

Characterization of Harness-Induced Excitation and Fixture Resonance in Automotive Electronic Module Testing

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Abstract

Environmental qualification of automotive electronic assemblies per ISO 16750 often combines vibration, temperature cycling, humidity exposure and electrical loading to accelerate potential field failure mechanisms. Failures observed during such testing are often attributed to deficiencies in product design without due consideration of the influence of the mounting boundary conditions and harness dynamics.

This paper describes a detailed root-cause investigation of localized connector pin discoloration in the connector header which is mounted on the picture circuit board assembly of a sheet metal enclosed control module. This pin discoloration was observed during combined environmental validation of an automotive electronic module. Initial observations indicated a vibration-induced degradation mechanism, because of significant resonance amplification in the DUT-fixture system. Resonance characterization showed transmissibility up to 18–25 g/g under rigid fixture conditions. Measures of subsequent fixture correlation reduced resonance amplification by around 50 to 70 percent, suggesting a strong sensitivity to mounting boundary conditions.

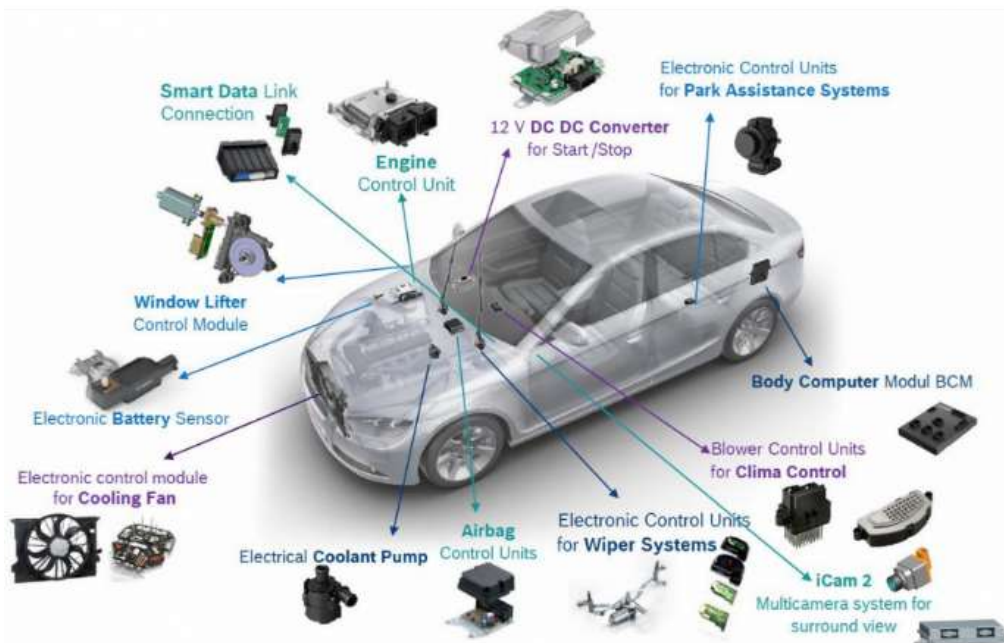
However, validation retesting demonstrated that optimization of harness fixation alone eliminated recurrence of the observed discoloration, even after removal of resonance-control measures. The results confirmed that harness-induced connector excitation, resulting from unsupported cable inertia and connector micro-motion, represented the primary degradation mechanism, whereas DUT resonance acted only as a secondary contributor.

The study demonstrates the importance of representative mounting conditions, harness management, and dynamic system-level assessment during environmental validation and provides a practical methodology for differentiating true product weaknesses from laboratory-induced artifacts.

Keywords—ISO 16750, connector reliability, fretting corrosion, vibration testing, resonance characterization, automotive electronics, harness dynamics, environmental validation.

1. Introduction

Modern vehicles have an assortment of computer modules distributed in a network across the vehicle. These modules are responsible for monitoring and controlling everything from passenger comfort systems to the vehicle's most sensitive functions including brake and ABS. Automotive electronic modules are increasingly required to withstand severe environmental conditions including vibration, temperature cycling, humidity exposure, and electrical loading throughout vehicle life depending on their location in cars.



Picture 1 – Generic overview of Different Control Modules in a passenger car

Automotive electronic systems operate in one of the harshest environments for electronic components. Unlike consumer electronics, which typically operate under controlled indoor conditions, automotive systems must withstand continuous exposure to dynamic and often extreme environmental changes.

Vehicles experience rapid temperature variations between day and night, seasonal climate shifts, engine heat, and cold starts in winter conditions. In addition, vibration from road conditions and mechanical stress from vehicle movement continuously affect electronic components.

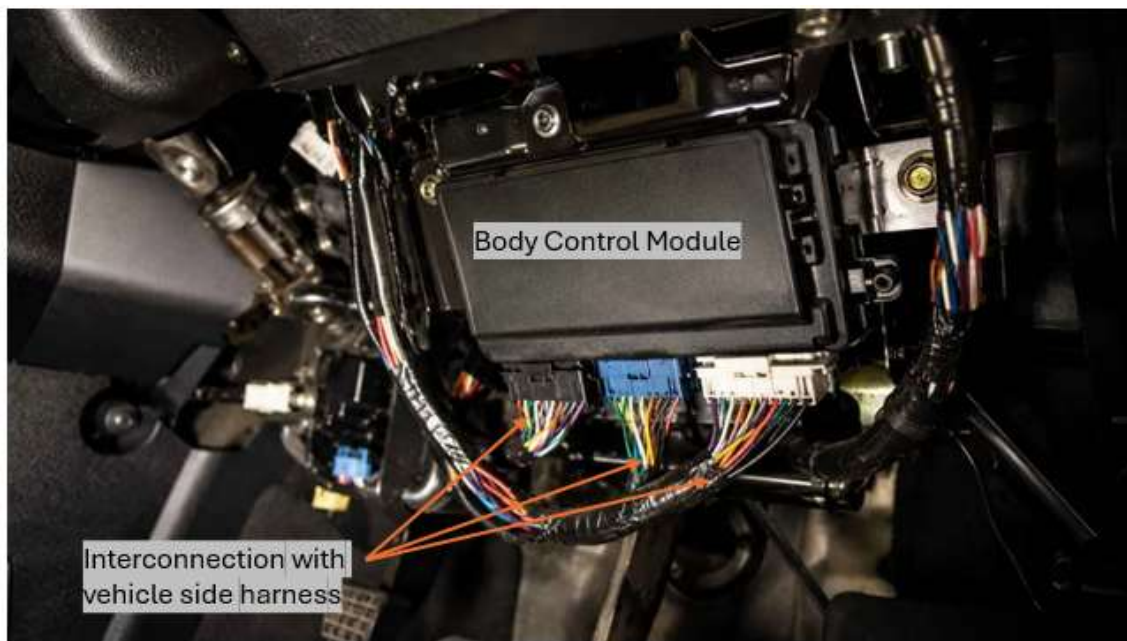
Without standardized testing, these environmental factors can lead to premature failures, system instability, or safety risks. To ensure durability, environmental validation programs are commonly performed according to ISO 16750.

ISO 16750-3 is the specific section of the ISO 16750 standard that defines vibration and mechanical load testing requirements for electrical and electronic equipment in road vehicles. These tests are designed to accelerate degradation mechanisms that may occur during vehicle operation while maintaining representative boundary conditions.

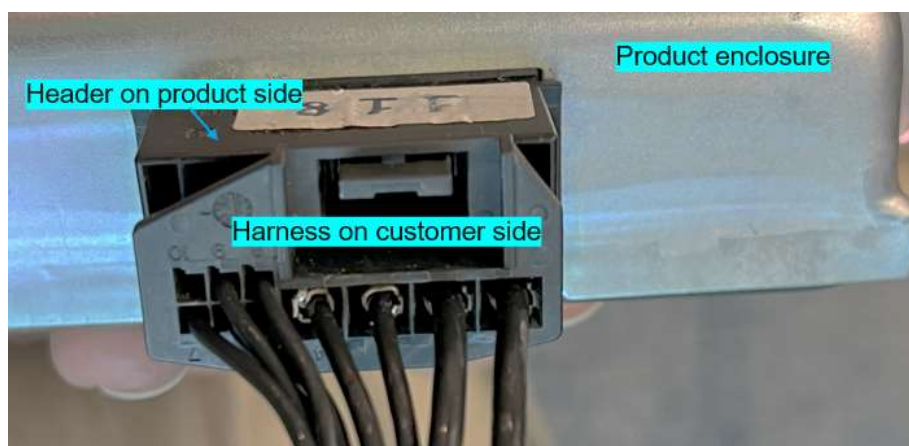
In the complete Control Module, the Connector systems used remain among the most vibration-sensitive elements of electronic assemblies. These connector systems also form the interconnection between module and vehicle harness side system. The connectors on module side are mated with counter receptacle connector on vehicle harness side, the female terminals to male terminals mating are quite critical as they form the connection for signal and current interconnection.

Relative motion between mating terminals during operation can result in:

- Fretting wear
- Oxide formation
- Contact resistance growth
- Thermal instability
- Electrical intermittency



Picture 2: Harness connection example of Body Control Module in a car



Picture 3: Connector mated view for reference and representation

A significant challenge during validation testing is distinguishing between:

1. Genuine product weaknesses that may occur in vehicle operation.
2. Artificial failure mechanisms introduced by non-representative laboratory boundary conditions.

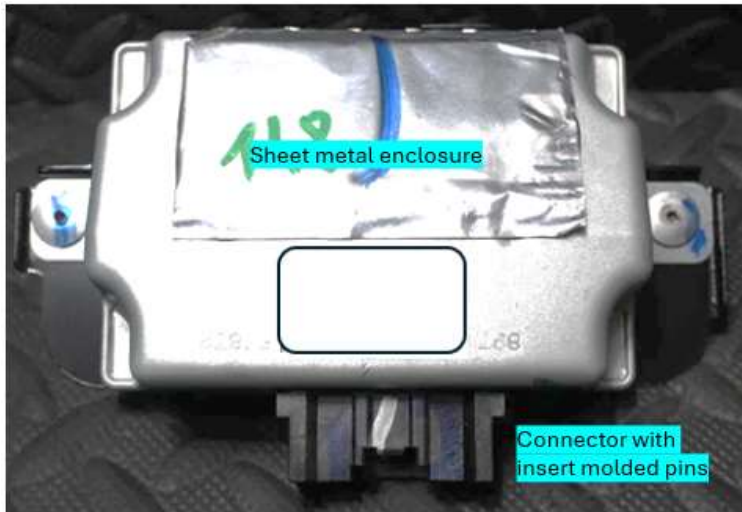
This work describes a comprehensive investigation of connector pin discoloration and local harness side plastic melt observed during combined environmental testing and demonstrates how resonance characterization and harness dynamic analysis were used to identify the actual root cause.

2. Product Description

The investigated product was an automotive control module assembly with sheet metal enclosure mounted through a customer-specified sheet-metal bracket and connected through a multi-pin automotive connector on vehicle harness side. The control module was mounted inside the cabin of a car behind the dashboard.

Key product characteristics:

- Sheet Metal Enclosure
- Hybrid connector with molded terminal pins
- Customer mounting through 1.6 mm SECC bracket
- Harness connected through standard automotive connector interface



Picture 4: Reference and representative picture of the control module

The customer vehicle-installed configuration includes:

- Sheet-metal mounting compliance
- Supported harness routing
- Vehicle body structural damping
- Joint friction and interface energy dissipation

These characteristics differ significantly from a rigid laboratory vibration fixture.

3. Qualification Environment

3.1 Combined Environmental Validation

Combined Environment Validation included exposure to both random vibration and temperature during continuous operation of the control module. Random vibration testing is used to reproduce the broadband, non-periodic vibration environment experienced by an automotive electronic module during real vehicle operation. Unlike a single-frequency sine test, random vibration simultaneously excites the DUT over a specified frequency range and therefore provides a more representative assessment of structural durability, resonance response, connector integrity, PCB reliability, solder-joint fatigue, and component robustness.

A random vibration test is primarily defined by **three parameters**:

Parameter	Details
Frequency range	Range over which vibration energy is applied
PSD level	Acceleration of energy density at each frequency
Overall GRMS	Total RMS acceleration obtained by integrating the PSD over the frequency range

This is combined with: -

- Temperature cycling from -40°C to +85°C
- Continuous electrical loading
- Duration: 8 hours / axis (Total 24 hours)

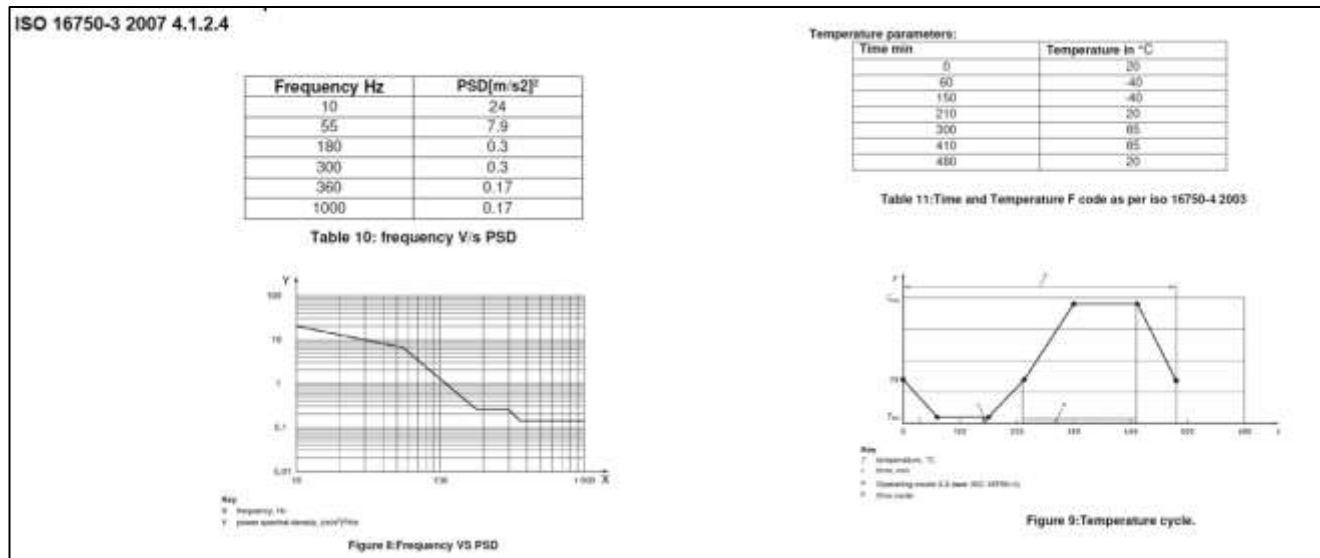
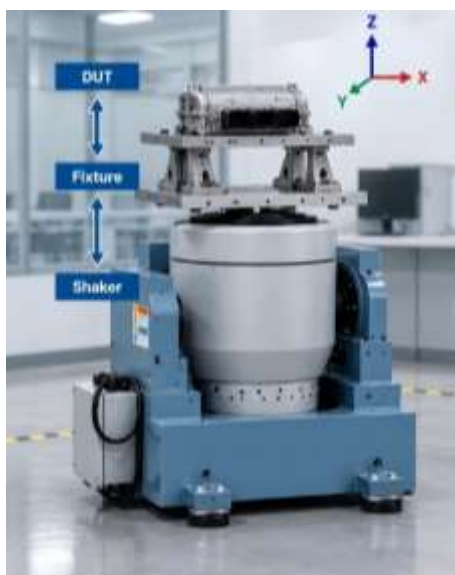


Figure 4: Representative Combined Validation Profile for ISO 16750-3

The Control module is mounted on the fixture to simulate the axial mountings in the vehicle.

The fixture is then mounted on the vibration shaker table and then for combined temperature the complete set-up was placed in a mobile chamber.



Picture 6: Reference and representative picture of DUT mounted on a vibration fixture and shaker configuration



Picture 6: Reference and representative picture of the vibration test set-up

The purpose of the test was to accelerate potential degradation mechanisms including:

- Terminal fretting
- Oxidation
- Thermal cycling fatigue
- Contact instability

The applied environment represented a severe multi-stress validation condition exceeding normal vehicle duty-cycle exposure.

3.2 Initial Observation

Following completion of testing, localized blackening/discoloration was observed on one connector pin and local melting of plastic and pin blackening on the female harness side.



Picture 7: Reference and representative picture of harness side local melt and terminal blackening

No evidence was found of:

- Contact resistance increases
- Electrical discontinuity
- Melting
- Thermal runaway
- Connector deformation
- Functional degradation

The condition was therefore categorized as a localized surface degradation phenomenon rather than a functional failure.

From Root Cause Analysis considering all the factors from process and functionality the main cause was focused on the Vibration Set-up and Harness Fixation which were evaluated by resonance characterization and re-validation.

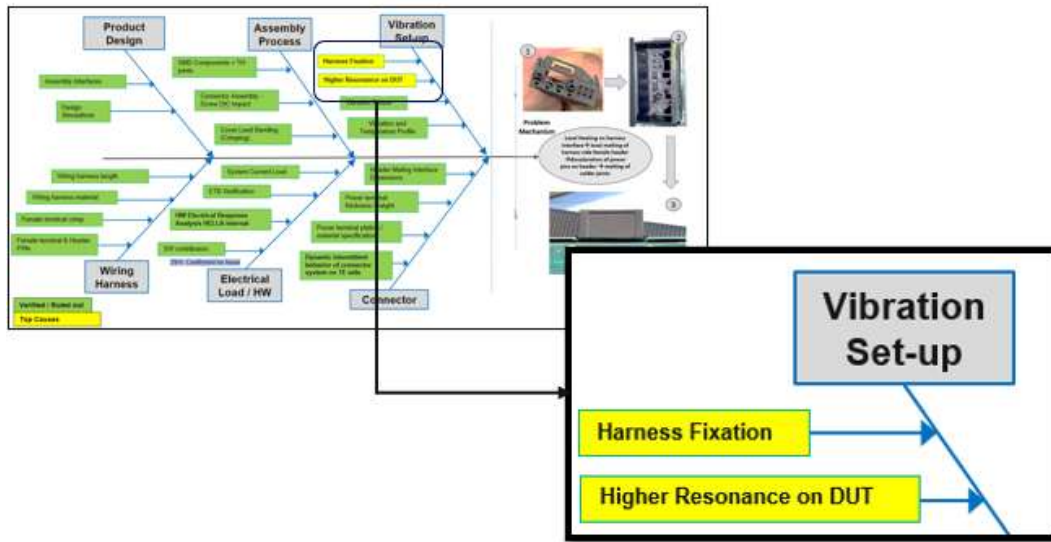


Figure 7: Cause and Effect Analysis – Ishikawa Diagram

4. Resonance Characterization

4.1 Objective

Because the observation occurred during vibration exposure, resonance characterization was performed to understand the dynamic behavior of the DUT-fixture system.

Accelerometers were placed on the DUT near to the connector area to observe the realistic resonance behavior.

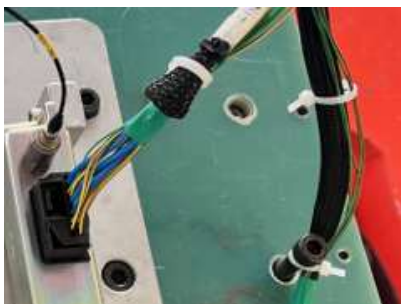


Figure 7: Accelerometer position reference

A sine sweep profile was selected because resonance identification requires excitation of individual frequencies sequentially.

Test conditions:

- Frequency range: 10–2000 Hz
- Sweep rate: 1 octave/min
- Excitation level: 10 m/s²
- Time Duration: 10 minutes

Unlike random vibration qualification, the purpose of this test was not durability assessment but identification of natural frequencies and amplification factors.

4.2 Results

Significant resonance peaks were identified across three orthogonal directions.

Measured peak transmissibility values reached:

- Direction X: up to approximately 25 g/g
- Direction Y: up to approximately 18 g/g
- Direction Z: up to approximately 20 g/g

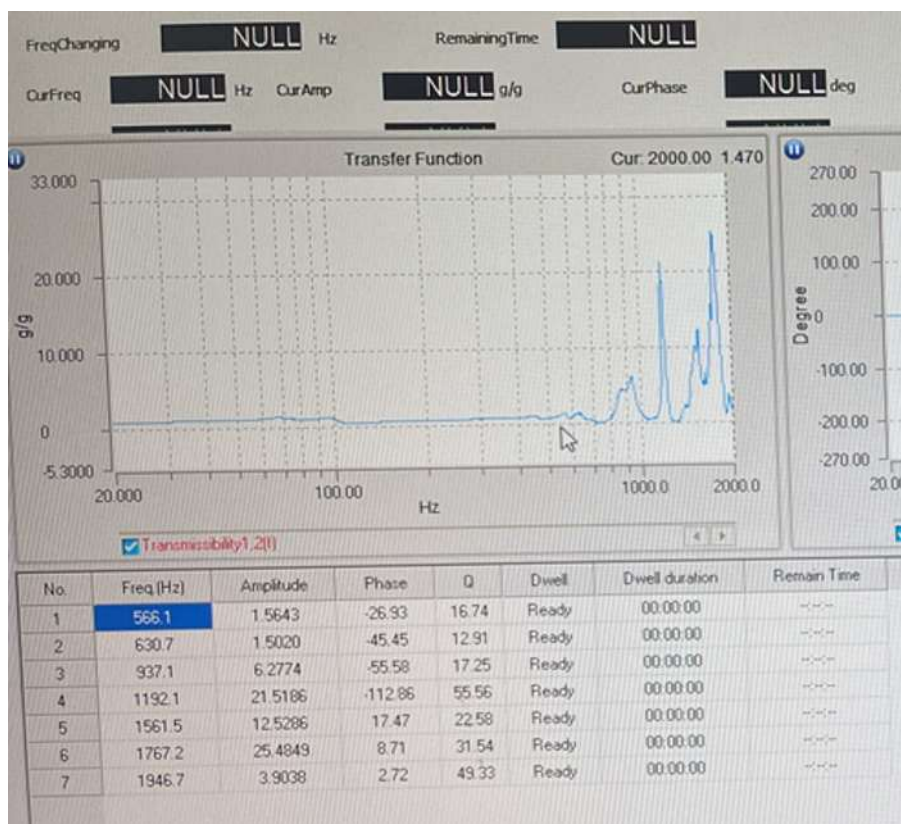


Figure 8: Highest peak ~25 g/g observed

Major resonance frequencies occurred between approximately 800 Hz and 1800 Hz.

The values indicated high resonance severity a compared to generic automotive standard guideline.

Peak Transmissibility (T)	Resonance Severity	Engineering Assessment
$T < 3$	Low	Well damped system
$3 \leq T < 5$	Moderate	Generally acceptable
$5 \leq T < 10$	Significant	Resonance present, review recommended
$10 \leq T < 20$	High	Strong resonance amplification
$T \geq 20$	Very High	Severe resonance, investigation recommended

But this does not mean that it can be direct root cause for the failure, it just shows the amplification of resonance on the connector area. This was evaluated and technically linked in next sections.

5. Dynamic Correlation Assessment

5.1 Vehicle Installation vs Laboratory Fixture

A comparison of mounting boundary conditions revealed significant differences.

Vehicle Installation

- 1.6 mm SECC bracket
- Approximate effective bracket length: 70 mm
- Structural compliance
- Bolted joint friction
- Harness support
- Vehicle body energy dissipation

Laboratory Fixture

- Rigid metallic structure
- Minimal compliance
- Minimal energy dissipation
- Higher resonance amplification

A simplified structural assessment indicated measurable bracket flexibility under vibration loading, whereas the fixture behaved as a near-rigid boundary condition.

But this does not mean that it can be direct root cause for the failure, it just shows the amplification of resonance on the connector area. This was evaluated and technically linked in next sections.

5.2 Fixture-Correlation Measures

To investigate the influence of boundary conditions, fixture-correlation measures were introduced.

The DUT was damped by suing rubber pads and also the harness fixation was optimized to avoid un-necessary weight and stress transfer on connector.

Objectives:

- Reduce non-representative resonance amplification
- Approximate vehicle-installed compliance
- Improve dynamic correlation

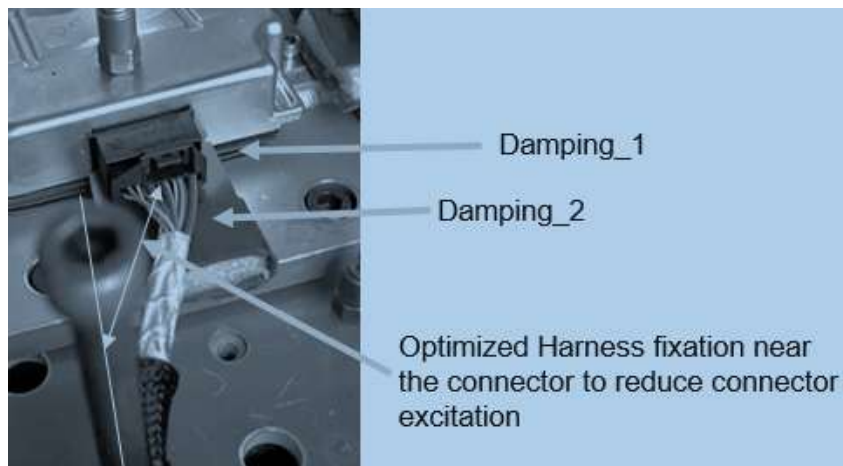


Figure 5: Optimized set-up reference

Measured results showed:

- Resonance amplification reduction: 50–70%
- Effective damping increase from ~2–3% to ~4–10%
- Significant reduction in peak transmissibility

Direction	Without Damping (Max g/g)	With optimization (Max g/g)	Reduction
Direction 1	18.8	5.3	~72%
Direction 2	25.5	12.3	~52%
Direction 3	18.9	8.8	~53%

The original fixture exhibited an effective damping level of approximately 2–3%, characteristic of a rigid metallic structure. Introduction of silicone damping increased effective system damping to approximately 4–10%, which is consistent with the range typically observed in mounted automotive sheet-metal assemblies.

The results confirmed that the original fixture amplified vibration response beyond the optimized condition. Now as next step the validation was re-run.

6. Harness Dynamic Investigation

Despite the reduction in resonance amplification, additional analysis identified substantial movement of the unsupported harness section adjacent to the connector.

The original setup contained:

- Long unsupported harness length
- Increased cable inertia
- Connector rocking motion
- Increased terminal micro-motion

These mechanisms directly influence connector contact interfaces and are known precursors to fretting-related degradation.

Visual observations during testing supported the hypothesis that harness dynamics contributed significantly to connector excitation.

7. Root Cause Validation

A final validation experiment was designed to separate the effects of resonance and harness dynamics.

The following changes were implemented:

- Harness fixation relocated near the connector
- Unsupported cable length minimized
- Fixture-correlation measures removed

The DUT was then subjected to repeat environmental validation.

Results:

- No pin discoloration observed
- No electrical discontinuity
- No increase in contact resistance
- No functional degradation

This outcome provided direct evidence that harness optimization alone was sufficient to eliminate the observed condition.

8. Root Cause Determination

Based on the complete investigation:

Potential Causes	Details	Countermeasure	Impact linked Failure Mode	Validation of Impact
Harness fixation optimization	Unsupported harness length and routing were identified as key contributors to connector excitation through cable inertia loading and connector rocking during vibration.	Harness fixation near the connector reduced cable inertia loading, connector micro-motion, and fretting-related contact movement at the terminal interface.	Primary Direct - Harness-induced connector excitation is considered the most likely driver of fretting-related contact degradation and localized pin discoloration.	Validated Primary Root Cause – Successful DV retest with harness fixation only and no pin discoloration observed, confirming harness-induced connector excitation as the primary failure driver.

Resonance Control Measure-Mounting Compliance Approximation	Fixture-correlation measures were introduced to compensate for the missing compliance and effective damping of the rigid laboratory fixture and to reduce non-representative resonance amplification during investigation.	Resonance amplification was reduced by approximately 50–70%, resulting in a dynamic response more representative of the vehicle-installed mounting condition as evident by damping ratio.	Fixture-correlation measures— Reduced structural resonance amplification on DUT	Improved dynamic response correlation; not identified as the primary cause of pin discoloration as per initial analysis.
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Conclusion

Harness-induced connector excitation was validated as the primary root cause through successful DV retesting with harness fixation optimization only. Fixture-correlation measures served as an investigative tool to reduce non-representative resonance amplification and improve correlation to vehicle-installed conditions and were not direct contributor for the failure mechanism.

9. Engineering Implications

The investigation demonstrates several important lessons for automotive validation programs:

1. Connector discoloration should not automatically be attributed to DUT resonance.
2. Harness dynamics can be a dominant excitation source.
3. Representative boundary conditions are critical during environmental testing.
4. Resonance characterization should be used as a diagnostic tool rather than a durability indicator.
5. Validation of corrective actions must isolate individual contributors.

10. Conclusions

A comprehensive investigation was conducted following observation of localized connector pin discoloration during combined environmental validation.

Resonance characterization initially identified significant fixture-induced amplification with transmissibility values up to 25 g/g. Fixture-correlation measures successfully reduced amplification by approximately 50–70%, demonstrating the influence of mounting boundary conditions.

However, repeat validation using harness fixation optimization alone completely eliminated recurrence of the observed condition. This result conclusively demonstrated that harness-induced connector excitation was the primary degradation mechanism.

The study highlights the importance of distinguishing genuine product weaknesses from laboratory-induced artifacts and provides a structured methodology for root-cause identification in automotive connector reliability investigations.

Future work should focus on quantitative correlation between harness inertia, connector micro-motion amplitude, and long-term fretting degradation under combined environmental loading.

Picture 1: <https://www.noblecontrols.com/automotive-programming.html>

Picture 2: https://4x4shop.ca/blogs/news/what-is-a-body-control-module-bcm-symptoms-fixes?srsId=AU7gw4W5g54BwqKtDabIv5z4VgOhSQJ8B5FcysWu_o-ixI0ZQcLgfDjF

Picture 3: <https://www.connectortips.com/connector-gathering-mating-designs/>

Picture 7: https://www.reddit.com/r/AskMechanics/comments/1fq7upx/burnt_connector/