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Robust Design and Mechanism Elucidation for Three-Cylinder Engine Idling Vibration Using Machine Learning in Multi-Dimensional Design Space Analysis

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1. Introduction

In modern automotive development, achieving high performance while reducing costs is essential. AI-driven surrogate models have emerged as tools to improve performance and efficiency. However, robust design that accounts for manufacturing variations remains challenging due to the iterative nature of traditional simulations. This study introduces the application of Gaussian Process (GP) regression to model and visualize the high-dimensional design space of 3-cylinder engine idle vibration, thereby facilitating both robust specification selection and mechanism identification.

2. Modelling Technology with Gaussian Process

The study employs an active learning-based GP model that quantifies prediction uncertainty. Unlike conventional space-filling methods, this approach adaptively samples query points near design boundaries to improve efficiency. In a 20-dimensional benchmark (Hartmann-Victor problem), the proposed method achieved an 85% reduction in Brier score compared to conventional methods, demonstrating high accuracy with significantly fewer data points.

3. Application to Engine Idling Vibration

The methodology was applied to a 9-dimensional design problem involving engine mount stiffness, positions, and crankshaft balance ratio. Three types of simulators were developed to calculate the engine's 1^{st} and 1.5^{th} order floor vibration. The model utilized 400 data points collected over four iterations to achieve high prediction accuracy, with a maximum floor vibration error of only 0.61%. This design remains feasible even when accounting for ±10% manufacturing variations in mount insulator stiffness.

4. Robust Design and Mechanism Analysis

A "robust design" point was required that remains within the feasible boundary despite these variations. To identify this point, we calculated the "inscribed hypercube" representing the largest orthogonal multi-dimensional box that fits inside the feasible region, thus avoiding iterative design studies. The center of this hypercube, defined as design point dp2, maximizes the margin from all feasible design boundaries. Verification plots (Fig. 1) confirmed that the entire range of mount stiffness variations for all variables was successfully contained within the feasible space.

The geometric visualization of feasible design boundaries using the GP model provided critical insights into the underlying physics. Notably, a linear correlation was identified between the left and right engine mount stiffness (z-direction) regarding the 1st-order floor vibration at 875 rpm. This boundary aligns with the 11.2 Hz contour line of the engine pitch natural frequency. However, initial correlation analysis between pitch natural frequency and floor vibration yielded a relatively low coefficient. Further investigation into the engine yaw mode revealed its influence on floor vibration. The eigenvalue ratio of the pitch and yaw modes demonstrated a strong correlation with floor vibration levels. This finding indicates that proximity between pitch and yaw modes amplifies vibration at 875 rpm. Consequently, robust idle vibration control requires mount stiffness settings that ensure adequate separation of these two eigenvalues.

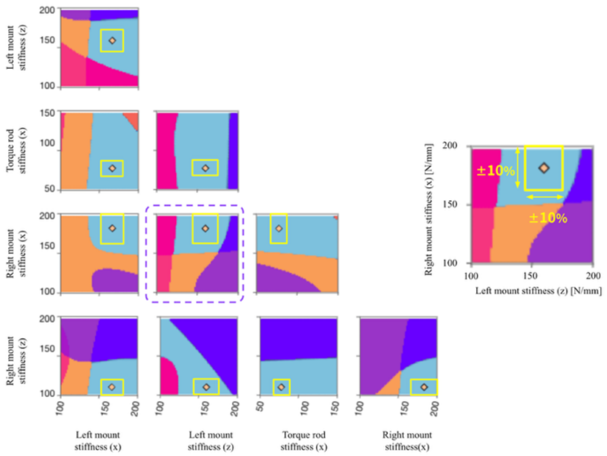

Fig.1 2D Plot with Variation Range at Slicing Point dp2

5. Conclusion

GP-based visualization effectively supports engineering decision-making in high-dimensional spaces. This technology does not replace engineers but augments their ability to gain physical insights and accumulate knowledge thereby enabling more competitive product development.