Vibration Transfer Path Testing and Analysis of Civil Aircraft Postprint

Authors: Li Yixuan

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Abstract

With the development of civil aircraft design technology, the current focus of passenger aircraft design has begun transitioning from structural safety to cabin comfort, with vibration comfort being one of the key factors. From the perspective of occupant vibration comfort in civil aircraft, vibration transfer path tests were conducted on a certain aircraft type under three operational conditions: aerial cruise, low-altitude flight, and runway taxiing. Based on the test data, a vibration transfer path model was established, and the key factors influencing passenger aircraft vibration comfort were investigated, leading to the following conclusions: Under cruise and low-altitude flight conditions, the cabin vibration response primarily originates from the coupling between excitations at the engine rotor fundamental frequency and its second harmonic with the aircraft structure; Under runway taxiing conditions, the cabin vibration response primarily originates from the coupling between excitations from the left and right main landing gears in the low-frequency range (particularly 50 Hz) with the aircraft structure. This test not only provides a basis for vibration reduction and isolation design of aircraft cabins, but also fills the domestic gap in full-aircraft vibration comfort testing and verification platforms.

Full Text

Preamble

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Li Yixuan, Bai Chunyu

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Corresponding Author: Li Yixuan

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Introduction

During aircraft operation, vibration sources such as engine excitation and landing gear bay excitation travel through different transfer paths to the cockpit and cabin, where they superimpose to form the total vibration response, causing passenger comfort issues. Comprehensive consideration of multiple excitations and transfer paths across various flight conditions makes the Transfer Path Analysis (TPA) method highly effective. Through TPA analysis, dominant links in the transfer paths affecting cockpit and cabin vibration can be identified, enabling vibration intensity and path sensitivity parameters to be maintained within reasonable ranges to meet aircraft vibration comfort requirements.

TPA technology has seen preliminary applications in the automotive industry to study interactions between vibration sources and transfer paths. For complex aerospace structures with coupled excitation sources and structural dynamics, particularly in full-aircraft TPA testing, vibrations and noise from each source propagate through different paths to multiple locations, creating response fields. Such models not only facilitate better understanding of the system itself but also enable targeted vibration and noise reduction. For any complex structure, the analysis model can be described by Equation !’ “.

When excessive response occurs at a target point (output), it may be caused by excitation sources, transfer functions, or their combined effects.

[Figure 1: see original paper] shows the on-site full-aircraft configuration for a certain aircraft type with outer wings removed. The test includes three typical operating conditions: runway taxiing (takeoff and landing roll), low-altitude flight (takeoff and landing low-altitude flight), and cruise flight. The corresponding vibration sources for each condition are listed in Table 1.

Table 1: Test Conditions and Vibration Sources for Transfer Path Analysis

Condition	Primary Vibration Sources
Cruise	Engine
Low-altitude Flight	Engine, Landing Gear Bay
Runway Taxiing	Engine, Landing Gear Bay, Landing Gear

Measurement points were arranged in the pilot seat area, first-class seat area, and economy-class seat area, with specific distribution shown in Figure 1. Each measurement point included triaxial vibration testing. The aircraft' s lift generated by the wings fully counteracts its weight, so only vertical loads were applied in testing.

Cruise Condition

Test Article Support and Loading

After determining the aircraft support configuration for cruise condition testing (shown in Figure 3 [Figure 3: see original paper]), engine loads were derived from ground engine run-up test responses through inverse calculation. The model was built and validated based on test data (Figure [Figure 1: see original paper]).

Figure 3: Engine Load Application for Cruise Condition

Model Building and Validation

The vibration transfer path model for cruise condition was constructed using test data (Figure [Figure 2: see original paper]). Validation showed that calculated responses from the model matched measured responses in trend and magnitude, confirming the model' s validity for further contribution analysis.

Figure 2: Comparison of TPA Calculated and Measured Values at Cabin Measurement Point (Cruise)

Low-Altitude Flight Condition

Test Article Support

The support configuration for low-altitude flight condition was identical to cruise condition.

Test Loads and Loading

For low-altitude flight condition, large-thrust electromagnetic exciters simulated left and right vertical engine vibration sources. Landing gear bay loads were calculated and applied (Figure [Figure 4: see original paper]), with vertical loads neglected. Figure [Figure 5: see original paper] shows the on-site loading configuration for landing gear bay and doors.

Figure 4: Engine Loads for Low-Altitude Flight Condition
Figure 5: On-Site Loading of Landing Gear Bay and Doors

Model Building and Validation

The vibration transfer path model for low-altitude flight condition was built using test data (Figure [Figure 6: see original paper]). Validation demonstrated consistent trends between calculated and measured responses, with good agreement, confirming model validity for contribution analysis.

Figure 6: Comparison of TPA Calculated and Measured Values at Cabin Measurement Point (Low-Altitude Flight)

Runway Taxiing Condition

Test Article Support

The aircraft was supported by a simulated lift suspension system and static pressure support cylinders, with remaining weight borne by static pressure cylinders beneath the landing gear (Figure [Figure 7: see original paper]).

Figure 7: Test Article Support for Runway Taxiing Condition

Test Loads and Loading

Runway taxiing condition involved three vibration source types: engine, landing gear bay, and landing gear. Landing gear bay loads were calculated, while landing gear loads were applied at the tire contact points using the San Francisco O" [runway spectrum (Figure [Figure 8: see original paper]). Figure [Figure 9: see original paper] shows the on-site loading configuration.

Figure 8: Excitation Force Loads for Runway Taxiing Condition
Figure 9: On-Site Loading of Landing Gear Bay and Landing Gear

Model Building and Validation

Data was first collected for each individual excitation source, then for the combined runway taxiing condition. The vibration transfer path model was built and validated using the new condition response data. Comparison showed the model was effective, with minor deviations only at individual low frequencies.

Contribution Analysis Results

Cruise Condition

Contribution analysis was performed at the right cabin seat track position (vertical direction). Results showed the right engine transfer path contributed at 3% b' and within the '%" d' !% b' range. Since aircraft support and engine excitation frequency distribution were essentially consistent with cruise condition, cabin vibration response primarily originated from engine excitation coupling with transfer path frequency response functions. Vibration reduction should focus on reducing transfer function peaks in the 3% b’ and ‘!% b’ ranges.

Low-Altitude Flight Condition

Under low-altitude flight condition, the landing gear bay excitation contributed minimally. Response contributions primarily came from front and main landing gear vertical excitations. The right engine transfer path showed slightly greater total contribution than the left.

Runway Taxiing Condition

Runway taxiing condition exhibited 1 vibration transfer path. The response at &% b’ was primarily caused by high loads from left and right main landing gear. Vibration reduction measures should consider implementing isolation before landing gear loads transfer to the aircraft structure. Additionally, the large response near % b’ was mainly due to high frequency response functions of the left and right main landing gear transfer paths.

Conclusion

This study addressed civil aircraft passenger vibration comfort by building vibration transfer path models for various operating conditions based on test data. Contribution analysis and decomposition identified excitation sources and structural transfer paths causing high cabin vibration responses:

- **Cruise condition**: Primary vibration source is engine excitation; focus on reducing transfer function peaks at 3% b’ and ‘!% b’ .
- **Low-altitude flight condition**: Landing gear bay excitation contributes minimally; primary contributions from landing gear paths.
- **Runway taxiing condition**: Front and main landing gear paths dominate; consider load isolation and transfer function reduction.

The analysis provides a basis for subsequent vibration reduction optimization of civil aircraft.

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Note: Figure translations are in progress. See original paper for figures.