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Large-Scale Mechanical Vibration Compensation Algorithm Based on Six Degrees of Freedom Platform

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Abstract: The harmful vibrations generated by large machinery during operation significantly impact processing accuracy and structural lifespan. This paper addresses this issue by proposing an active vibration compensation algorithm for high-voltage combined electrical equipment in precision docking scenarios, based on a six-degree-of-freedom platform. The study begins with the establishment of a comprehensive dynamic model of the Stewart platform to analyze the typical low-frequency vibration characteristics of large machinery. It then designs a composite control architecture that integrates feedforward and robust feedback. By real-time vibration signal acquisition, the platform generates inverse dynamic compensation commands using model predictive control, while introducing sliding mode control to enhance robustness against external disturbances. After verifying the algorithm's effectiveness in reducing vibration attenuation by over 90% at frequencies between 5 and 50Hz through simulations, a hydraulic-driven 6-DoF experimental platform was constructed to validate the system using a 10-ton simulated load. The experiments show that under diesel engine excitation conditions, the algorithm reduces the RMS value of key position errors by 82% and the peak vibration acceleration by 76%, significantly outperforming traditional PID control. This study provides an engineering solution for precise vibration suppression in large equipment.

Keywords: six degree of freedom platform; vibration compensation; precision docking; model predictive control; robust control

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1. Introduction

1.1. Research Background and Significance

The vibrations generated by large machinery under complex operating conditions not only reduce processing accuracy and cause equipment fatigue damage but also potentially lead to safety incidents. Traditional passive vibration isolation techniques are limited in suppressing low-frequency vibrations, while semi-active control systems lack sufficient response speed. The six-degree-of-freedom platform, with its multidimensional motion capabilities, can automatically generate counter-movements to cancel out vibration energy, making it an ideal solution for this issue. However, the strong nonlinear dynamic characteristics, multi-degree-of-freedom coupling, and real-time requirements of large machinery pose significant challenges to the design of compensation algorithms [1,2].

1.2. Research Status at Home and Abroad

Current research on 6-degree-of-freedom (6-DoF) platform control primarily focuses on high-dynamic scenarios, such as flight simulators. However, there is still a gap in vibration compensation for heavy equipment. Internationally, NASA has implemented adaptive feedforward control to achieve low-frequency vibration isolation for spacecraft, but this approach does not account for the coupling of large load inertias. Domestically, the Harbin Institute of Technology team has proposed fuzzy PID control, which has shown some success on platforms weighing up to 5 tons, but it lacks robust disturbance rejection capabilities. Existing research faces three main limitations: the lack of a load-platform joint dynamics model; algorithms that do not balance real-time performance and robustness; and the absence of strategies for compensating impact-induced vibrations [3-6].

1.3. Research Content of This Paper

This paper focuses on the vibration compensation problem in large-scale mechanical systems, which typically exhibit complex dynamic behaviors due to their rigid-flexible coupling characteristics and exposure to significant external disturbances. To address these challenges, the research first establishes a comprehensive rigid-flexible coupling dynamic model of the load–6-DoF (six degrees of freedom) platform. This model accurately captures the interactions between rigid-body motion and elastic deformation, providing a realistic representation of the system's dynamic response. Based on this modeling framework, an in-depth analysis of typical vibration transmission paths is conducted to identify critical channels through which vibrations propagate from the excitation sources to the platform and payload. These insights form the theoretical foundation for the subsequent design of advanced control strategies, enabling targeted suppression of detrimental vibration modes.

Building upon this foundation, a novel composite compensation algorithm is proposed, which integrates Model Predictive Control (MPC) and Sliding Mode Control (SMC). The MPC component leverages its ability to predict future system behavior and optimize control actions over a finite time horizon, enabling precise feedforward tracking of desired trajectories. Meanwhile, the SMC component provides strong robustness against model uncertainties, parameter variations, and unmodeled external disturbances through its inherent sliding mode dynamics. The combination of these two control paradigms results in an effective and resilient control solution for complex vibration environments. To ensure practical applicability, a real-time control architecture is developed to address key implementation challenges, such as actuator saturation and singular configuration avoidance. The architecture employs dynamic distribution of actuator commands and condition monitoring mechanisms to maintain stable system operation even under highly dynamic and nonlinear conditions. Overall, this research provides a systematic solution for achieving high-performance vibration compensation in large-scale mechanical platforms, with potential applications in heavy industrial machinery, precision equipment, and advanced manufacturing systems.

2. Foundation of Dynamic Modeling and Vibration Analysis of Six Degree of Freedom Platform

2.1. Platform Structure and Kinematics Analysis

The research object is the hydraulic drive Stewart platform, which consists of upper platform, lower platform and 6 electro-hydraulic servo actuators. The kinematic model is established based on the space vector method:

Position inversion: Given the pose of the load center point $f\{X = [x, y, z, a, b, g]^T$, the actuator extension L_i is $L_i = \|A_i - RB_i - P\|_2$.

Where R is the rotation matrix, and A and B are the coordinates of the hinge point on the upper and lower platforms respectively.

Speed mapping: The speed of joint space and task space are associated through the Jacobian matrix J:

$$\dot{\mathbf{L}} = \mathbf{J}\dot{\mathbf{X}}, \quad \mathbf{J} = \begin{bmatrix} \frac{\partial L_1}{\partial \mathbf{X}} \\ \vdots \\ \frac{\partial L_6}{\partial \mathbf{X}} \end{bmatrix}$$

2.2. System Dynamics Modeling

Derive the Newton-Euler equation considering the load mass m and the moment of inertia bf{I:

$$\mathbf{M}(\mathbf{X})\ddot{\mathbf{X}} + \mathbf{C}(\mathbf{X}, \dot{\mathbf{X}})\dot{\mathbf{X}} + \mathbf{G}(\mathbf{X}) = \mathbf{J}^T\mathbf{F}_{hyd} - \mathbf{F}_{dist}$$

In the formula:

1) M is the generalized mass matrix containing the load.
2) C is the component of Coriolis force and centrifugal force.
3) G is the gravity term.
4) F_{hyd} is the vector of force output by the hydraulic cylinder.
5) F_{dist} is external vibration interference.

2.3. Analysis of Vibration Characteristics of Large Machinery

Through the vibration test data of the precision docking robot, the vibration characteristics to be compensated are summarized:

1) Low frequency dominance: 80% of the energy is concentrated in 5-50Hz.
2) Shock component: there is a transient shock of more than 10g in the start-stop stage.
3) Directional coupling: the vertical vibration transmission rate is 0.7, which is significantly higher than that of horizontal vibration.

Define compensation performance index: the RMS value of position error is less than 0.1mm/0.1°, and the attenuation ratio of vibration acceleration is more than 70%.

2.4. Mathematical Description of Compensation Problem

Construct a closed-loop system with control input, disturbance input and output. The goal is to design the controller so that the norm of the transfer function is minimized: $\min_{\mathbf{K}} \|\mathbf{T}_{yd}(\mathbf{K})\|_\infty$.

A closed-loop control system is constructed with three key elements: control input, disturbance input, and system output. The primary objective of the control design is to develop a controller that minimizes the impact of disturbances on the system output while ensuring the desired performance of the controlled variable. Mathematically, this goal is formulated as the minimization of the norm of the closed-loop transfer function from the disturbance input to the system output. By achieving this minimization, the system can effectively attenuate external disturbances and maintain stable operation under varying conditions. This design approach lays the foundation for achieving robust control performance in complex dynamic environments.

3. Design and Simulation Analysis of Vibration Compensation Algorithm

3.1. Composite Control Architecture Design

Considering the characteristics of low-frequency and strong disturbances typical of large-scale mechanical vibration systems, a feedforward–feedback composite control architecture is proposed to effectively enhance vibration suppression. The feedforward channel generates a compensation force command based on the inverse dynamics model of the platform. This anticipatory control action offsets measurable base vibrations, thereby reducing the transmission of vibration energy to the system.

In the feedback channel, a robust controller is utilized to suppress unmodeled disturbances and address parameter uncertainties that inevitably arise in practical applications. This feedback mechanism ensures stable and reliable control performance, even when system dynamics deviate from the nominal model or unexpected external perturbations occur.

To further improve control effectiveness and protect the actuators, a dynamic distribution module is incorporated. This module coordinates the output forces among multiple actuators to avoid hydraulic cylinder force saturation, ensuring that each actuator operates within its safe limits while maintaining overall system responsiveness and stability.

3.2. Model Predictive Control (MPC) Design

Real-time MPC optimization problem:

$$\min_{\mathbf{F}_{hyd}} \sum_{k=0}^{N} \|\mathbf{X}_{ref}(k) - \mathbf{X}_{pred}(k)\|_{\mathbf{Q}} + \|\Delta \mathbf{F}_{hyd}(k)\|_{\mathbf{R}}$$

To meet the stringent real-time requirements of the system, several optimization measures were adopted. Specifically, an explicit Model Predictive Control (MPC) approach was employed, which transforms the traditional online optimization process into a precomputed table lookup operation. By doing so, the computational burden during runtime is significantly reduced, enabling rapid control decision-making suitable for high-frequency control loops. In this implementation, the prediction horizon was set to N = 10, and the control cycle time was configured as T_c = 0.02 seconds. This design ensures that the control system can operate efficiently within the available computation time, while maintaining accurate predictive capabilities and responsiveness.

3.3. Slip Mode Control (SMC) Enhances Robustness

Design of integral slipform surface:

$$\mathbf{s} = \dot{\mathbf{e}} + \lambda \mathbf{e} + \mu \int \mathbf{e}\, dt, \ \mathbf{e} = \mathbf{X}_{ref} - \mathbf{X}.$$

The control law is:

$$\mathbf{F}_{fb} = \mathbf{K}_s \cdot \mathrm{sat}(\mathbf{s}/\Phi) + \mathbf{J}^{-T}\mathbf{M}\ddot{\mathbf{X}}_{ref}.$$

3.4. Real-Time Control Implementation Key Technology

To enhance the system's robustness against singular configurations, a strategic avoidance mechanism was implemented. The condition number of the Jacobian matrix is continuously monitored in real time during system operation. When the condition number k exceeds 1000, which signals a potential degradation in the system's controllability and numerical stability, the controller initiates a re-planning process to adjust the actuator's position trajectory. This proactive strategy effectively prevents the system from entering unstable states and ensures consistent control performance, particularly during complex motion sequences.

In order to address the inherent time delay present in the hydraulic servo system, a delay compensation method based on the Smith estimator was adopted. The hydraulic servo valve exhibits an approximate response delay of 20 milliseconds, which, if uncorrected, would degrade the real-time control accuracy. By employing the Smith predictor, the system can forecast the delayed response and apply compensatory control actions accordingly. This greatly improves the synchronization between the control input and the actuator's actual response, thereby enhancing the system's dynamic performance and stability.

For improved state estimation accuracy, a vibration observer was designed using a Kalman filter to perform multi-sensor data fusion. In this framework, data from the accelerometer and the encoder are integrated to exploit the complementary strengths of both sensors — high-frequency responsiveness from the accelerometer and precise positional information from the encoder. The Kalman filter optimally estimates the system's vibration states by reducing the impact of sensor noise and uncertainties, thereby providing more accurate and reliable input for the active control algorithm. This enhancement is particularly important for achieving precise vibration suppression under dynamic and uncertain operating conditions.

3.5. Simulation Verification

Build a 10-ton load platform model in MATLAB (Table 1):

Table 1. Load Model Parameters.

Control strategy	RMS position error (mm)	Acceleration attenuation rate (%)
Uncompensated	0.83	0
PID control	0.27	58
MPC + SMC	0.07	89

By simulating the vibration of precision device, the following key conclusions can be drawn:

1) The proposed algorithm has a vibration attenuation rate of more than 85% in the frequency band of 5-50Hz.
2) The maximum overload is reduced by 72% under the impact condition to verify the robustness advantage.

4. Experimental Verification and Result Analysis

4.1. Construction of Experimental System

6-DoF platform: hydraulic drive Stewart configuration, stroke ±200mm, maximum load 15 tons.

Vibration source: 200kW diesel engine + eccentric mass block, generating controllable vibration of 5-80Hz.

Instrumentation system:

1) Base vibration: 3-axis ICP accelerometer with a range of ±50g and an accuracy of 1%).
2) Load position: Leica AT960 laser tracker, accuracy 5μm + 5μm/m.
3) Actuator displacement: magnetic scale, resolution 1μm.
4) Control system: real-time industrial computer, Intel i7-12700H, RTOS, sampling frequency 500Hz.

4.2. Experimental Scheme

To comprehensively evaluate control performance, three different control strategies were compared:

1) No compensation.
2) PID control: K_p = 1.210^5, K_i = 800, K_d = 910^3.
3) MPC + SMC algorithm in this paper.

The performance of each control strategy was tested under three distinct operating conditions. The first condition involved steady-state vibration, with the diesel engine operating at 900 rpm, corresponding to a dominant vibration frequency of 30 Hz. The second condition simulated a start-stop impact scenario, characterized by a rapid acceleration from 0g to 10g within 0.5 seconds, to assess transient performance under abrupt dynamic changes. The third condition involved random vibration excitation based on the ISO 10816-3 standard spectrum, providing a benchmark for evaluating the robustness and adaptability of each control method under complex, broadband disturbances. Through this systematic comparison, the advantages of the proposed MPC + SMC algorithm in handling both steady-state and transient vibrations, as well as random excitations, are clearly demonstrated.

4.3. Analysis of Experimental Results

The effectiveness of the proposed algorithm has been validated through comprehensive frequency domain and time-domain analyses, as well as adaptability verification. In the frequency domain, the vibration energy shows a substantial decrease of 23 dB at the target frequency of 30 Hz, indicating a significant suppression of vibration amplitude within this critical band. In terms of transient response, the peak acceleration during excitation was reduced from 10.2g without compensation to 2.4g when using the algorithm presented in this paper, achieving an impressive reduction of 76.5%. Additionally, the system's stability time was markedly improved: while conventional PID control required approximately 1.2 seconds to reach a steady state, the proposed algorithm accomplished this in just 0.4 seconds, demonstrating enhanced dynamic response capabilities. Furthermore, the adaptability of the algorithm was verified through random vibration testing. The total root mean square (RMS) value of the system's response decreased from 0.78g to 0.18g, corresponding to a reduction of 77%. This result not only confirms the robustness of the algorithm under random excitation but also shows compliance with ISO safety limits, further validating its practical applicability (Table 2).

Table 2. Performance Comparison.

Metric	Uncompensated	PID	Algorithm of this paper
RMS error (mm)	0.91	0.31	0.12
peak error (mm)	2.7	1.1	0.4
Acceleration attenuation (%)	0	62	84

4.4. Discussion of Engineering Application Challenges

The system performance is influenced by several key factors. Firstly, the impact of model mismatch is evident: when the system load increases by approximately 20%, the algorithm's performance decreases by about 12%. This highlights the algorithm's sensitivity to deviations between the actual system dynamics and the modeled parameters, underscoring the importance of accurate modeling under varying load conditions. Secondly, a real-time computational bottleneck is observed in the Model Predictive Control (MPC) algorithm. Specifically, each MPC calculation takes around 8.3 milliseconds, which accounts for roughly 16.6% of a single control cycle. This significant computational load necessitates the use of hardware acceleration — such as FPGA-based implementations — to ensure that real-time performance requirements are met. Lastly, sensor noise, particularly from the accelerometer, also affects system performance. When the accelerometer noise level exceeds 0.01g, the compensation effect in the high-frequency band noticeably degrades. This demonstrates the critical role of sensor quality and noise suppression techniques in maintaining control performance, especially in scenarios with high-frequency dynamics.

5. Conclusion and Prospect

This paper proposes an active compensation solution based on six-degree-of-freedom platform for the problem of low-frequency vibration suppression of large machinery. The main work includes:

1) Modeling and analysis: A load-platform rigid-flexible coupling dynamic model was established to quantify the dominant characteristics of the vibration source in the frequency band of 5-50Hz.
2) Algorithm innovation: A feedforward (MPC) + feedback (SMC) composite controller is designed to solve the inverse dynamic instruction in real time through explicit MPC, and the sliding mode control is combined to enhance the anti-disturbance capability.

3) Project implementation: Key technologies such as dynamic allocation, singular avoidance and delay compensation were developed to ensure the stability of 10-ton platform under 500Hz high real-time control.
4) Experimental verification: The hydraulic experimental system was built to verify that the RMS value of position error was reduced by 82% and the attenuation rate of acceleration was 84% under the condition of impact and random vibration.

The current research still has the following shortcomings:

1) Model dependence: The performance of the algorithm depends on the accuracy of the platform dynamic model, and the robustness decreases by 12% when the load parameter changes more than 20%.
2) High frequency vibration suppression: the attenuation rate of vibration greater than 100Hz is less than 40%, which is limited by the bandwidth of hydraulic actuator.
3) Multi-source disturbance coupling: the time-varying influence of temperature and oil viscosity on the hydraulic system is not considered.

This study provides a theoretical framework and empirical basis for the active control of large-scale mechanical vibration, and the proposed algorithm has been applied to a certain type of Marine power test platform. With the development of high-end equipment towards high precision and long life, six-degree-of-freedom compensation technology will show a broader application prospect.

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