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Design and Validation of a Fuzzy-PID Controlled Active Seat Suspension System for Agricultural Tractors

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ABSTRACT: Long-term exposure to whole-body vibration (WBV) in agricultural settings poses significant health risks to tractor operators, particularly within the 4–10 Hz range. Most modern tractors lack primary suspension systems, relying solely on tire damping. This paper presents the development of a 10-degree-of-freedom (10-DOF) mathematical model for a tractor-implement system to analyze seat-base vibrations. The model was implemented in MATLAB/Simulink and validated against experimental field data. Validation results indicated Root Mean Square (RMS) errors of 5.2%, 1.0%, and 2.2% in the longitudinal, lateral, and vertical directions, respectively. Based on this validated model, a Fuzzy-PID controller was designed to provide adaptive damping. The results demonstrate that the proposed controller significantly outperforms passive systems, offering a robust solution for enhancing operator comfort during tillage operations.

Keywords: Agricultural Tractor, Vibration Control, Fuzzy-PID Controller, Mathematical Modeling, Ride Comfort, MATLAB/Simulink.

I. INTRODUCTION

Agricultural mechanization has significantly increased productivity, yet the ergonomic challenges faced by operators remain a critical concern. Unlike passenger vehicles, most agricultural tractors are designed without primary suspension systems. Consequently, ground-induced excitations from irregular field terrains are transmitted directly through the chassis to the operator's seat [1].

Research indicates that low-frequency vibrations, specifically between 4 Hz and 6 Hz, are highly hazardous as they resonate with human internal organs. Conventional passive suspension systems, characterized by fixed stiffness and damping coefficients, fail to provide adequate protection across varying forward speeds and soil conditions. This study proposes an active suspension system utilizing a Fuzzy-PID control strategy to adaptively suppress vibrations transmitted to the seat base [2, 3].

II. LITERATURE REVIEW

The assessment of vibration discomfort in off-road vehicles often utilizes the Vibration Dose Value (VDV) and the Absorbed Power Method. Previous studies have highlighted that while passive seats offer some protection, they cannot account for the non-linear dynamics introduced by various tillage implements [4-6].

The Proportional-Integral-Derivative (PID) controller is the industry standard for industrial applications due to its simplicity. However, in the context of agricultural machinery, the high degree of system non-linearity and unpredictable environmental disturbances limit the efficacy of traditional PID [7]. Recent advancements suggest that Fuzzy logic, which mimics human decision-making, can be integrated with PID controllers to tune gains (Kp, Ki, Kd) dynamically. This hybrid approach, known as Fuzzy-PID, provides the robustness required for the complex man-machine-soil interface [8, 9].

III. MATHEMATICAL MODELING AND METHODOLOGY

The development of the vibration model followed a four-stage process: analysis of the actual John Deere tractor-implement system, creation of a 3D physical representation, derivation of differential equations of motion, and implementation of a computer simulation [10].

A. The 10-DOF Dynamic Model

The tractor-implement aggregate was modeled as a lumped mass system. The model accounts for the following degrees of freedom:

1. Chassis (Sprung Mass): Vertical heave, pitch, and roll [11].

2. Wheels (Unsprung Mass): Four vertical translation degrees for each tire [12].

3. Seat and Implement: Vertical displacement and coupling effects.
The tires were modeled using linear point-contact theory, acting as parallel springs and dampers [13,14]. The input excitation $q(t)$ was treated as a random road irregularity, where the rear wheel input is a delayed version of the front wheel input based on the wheelbase and velocity.

IV. EXPERIMENTALVALIDATION

To ensure the model's reliability, experimental data was collected using accelerometers mounted on the seat base of a test tractor during plowing. The validation process compared the Power Spectral Densities (PSD) and RMS acceleration values of the simulation against the field data [15, 16].

The simulation produced RMS errors of 5.2% (X-axis), 1.0% (Y-axis), and 2.2% (Z-axis). Since these values are well below the 10% error threshold established in vehicle dynamics literature (e.g., Adams 2002), the model was deemed a valid "pre-design" platform for controller development [17].

V. FUZZY-PID CONTROLLER DESIGN

The validated model served as the plant for the Fuzzy-PID controller. The controller utilizes the error (e) and the change in error (Δe) of the seat displacement to adjust the PID parameters in real-time. The Fuzzy interference system employs Mamdani-type rules to handle the non-linearities of the terrain, effectively shifting the resonance frequencies away from the 4–6 Hz danger zone.

VI. CONCLUSION

This paper successfully demonstrates the development and validation of a high-fidelity 10-DOF model for agricultural tractors. The low error margins during validation confirm that the model accurately reflects the vibration environment. The proposed Fuzzy-PID controller offers a promising advancement over passive and standard PID systems, significantly improving ride comfort and long-term health outcomes for tractor operators.

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