Automotive Design for NVH Control

Noise, Vibration, and Harshness: Stiffening, Tuning, Isolation, and Validation

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Course Outline

Learning Objectives

- Define automotive NVH and distinguish noise, vibration, and harshness.
- Explain source–path–receiver methodology for diagnosis and control.
- Relate structural stiffness, mass, and damping to resonance behavior.
- Interpret vibration isolation using transmissibility and damping ratio.
- Compare bushings, mounts, damping treatments, and acoustic countermeasures.
- Understand experimental and CAE-based NVH development workflow.

Introduction to NVH

Definition

Noise, Vibration, and Harshness (NVH) is the engineering discipline concerned with generation, transmission, measurement, and mitigation of unwanted sound and mechanical oscillation in vehicles.

- **Noise:** Airborne acoustic energy, measured in dB.
- **Vibration:** Structure-borne oscillation, measured by displacement, velocity, or acceleration.
- **Harshness:** Human subjective perception of shock, roughness, and impulsive discomfort.

Why NVH Matters in Vehicle Design

- Passenger comfort and brand refinement are strongly tied to perceived NVH quality.
- Reduced vibration improves durability of trim, joints, connectors, and electronics.
- Exterior and interior noise must satisfy regulatory and market expectations.
- Good NVH design improves ride quality, steering feel, and structural integrity simultaneously.
- In EVs, low background powertrain noise makes secondary noise sources far more noticeable.

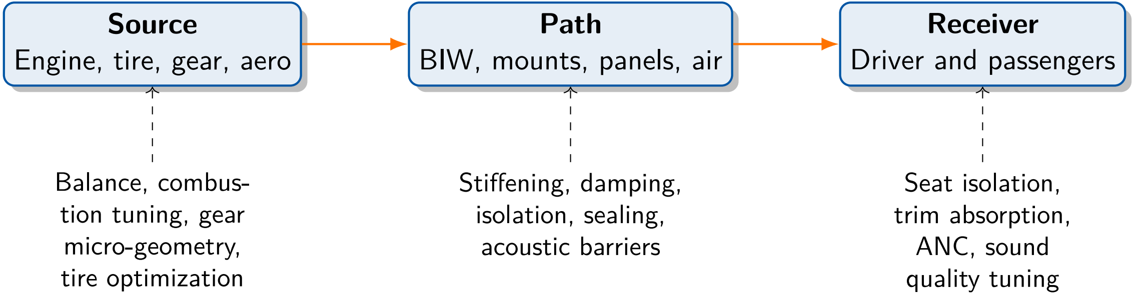
The Source–Path–Receiver Model

- **Source:** Engine firing forces, road-tire contact, gear meshing, wind, pumps, compressors.
- **Path:** Chassis members, body panels, bushings, mounts, cavities, glazing, and air paths.
- **Receiver:** Driver and passengers receiving acoustic and tactile response.

Engineering Strategy

Control can be achieved by reducing source excitation, interrupting the transmission path, or reducing response at the receiver location.

Flow Diagram: NVH Mitigation Strategy



Noise, Vibration, and Harshness: Distinction

Quantity	Physical Nature	Measurement	Typical Example
Noise	Airborne pressure fluctuation	SPL, spectrum, psychoacoustics	Wind rush, motor whine
Vibration	Oscillatory motion of structure	Acceleration, FRF, PSD	Steering wheel shake
Harshness	Subjective transient severity	Jury rating, shock metrics	Pothole impact, door slam

Primary Excitation Sources in a Vehicle

Powertrain-related

- Combustion pressure fluctuation
- Reciprocating inertia forces
- Gear meshing and transmission error
- Electric motor electromagnetic forces

Road and aerodynamic

- Tire tread impact and cavity resonance
- Suspension input from rough road
- Wind buffeting and mirror vortex shedding
- HVAC and auxiliary rotating machines

Human Perception and Cabin Response

- Low-frequency boom is often associated with body cavity resonance and powertrain orders.
- Mid-frequency band strongly affects speech intelligibility and perceived refinement.
- High-frequency tones are easily detected in EVs due to absence of masking engine noise.
- Tactile vibration at seat track, steering wheel, and floor is critical for ride comfort evaluation.

Design Insight

Objective measurements must be correlated with subjective assessments because harshness is a perception-based quantity.

Role of Body-in-White (BIW) in NVH

- BIW is the main structural transmission path for structure-borne vibration.
- Global torsional and bending stiffness govern major body mode frequencies.
- Local stiffness at suspension towers, mount brackets, and subframe joints controls isolator boundary compliance.
- Flexible panels can radiate noise by converting vibration to airborne sound.

Objective of Structural Stiffening

Key Principle

Increasing stiffness K raises natural frequency according to $\omega_n = \sqrt{K/M}$, provided mass M does not increase disproportionately.

- Shift resonances away from engine order, tire order, and road excitation frequencies.
- Reduce deformation amplitude and secondary panel radiation.
- Improve mount effectiveness by providing stiffer support boundaries.
- Enhance both NVH and handling through improved torsional rigidity.

Structural Dynamics Model

The general linear equation of motion for a vehicle structure is

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F(t)\}$$

where:

- $[M]$ = mass matrix,
- $[C]$ = damping matrix,
- $[K]$ = stiffness matrix,
- $\{F(t)\}$ = excitation vector.

Design target: separate structural eigenfrequencies from dominant forcing spectra.

Global Stiffness versus Local Stiffness

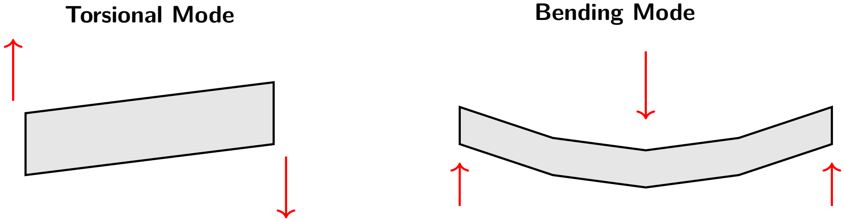
Global stiffness

- Entire BIW response
- Torsion and bending modes
- Influences shake, boom, and overall body feel
- Improved by ring structures, cross-members, closed sections

Local stiffness

- Mounts, brackets, towers, joints
- Controls boundary conditions of isolators
- Prevents local compliance-induced amplification
- Improved by ribs, gussets, patch reinforcements

Vehicle Mode Shapes: Torsion and Bending

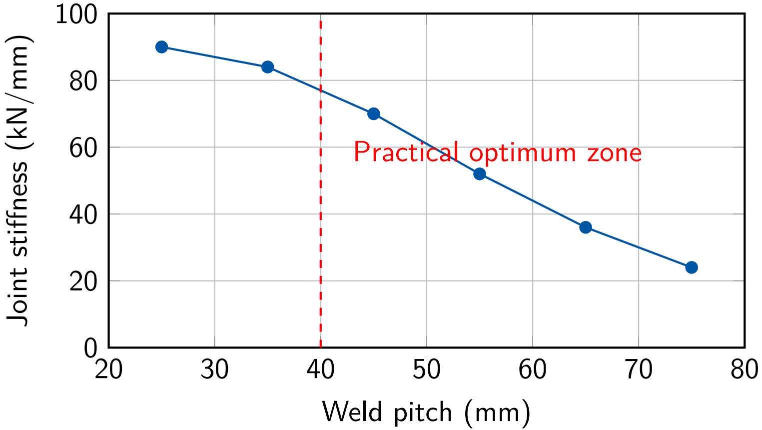


Target practice: maintain adequate separation between first torsion and first bending modes to avoid modal coupling and cabin boom amplification.

Joint Design, Weld Points, and Load Paths

- Stiffness of assembled structures depends strongly on joint efficiency.
- Spot weld pitch affects load transfer continuity and local flexibility.
- A-pillar, B-pillar, roof rail, and suspension turret joints are critical NVH zones.
- Continuous load paths reduce local relative motion and squeak-rattle propensity.

Effect of Weld Pitch on Joint Stiffness



Joint Technologies for NVH Performance

Joint method	**Stiffness**	**Damping**	**Complexity**
Spot welding	Moderate	Very low	Low
Laser welding	High	Low	High
Structural adhesive	High	High	Moderate
Weld-bonding	Very high	High	High

Structural adhesives are especially valuable because they improve both stiffness continuity and energy dissipation over the bonded flange length.

Structural Tuning by Mass and Stiffness Change

- Add ribs, beads, embossments, or brackets to increase local stiffness.
- Alter panel curvature to increase bending rigidity without large mass penalty.
- Add localized dead mass or tuned mass dampers where stiffening is impractical.

$$\omega_{new} = \sqrt{\frac{K + \Delta K}{M + \Delta M}}$$

Engineering Decision

Stiffness modification generally shifts frequency upward; added mass shifts frequency downward.

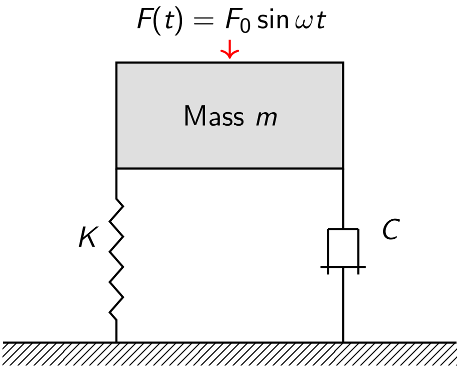
Principle of Vibration Isolation

- If source excitation cannot be eliminated, the transmission path must be decoupled.
- Isolators support static load while reducing dynamic force transfer.
- Every practical mount combines elasticity and damping.

Functional Elements

Spring stiffness K governs static deflection and natural frequency, while damping C limits resonance amplitude.

Mass–Spring–Damper Representation



Transmissibility Theory

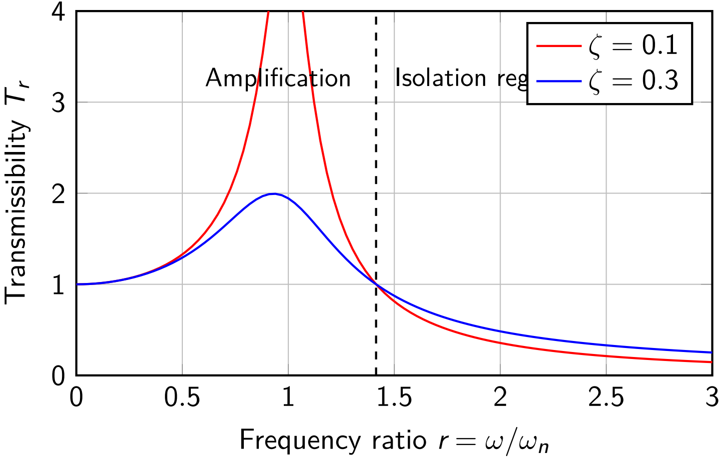
For force transmissibility in a damped single-degree-of-freedom system,

$$T_r = \sqrt{\frac{1 + (2\zeta r)^2}{(1 - r^2)^2 + (2\zeta r)^2}}$$

where $r = \omega/\omega_n$ and $\zeta = C/(2\sqrt{Km})$.

- If $r < \sqrt{2}$, amplification occurs.
- If $r > \sqrt{2}$, isolation begins.
- Damping reduces resonance peak but slightly worsens very high-frequency isolation.

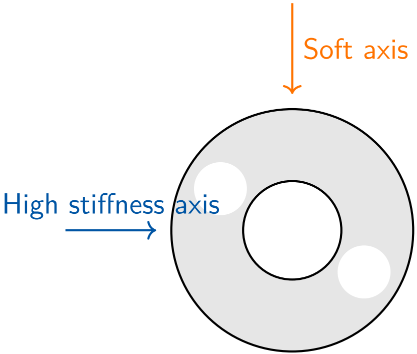
Transmissibility Curve and Isolation Region



Bushings and Direction-Dependent Compliance

- Suspension bushings must satisfy conflicting requirements of ride comfort and handling precision.
- Soft radial/longitudinal compliance reduces road harshness and high-frequency transmission.
- High lateral and axial stiffness preserves suspension geometry under braking and cornering.
- Voided bushings provide anisotropic stiffness through tailored elastomer geometry.

Directional Stiffness Concept in a Voided Bushing



Voids tailor compliance and damping by direction

Engine Mount Functions and Design Conflict

1. Support the static engine-transmission mass.
2. Isolate low-frequency powertrain shake at idle.
3. Limit roll, pitch, and torque reaction during acceleration and braking.
4. Prevent high-frequency structure-borne noise transmission into the body.

Conflict: high damping is desirable near idle resonance, but low dynamic stiffness is preferred at higher frequencies.

Elastomeric versus Hydraulic Mounts

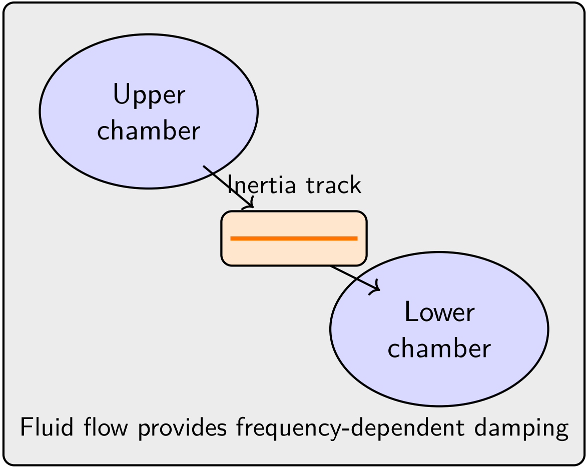
Elastomeric mount

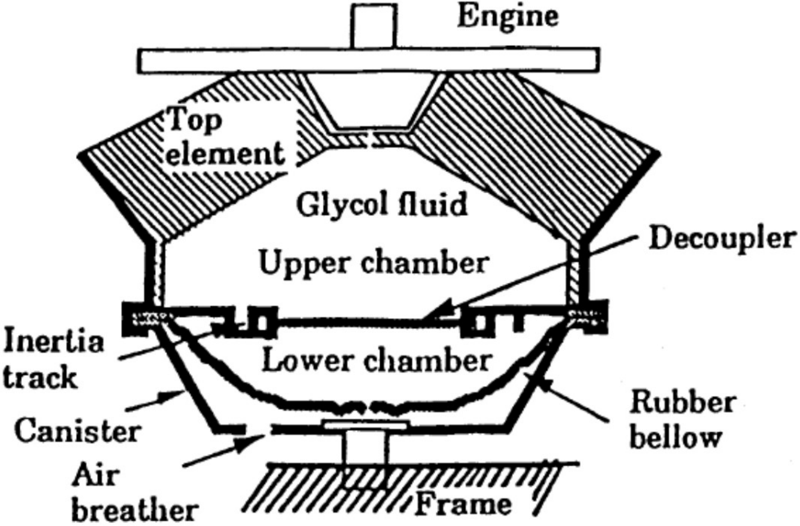
- Simple and durable
- Fixed stiffness and damping
- Cost-effective but compromise-based

Hydraulic mount

- Two fluid chambers with inertia track
- Frequency-dependent dynamic behavior
- High damping at low frequency, improved isolation at high frequency

Hydraulic Mount Schematic




Engine
Top
element
Glycol fluid
Decoupler
Upper chamber
Inertia
track
Lower chamber
Canister
Rubber
bellow
Air
breather
Frame

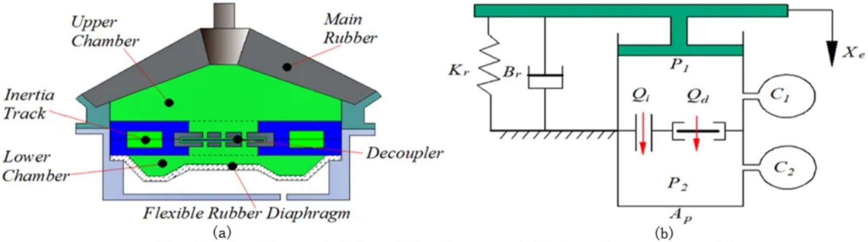


Fig. 1 Hydraulic mount (a) profile diagram and (b) lumped parameter model

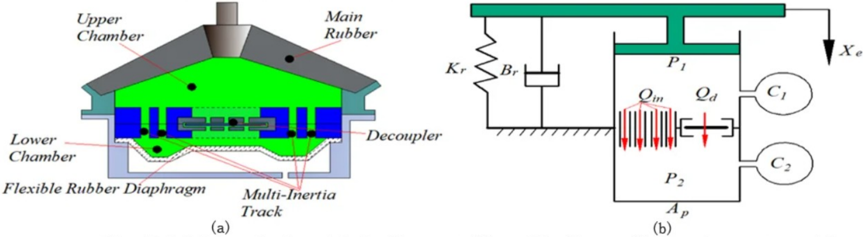


Fig. 10 Multi-inertia channel hydraulic mount (a) profile diagram (b) lumped parameter model

Active and Semi-Active Mount Technologies

- **Semi-active mounts:** damping or fluid characteristics are altered in real time using controllable media.
- **Active mounts:** actuator generates a secondary force opposite in phase to the disturbance.
- These systems are useful for cylinder deactivation, hybrid mode switching, and premium EV refinement.
- Trade-off includes cost, controls complexity, reliability, and calibration effort.

Cabin and Body Mounting in Body-on-Frame Vehicles

- Body mounts isolate the cabin from ladder-frame vibration and road-induced shake.
- Shear-type rubber elements can provide softer effective rate than compression mounts.
- Mount placement affects cab bounce, pitch, and fore-aft shake.
- Commercial vehicles demand durability, load capacity, and acceptable driver comfort simultaneously.

Suspension Dampers and Secondary Ride Harshness

- Shock absorbers dissipate suspension energy and influence transient impact feel.
- Damper valve tuning affects wheel-hop, body control, and impact harshness.
- Top mounts isolate high-frequency hydraulic noise from the body structure.
- Dual-path top mounts separate spring load path from damper force path for better NVH refinement.

Acoustic Materials and Interior Treatments

Barrier and damping materials

- Constrained layer damping sheets
- Mastic pads and bitumen alternatives
- Mass-loaded vinyl barriers

Absorption and sealing

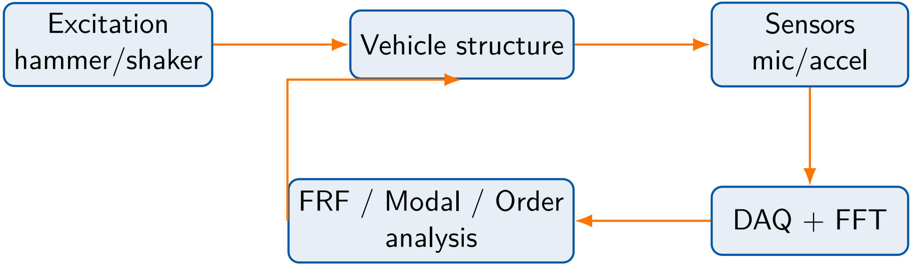
- Polyurethane foams
- Dash insulators and carpets
- Door seals and cavity sealing

Rule: damping reduces panel vibration; absorption reduces reflected airborne sound; barriers block transmission.

Measurement Chain for NVH Testing

- Excitation source: impact hammer, shaker, 4-poster rig, chassis dynamometer.
- Sensors: accelerometers, microphones, laser vibrometers, force transducers.
- Signal conditioning: charge amplifiers, ICP conditioning, anti-alias filtering.
- Data acquisition and processing: FFT, FRF, order tracking, spectrograms, operational deflection shapes.

Experimental NVH Testing Setup



CAE Workflow for NVH Development

1. Create FE model of BIW, closures, subframes, mounts, and trims.
2. Perform modal analysis to obtain natural frequencies and mode shapes.
3. Compute frequency response, transfer path, and acoustic cavity coupling.
4. Correlate FE model with test data using FRFs and modal assurance criteria.
5. Implement structural or isolation modifications and revalidate.

Modern NVH Challenge: Electric Vehicles

Masking effect is reduced

In conventional vehicles, engine noise masks several secondary noise sources. In EVs, many of those sources become clearly audible.

- High-frequency tonal motor and inverter whine.
- Road and tire noise become dominant contributors.
- HVAC, coolant pumps, and reduction gear noise become prominent.
- Requirement for better acoustic glazing, damping, sealing, and motor mount tuning.

NVH Design Checklist for Automotive Engineers

- Identify dominant source frequencies, orders, and operating conditions.
- Check structural modal separation from excitation bands.
- Ensure adequate local stiffness at mount and suspension interfaces.
- Select isolators using load, stiffness, damping, and durability requirements.
- Use damping and acoustic materials according to mechanism: damping, barrier, or absorption.
- Validate through CAE-test correlation and subjective assessment.

Illustrative Case Study: Idle Shake Improvement

- Problem: steering wheel shake observed at engine idle near body-mount coupled resonance.
- Diagnosis: mount mode close to excitation order, with insufficient bracket stiffness.
- Countermeasures: increase bracket stiffness, revise hydraulic mount tuning, improve subframe local rigidity.
- Result expectation: reduced transmissibility at steering column and improved cabin perceived refinement.

Summary

- NVH engineering is governed by source, path, and receiver interactions.
- Structural stiffening shifts modes and reduces panel response.
- Isolation performance depends on stiffness, mass, damping, and excitation frequency ratio.
- Bushings, mounts, dampers, adhesives, and acoustic materials must be selected as a coordinated system.
- Testing and CAE correlation are essential for robust automotive NVH design.

Thank You

Automotive NVH Control

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Recommended Reading

- M. P. Norton, *Fundamentals of Noise and Vibration Analysis for Engineers*.
- Xu Wang, *Vehicle Noise and Vibration Refinement*.
- ISO 2631 for human exposure to whole-body vibration.
- SAE and ISO literature on vehicle NVH testing, mounts, bushings, and sound quality analysis.