories; taking advantage of data to learn unmodeled dynamics and design more intelligent controllers.
(2) Cross-scale modeling and analysis: establishing a unified cross-scale analysis framework spanning from microscopic material nonlinearities to macroscopic system-level dynamics.
(3) Dedicated computing hardware: designing specialized AI chips or FPGA architectures for complex nonlinear control algorithms to address real-time performance bottlenecks.

Addressing these challenges will significantly advance the development of next-generation electromechanical equipment. We hope, therefore, that this Special Issue can provide new perspectives on the research and design of nonlinear dynamics and products.

The Guest Editors of this Special Issue would like to thank all the authors of the collections, for their kind support. This Special Issue presents advanced developments and applications of nonlinear dynamics in electromechanical systems. As Guest Editors, we hope the collections will promote researchers to dig deep in the fields of electromechanical systems.

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