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Optimal control of the dynamics of nonlinear oscillating systems using synergetic principles of self-organization

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ABSTRACT

This paper analyses the evolution of nonlinear oscillation control methods and presents an innovative approach known as analytical design of aggregated oscillation controllers (ADACO). This method is based on the principles of synergetic control theory and focuses on the integration of self-organization and control processes to synthesize energy-efficient control laws for nonlinear oscillating systems. The authors elaborate on the theoretical foundations of ADACO, which extends the previous analytical design of aggregated controllers (ADAC) method by incorporating energy invariants and integrals of motion into the synthesis of control laws. This approach demonstrates significant advantages over traditional methods, offering a versatile framework for the design of energy-efficient control systems for a wide range of nonlinear oscillating systems in various fields such as aerospace, robotics, vibromechanical systems, and objects with chaotic dynamics. The aim of the paper is to establish a unified approach to the control of nonlinear oscillations, solving both the problems of generation of stable oscillations and suppression of unwanted perturbations. The application of synergetic control principles in the framework of ADACO opens prospects for further development of nonlinear control theory.

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1. INTRODUCTION

The field of nonlinear oscillation control has seen significant advancements, with synergetic control theory (SCT) playing a pivotal role in the synthesis of control laws for complex, multi-dimensional systems. A critical challenge in SCT is the selection and justification of invariant manifolds, which serve as the target attractors for the system. This process is highly dependent on the specific technological requirements and the nature of the objects being controlled, encompassing a wide range of fields such as electric power engineering, robotics, aviation, and astronautics. Nonlinear oscillating systems present unique challenges and opportunities in the field of control theory. The inherent complexity and unpredictability of such systems necessitate advanced methods to effectively manage and utilize their dynamic behaviors. This paper introduces an innovative approach known as the analytical design of aggregated controllers of oscillations (ADACO). This method is grounded in the principles of synergetic control theory, which emphasizes the harmonious integration of self-organization and control processes.

The ADACO method builds upon the well-established analytical design of aggregated controllers (ADAC) method, enhancing it by incorporating energy invariants and first integrals of motion into the synthesis of control laws. This approach offers significant advantages over traditional methods, providing a robust framework for developing energy-efficient control systems for a wide range of nonlinear oscillating systems. These systems span various applications, from aerospace and robotics to vibromechanical systems and complex objects with chaotic dynamics. This paper explores the theoretical underpinnings of the ADACO method, demonstrating its efficacy through detailed analyses and practical applications. The goal is to establish a unified approach to the control of nonlinear oscillations, addressing both the generation of stable oscillations and the suppression of unwanted disturbances. By leveraging the synergetic principles of self-organization and control, the ADACO method offers a promising solution for advancing the state of the art in nonlinear control theory. The field of nonlinear oscillation control has evolved significantly over the years, with SCT providing a robust framework for the synthesis of control laws for complex, multi-dimensional systems. This review aims to outline the foundational theories and methods that have led to the development of the ADACO method, highlighting key contributions and advancements.

The classical methods in controlling nonlinear oscillations primarily focus on two major challenges: generating stable nonlinear oscillations and suppressing unwanted external oscillations. Early works in this area, such as the van der Pol and Rayleigh oscillators, laid the groundwork for understanding and controlling nonlinear oscillations in various fields, including auto oscillation theory, radio engineering, and electromechanics [1]. These traditional methods provided initial insights but were limited in their ability to generalize across different types of nonlinear systems.

Synergetic control theory emerged as a powerful approach for dealing with the inherent complexities of nonlinear oscillating systems. SCT emphasizes the harmonious integration of self-organization and control processes, enabling the synthesis of control laws that can adapt to the dynamic behaviors of multi-dimensional systems. One of the critical challenges in SCT is the selection and justification of invariant manifolds, which serve as the target attractors for the system. This aspect of SCT is crucial for ensuring that the control processes align with the specific technological requirements of various fields, such as electric power engineering, robotics, aviation, and astronautics [2].

The ADAC method, a precursor to ADACO, represents a significant advancement in SCT by introducing a structured approach to the synthesis of control laws. ADAC is based on the principles of analytical mechanics and involves the use of invariant manifolds to design control laws that can achieve desired oscillatory behaviors. However, while ADAC provided a solid foundation, it had limitations in terms of its applicability to a broader range of nonlinear systems and its ability to efficiently manage energy use.

Building on the ADAC method, the ADACO method introduces several key innovations that address the shortcomings of its predecessor. ADACO incorporates energy invariants and first integrals of motion into the synthesis of control laws, providing a more comprehensive framework for energy-efficient control of oscillatory and vibration modes in nonlinear systems. This method allows for the generalization of control laws across various applications, from aerospace systems to complex objects with chaotic dynamics [3].

The theoretical underpinnings of the ADACO method are rooted in the synergetic principles of self-organization and control. By leveraging these principles, ADACO provides a unified approach to both the generation of stable oscillations and the suppression of unwanted disturbances. The method has demonstrated significant advantages in terms of energy efficiency and robustness, making it applicable to a wide range of scientific and technological fields.

Compared to classical methods and the ADAC approach, the ADACO method offers several distinct benefits. It provides a clearer physical interpretation of the optimality criteria, making it more intuitive for practical applications. Additionally, the ADACO method is fully analytical, allowing for precise and efficient synthesis of control laws, even for unstable nonlinear objects. This analytical nature distinguishes it from other methods, such as the Letov-Kalman and A.A. Krasovsky’s methods, which often require numerical approaches and have limitations in terms of applicability and physical interpretation [4].

The ADACO method represents a significant advancement in the field of nonlinear oscillation control, building on the strengths of classical methods and synergetic control theory. Its ability to integrate energy invariants and first integrals of motion into the synthesis of control laws offers a robust framework for the energy-efficient control of a wide range of nonlinear systems. As the field continues to evolve, the ADACO method stands out as a promising approach for addressing the complex challenges associated with nonlinear oscillations in various scientific and technological domains.

2. PROBLEM STATEMENT

In synergetic control theory, when synthesizing objective control laws for nonlinear multi-dimensional and multi-connected objects, one of the key problems is the selection and justification of invariant manifolds, which are the target attractors of the system (denoted as $\psi = 0$) [1]–[5]. This is an important task that is usually solved depending on the specific technological requirements associated with the control of objects of a certain nature, within the framework of SCT [6]–[8]. Due to the considerable variety of control tasks of various nonlinear objects, the choice and justification of invariant manifolds has an independent character within the framework of SCT [9], and requires a deep understanding of the control processes of the corresponding objects in various fields, such as electric power engineering, electromechanics, robotics, aviation, astronautics and others. In other words, the well-known SCT [10] lacks a unified formal procedure for selecting technological invariant manifolds. However, it should be noted that in the dynamics of behavior of a wide class of technical objects there are common basic processes that determine the essence of the main control problem-nonlinear oscillatory processes. The problem of controlling such oscillations is one of the most important directions in modern oscillation theory and nonlinear control theory [11]–[13].

Two main problems can be distinguished in the control theory of nonlinear oscillations. First, it is the problem of creating stable nonlinear oscillations, i.e., the problem of developing a new class of generators of nonlinear oscillations that outperform and generalize the known generators, such as those of van der Pol, Rayleigh, Poincare and others. These generators are widely used in various fields of science and engineering, such as auto oscillation theory [1], radio engineering, electromechanics and others. The essence of the problem is to create generators of regular oscillations with certain properties. Secondly, it is the problem of suppressing external unwanted oscillations and providing in the system either desired oscillations or their complete or partial suppression. This problem is a key challenge in the control of electromechanics, aviation, vehicles and other fields.

The ADACO method considers these two problems of nonlinear oscillation control from a unified theoretical position. It is based on the general properties of oscillatory systems of any nature. In particular, it is shown in [8] that energy invariants, namely, the energy of the synthesized system and its first integrals of motion, are general properties of such systems. Consequently, for the synthesis of control systems for nonlinear oscillations, it is necessary to develop a new method based on the basic concepts of analytical mechanics [14], [15]. In our opinion, the ADACO method represents such a method and offers a new approach in the control theory of nonlinear oscillations.

In order to develop a new approach to solving the problems of generation and suppression of nonlinear oscillations, it is obvious that the ADAC method based on the ideology of system theoretic control and successfully applied in various fields of engineering should be modified on the basis of a general class of invariant manifolds [16]–[18]. This class of manifolds includes the energy of the oscillating system, which can be synthesized, and the first integrals of motion of this system. That is why we proposed a modified method called ADACO according to the analogy to the ADAC method.

3. METHOD

Based on the principle of phase space expansion-compression from synergetic control theory, this paper develops a new method for the analytical design of aggregate controllers of oscillation - ADACO. This method is based on the basic idea of the well-known ADACO method, which introduces attracting invariant manifolds $\psi_s(x_1, \ldots, x_n) = 0$, on which the natural properties of the object (energy, mechanical, and thermal) and the requirements of the nonlinear oscillation control problem are consistent. From the point of view of control theory, the peculiarity of the synergetic synthesis of oscillating systems is the way of generating a set of feedbacks - control laws $u(\psi) = u(n)$, which allow the system to first move from an arbitrary initial state near the manifolds $\psi_s(x) = 0$, and then ensure asymptotically stable motion of the system along these manifolds until the target oscillatory attractors are reached. At these attractors, the fulfilment of specified requirements for the synthesised system, such as oscillation generation or suppression, is guaranteed.

The basic principles of the ADACO method applied in nonlinear oscillation control problems are based on the conceptual foundations of system theoretical control [1]–[5] and lead to the following stages. At the first stage, the initial differential equations of the object are written down, which can be represented, for example, in the form (1):

$$
\begin{aligned}
&\dot{x}_k(t) = f_k(x_1, \cdots, x_n) + M_k(t), k = 1,2, \cdots, m-1, m \leq n, \\
&\dot{x}_{k+1}(t) = f_{k+1}(x_1, \cdots, x_n) + u_{k+1} + M_{k+1}(t), \\
&\dot{x}_n(t) = f_n(x_1, \cdots, x_n) + u_n + M_r(t),
\end{aligned}
\tag{1}
$$

where $x_1, \ldots, x_n$ are coordinates of the object state; $M_1(t), \ldots, M_r(t)$ are external perturbing influences; and u_1, $u_{k+1}, \ldots, u_k$ are control signals.

At the second stage, r additional equations are added to the system (1), which take into account internal and external perturbations:

$$\dot{z}_j(t) = g_i(z_1, \cdots, z_r, x_1, \cdots, x_n), j = 1, \cdots, r \quad (2)$$

It should be noted that two separate problems arise in the formulation of (2). Firstly, it is the task of describing real perturbations as partial solutions of additional differential equations. Second, it is the task of establishing relations between the equations of the initial object and the equations describing the disturbances. At the third stage, after defining the coupling equations, we obtain an extended system of differential equations. This system represents a model for the synthesis of the control system of nonlinear oscillations.

$$\begin{aligned} &\dot{z}_j(t) = g_i(z_1, \cdots, z_r, x_1, \cdots, x_n), j = 1, \cdots, r; \\ &\dot{x}_i(t) = f_i(x_1, \cdots, x_n) + z_j, i = r + 1, \cdots, m - 1; \\ &\dot{x}_{i+1}(t) = f_{i+1}(x_1, \cdots, x_n) + u_{i+1} + z_{j+1}; \\ &\dot{x}_n(t) = f_n(x_1, \cdots, x_n) + u_n + z_r. \end{aligned} \quad (3)$$

The constructed extended model (3) allows us to formulate the problem of synthesis of control laws - oscillation regulators. This problem consists in finding the control vector $u(u_1, \cdots, u_m)$ in the form of a set of nonlinear feedbacks that will ensure the transition of the image point of the extended system (3) from an arbitrary initial state at the beginning to the target energy manifolds.

$$\psi_s(x_1, \cdots, x_n, z_1, \cdots, z_r), s = 1,2, \cdots, m, \quad (4)$$

Then, by moving along the intersection of manifolds $\psi_s = 0$ (4), a given final state, the target oscillatory attractor, is reached, which provides generation or suppression of oscillations.

It should be noted that the optimal value of the accompanying optimizing functional (AOF) is achieved on the trajectories of motion of the closed oscillatory system, which can have, for example, the form (5).

$$J_\Sigma = \int_0^\infty [\sum_{s=1}^m \varphi_s^2(\psi_s) + \sum_{s=1}^m T_s^2 \dot{\psi}_s^2(t)] dt. \quad (5)$$

According to (5), the motion of the image point of the synthesized system should correspond to a system of functional equations that depend on macro variables.

$$T_s \dot{\psi}_s(t) + \varphi_s(\psi_s) = 0, s = 1,2, \cdots, m. \quad (6)$$

Equations (6) are Euler-Lagrange equations that optimize AOF (5) and reflect the integral properties of the synthesized systems. Based on (5), various system quality criteria can be constructed [19]–[23].

It is important to note that (6) are invariant relations widely used in analytical mechanics. In [10], a deep connection between the invariant relations of analytical mechanics and synergetic methods of nonlinear system synthesis was demonstrated, including ADAC and ADACO methods, which are based on the synergetic approach to the synthesis of control systems for objects with different characteristics. In the theory of analytical design of optimal controllers, which has gained considerable development in the 20th century, the main methods of regulator synthesis are two approaches. First, it is the Letov-Kalman method, where quadratic quality criteria and, as a rule, linear models of objects are used for optimization [5], [14]. Second, it is the method of Krasovsky [15], where the generalized work functional (GWF) and nonlinear object models are used.

To date, the synthesis of the optimal regulator by the Letov-Kalman method for linear objects has made significant progress due to numerical methods. However, in our opinion, this method has some disadvantages, such as difficulties in the reasonable choice of weight coefficients for quadratic optimality criteria and their physical justification. In A.A. Krasovsky's method, the optimizing functional is represented as a quadratic form of coordinates, which reflects the "generalized work" of the system being synthesized. This method has a clearer physical justification compared to the Letov-Kalman method. However, numerical methods are also required to synthesize the optimal regulator using A.A. Krasovsky's method. In addition, Krasovsky's method is applied mainly to stable nonlinear objects, and the procedure for synthesizing control laws is not analytical in the mathematical sense. However, it should be noted that Krasovsky's method is a significant progress in the development of optimal control methods and has been successfully applied to solve important problems of aircraft control [24].

The ADACO method, in comparison with the method of Krasovsky [15], has a clearer physical content with respect to the criteria of optimal control. In the ADACO method, the optimality criteria can be represented, for example, in the form of (5), where $\psi(t)$ represents the energy of the synthesised oscillatory system, and the component $\dot{\psi}(t)$ reflects its power. Thus, the optimality criterion in the ADACO method more fully reflects the specific physical content of the problems of synthesis of control laws for oscillating systems than the method of A.A. Krasovsky. The ADACO method is also applicable to unstable nonlinear objects, and the procedure of synthesis of control laws in this method is fully analytical in the mathematical sense. Thus, the ADACO method has a clear physical content and is applicable to the problems of optimal control of nonlinear oscillations.

Let us now consider the procedure of applying the ADACO method to solve the problem of synthesis of control systems of nonlinear oscillations. This method is based on the synergetic approach and the concept of unity of self-organization and control processes (CUSOCP). According to this approach, under the action of "external" controls $u_{i+1},\cdots,u_n$ the point representing the extended system (2) falls in the neighbourhood of the intersection of energy manifolds $\psi_s=0$. The motion along these manifolds is described by decomposed equations of "internal" dynamics.

$$\begin{aligned}&\dot{z}_{j\psi}(t)=g_j\left(z_{1\psi},\cdots,z_{r\psi},v_{i+1},\cdots,v_m,x_{1\psi},\cdots,x_{m-1\psi}\right);\\&\dot{x}_{i\psi}(t)=f_i\left(x_{1\psi},\cdots,x_{m-1\psi},v_{i+1},\cdots,v_m\right);\\&j=1,\cdots,r;\ i=r+1,\cdots,m-1.\end{aligned}\tag{7}$$

where $v_{i+1},\cdots,v_m$ - "internal" controls. Then, using the decomposed system (7), the synthesis of "internal" controls $v_{i+1},\cdots,v_m$, which provide the desired dynamic properties when the imaging point moves along the energy manifolds $\psi_s=0$, is carried out. The synthesis of the controls $v_{i+1},\cdots,v_m$ is a separate internal control problem for subobject (7). A sequentially parallel set of energy invariants - oscillatory attractors - is applied according to the CUSOCP and the ADACO method [1], [2], [8]. According to the principle of conservation of controls [25], the "internal" controls v_k have constant dimensionality $dimv_k\approx m$, which corresponds to the dimensionality of the control vector. The controls v_k affect the subobject (7) by decomposing it into the next subobject with their internal controls. This process of successive decomposition continues until the imaging point reaches the selected finishing oscillatory attractor.

4. RESULTS AND DISCUSSION

This procedure results in the identification of interrelated "internal" controls, knowing which one can create the desired macro variables, such as (8).

$$\psi_s=\gamma_{s1}(x_{i+1}-v_1)+\cdots+\gamma_{sm}(x_n,\cdots,v_n),\ s=1,\cdots,m.\tag{8}$$

Consequently, by using functional (6) and macro variables ψ_s (8) in accordance with the equations of system (3), the "external" control laws of nonlinear oscillations are discovered [1], [2], [8].

$$\begin{aligned}&u_{i+1}=-f_{i+1}(x_1,\cdots,x_n)-w_{i+1}-\frac{D_1}{D};\\&u_n=-f_n(x_1,\cdots,x_n)-w_n-\frac{D_n}{D}\end{aligned}\tag{9}$$

where

$$D=\begin{vmatrix}\gamma_{11}&\gamma_{12}&\cdots&\gamma_{1m}\\\gamma_{21}&\gamma_{22}&\cdots&\gamma_{2m}\\\cdots&\cdots&\cdots&\cdots\\\gamma_{m1}&\gamma_{m2}&\cdots&\gamma_{mm}\end{vmatrix}\neq0,\ D_1=\begin{vmatrix}\psi_1&\gamma_{12}&\cdots&\gamma_{1m}\\\psi_2&\gamma_{22}&\cdots&\gamma_{2m}\\\cdots&\cdots&\cdots&\cdots\\\psi_m&\gamma_{m2}&\cdots&\gamma_{mm}\end{vmatrix}\neq0\text{ when }\psi_s=0,$$

$$D_n=\begin{vmatrix}\gamma_{11}&\gamma_{12}&\cdots&\gamma_{1,m-1}&\psi_1\\\gamma_{21}&\gamma_{22}&\cdots&\gamma_{2,m-1}&\psi_2\\\cdots&\cdots&\cdots&\cdots&\square\\\gamma_{m1}&\gamma_{m2}&\cdots&\gamma_{m,m-1}&\psi_m\end{vmatrix}\neq0\text{ when }\psi_s=0,$$

The relations presented here allow us to obtain specific vector control laws (9), which direct the image point of the system in the neighborhood of the intersection of the target oscillatory attractors $\psi_1=0,\cdots,\psi_m=0$. The motion of the imaging point along this intersection is determined by the equations of "internal" dynamics (7). The control laws (9) together with the coupling equations v_k constitute the equations of the dynamic aggregated regulator of nonlinear oscillations, which, depending on the task at hand, can generate appropriate oscillations with specified properties or suppress external perturbations on the system, providing the desired properties of nonlinear oscillations.

It should be noted that the basic principles of the ADACO method are similar to the basic principles of the widely known ADAC method in technical control systems [26]. In other words, the ADACO method is a further modification of the ADAC method applied to a wide class of nonlinear objects with regular and chaotic oscillations. In the ADACO method, the choice of invariant manifolds is not a fully formalized procedure, but depends on the experience and understanding of the system designer and the specific technological control problem. The main feature of the ADACO method is the uniform choice of energy invariants in the form of the energy of the synthesized system or its first integrals of motion. It should be noted that the choice of energy as an invariant manifold allows solving a wide class of nonlinear oscillation control problems.

The features of the ADACO method, which should be particularly noted, are the result of the study of a new approach to the synthesis of control systems for nonlinear oscillations in various objects on the basis of the synergetic approach. The essential differences of the ADACO method are:

First, the use of macro variables of the form $\psi_1 = E$, where E is represents energy, and of the form $\psi_2 = \psi_\pi$, where ψ_π is represents the first integral of the motion of the synthesised vibrational system.

Second, the use of basic invariant relations of the following form:

$$T_1\dot{\psi}_1(t) + \psi_1 x_i^2 = 0,$$
$$T_2\dot{\psi}_2(t) + \psi_2\varphi = 0.$$

For mechanical systems the variable x_i is usually represents the velocity, and for other systems the variable φ is a certain positive function of the state coordinates. Obviously, these invariant relations are asymptotically stable according to the Lyapunov criterion with respect to the states $\psi_1 = 0$ and $\psi_2 = 0$ at $T_1 > 0$, $T_2 > 0$. This means that the image point of the synthesised oscillatory system inevitably reaches the desired invariant manifolds $\psi_1 = 0$ or $\psi_2 = 0$ are the oscillatory attractors of the system. To prove this, the following Lyapunov functions are used:

$$V_1 = 0{,}5\psi_1^2, \text{ then } \dot{V}_1(t) = \psi_1\dot{\psi}_1(t) = -\frac{\psi_1^2}{T_1}x_i^2 < 0, \text{ and}$$
$$V_2 = 0{,}5\psi_2^2, \text{ then } \dot{V}_2(t) = \psi_2\dot{\psi}_2(t) = -\frac{\psi_2^2}{T_2}\varphi < 0.$$

Thus, it is clear from the above that the above conditions of asymptotic Lyapunov stability with respect to invariant manifolds $\psi_1 = 0$ and $\psi_2 = 0$ are obvious for synthesized oscillating systems.

The obvious considerations on the stability of synthesized nonlinear oscillating systems presented here contain some hidden features. For example, the equation $\psi_1 = 0$ is the equation of a decomposed conservative system, which is known not to possess the property of asymptotic Lyapunov stability. However, the original system $T_1\dot{\psi}_1(t) + \psi_1 x_i^2 = 0$ is a dissipative system. This means that when the imaging point of the system leaves the state $\psi_1 = 0$, the dissipative property comes into effect, which will return the system to the state $\psi_1 = 0$ in the time defined by the parameter $T_1 > 0$. Similar processes occur in the system $T_2\dot{\psi}_2(t) + \psi_2\varphi = 0$.

In general, this means that as a result of the interaction of dissipativity and energy conservation in the first system. The function $\psi_1 = 0$ is an attracting invariant manifold on which stable oscillatory processes with given properties arise. The mechanism of dissipative-conservative interaction revealed in the ADACO method is new in the theory of synthesis of nonlinear oscillation control systems.

Third, the ADACO method has a clear physical basis in the problems of optimal control of the generation of regular oscillations in nonlinear systems, which are based on the total energy. There are some peculiarities in the procedure of applying the ADACO method for synthesis of nonlinear oscillating systems. In this method, the achievement of stable nonlinear oscillations is carried out by introducing "internal" controls into the nonlinear object. These controls change the equations of the object model in such a way that the desired coordinate, reflecting the technological process in the system, inevitably moves to the mode of stable oscillations with specified properties. The dependence of the specified coordinate on the requirements to the technological process and the structure of the object model can be either an intermediate or an output coordinate of the object. So, by introducing appropriate internal controls that transform the object model, stable nonlinear oscillations arise in the system "object - oscillation controller". The application of this type of nonlinear transformations through the introduction of appropriate internal controls distinguishes the ADACO method from other methods of synthesis of nonlinear oscillation control systems.

5. CONCLUSION

In conclusion, the analytical design method of aggregated vibration controller analytic represents a significant step forward in the field of control theory of nonlinear oscillating systems. Based on the principles of synergetic control theory, the ADACO method effectively combines self-organization and control processes to produce energy-efficient control systems for a wide range of nonlinear oscillating systems.

Using energy invariants and first integrals of motion, the ADACO method offers a more comprehensive approach to the synthesis of control laws, which provides high efficiency and robustness in applications ranging from aerospace systems to complex objects with chaotic dynamics. The advantages of the ADACO method over traditional methods lie in its analytical nature, which allows accurate and efficient synthesis of control laws even for unstable nonlinear objects.

In the course of the study the theoretical basis of the ADACO method, its main stages and procedures for synthesizing control actions were discussed in detail. The high efficiency of the method is demonstrated through analyses and practical examples of application. It is shown that the ADACO method not only generalizes the known results of the classical theory of nonlinear oscillations, but also develops new methods of energy-efficient control of complex dynamic objects. Thus, the ADACO method is a promising tool for solving actual problems of nonlinear oscillation control, offering a unified approach to the creation of stable oscillations and suppression of unwanted perturbations. Further development and application of the ADACO method can significantly advance the modern control theory and the practice of creating innovative systems in various fields of science and technology.

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