Diesel Engine Noise

Evelynn Stirling

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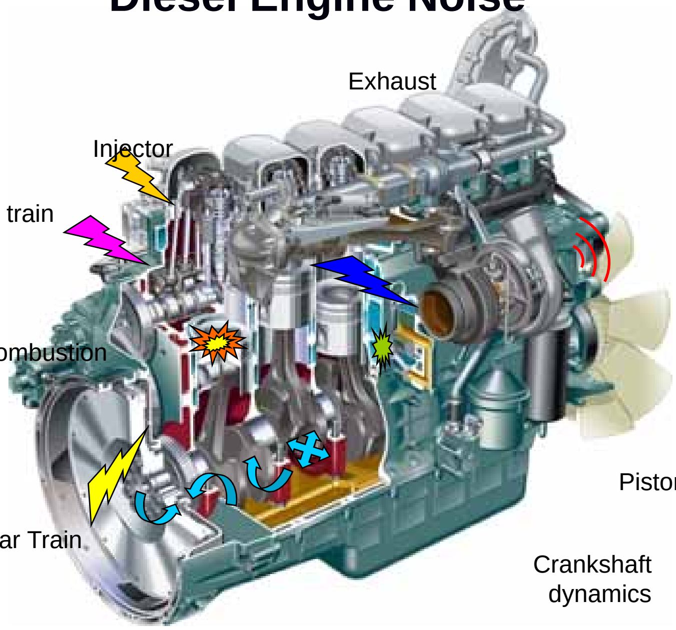
Diesel Engine Noise

- Introduction
- Regulatory noise requirements
- Diesel engine sound quality
- Engine noise historical trends
- The Source–Path–Receiver model
- Engine noise reduction – source
- Engine noise reduction – path
- Engine noise reduction – receiver

Diesel Engine Noise



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Why Do We Care About Engine Noise?

Noise can be described as 'unwanted sound'. The challenge is to deliver the required sound characteristics for the market, installation and application:

- Capable of meeting regulatory requirements
  - A potential barrier to entry – OEMs must meet legal requirements
- Appropriate sound quality and sound level characteristics:
  - 'Informative', 'Pleasant', 'Appropriate' etc.
  - 'Silent' may be good for a refrigerator, but not for a sport car
- Makes the best tradeoffs against other attributes:
  - Initial cost; fuel efficiency, performance, reliability, serviceability etc.

Regulatory Requirements

- Unlike exhaust emissions, we are generally not responsible for certification of the end product
  - Even so, we must work closely with OEMs so that they can meet legal requirements
  - Lower engine noise may allow the OEM to take out cost by reducing equipment or vehicle sound treatments
  - There are some exceptions, such as generator sets, where we are directly responsible for demonstrating compliance
  - Requirements may vary by country, region/ locality, application, rating, etc.

Diesel Engine Sound Quality

- Two engines with the same overall level can sound completely different due to:
  - Pure tones
  - High levels at high frequency
  - Impulsive sounds
  - Combustion event stability / cyclic variation
- An increasing share of our effort is devoted to sound quality

Diesel Engine
Sound Quality Requirements

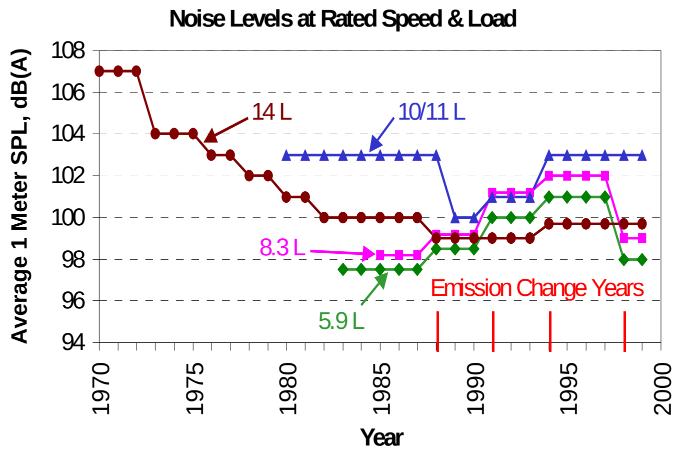
- Expectations vary by application, but desirable attributes are typically:
  - 'Pleasant' sound
  - Sound which suggests power and strength
  - Sound which is consistent with the operating condition
  - No knocks or rattles
  - Steady, smooth sound with no irregularity
  - No sound which suggests a potential problem
  - Low level of interference with speech, radio, cell phone, etc.

Engine Noise Historical Trends

- Through the '70's, '80s and '90s :
  - Primary efforts were aimed at improving the transmission path and exterior surfaces
  - Noise reductions were achieved by testing and hardware mitigation rather than through initial design and analysis
  - Forcing functions were generally taken as a given
  - The focus was on Noise Level rather than Sound Quality
- Meanwhile:
  - Injection pressures ~ doubled
  - Cylinder pressures 10 - 30% higher
  - More gear train torsional input from crank and fuel system
  - More severe gear backlash impacts

Early Engine Noise Trends

After some initial gains, noise levels deteriorated as cylinder and injection pressures increased to meet emission requirements:



More Recently…

- Improvements have been made by introducing:
  - Stiffer block structures
  - Cover and oil pan design optimization
  - Pan and cover isolation
  - Common Rail fuel systems
  - Pilot injection – rate shaping
  - Noise as a primary consideration in combustion recipe optimization
  - Lower cyclic torques & gear impacts
  - Rear gear trains
  - Scissors gears
  - Enclosures

Noise Reduction – ‘Are We There Yet?’

As sound quality becomes more important and overall noise levels are reduced, more noise sources become significant –

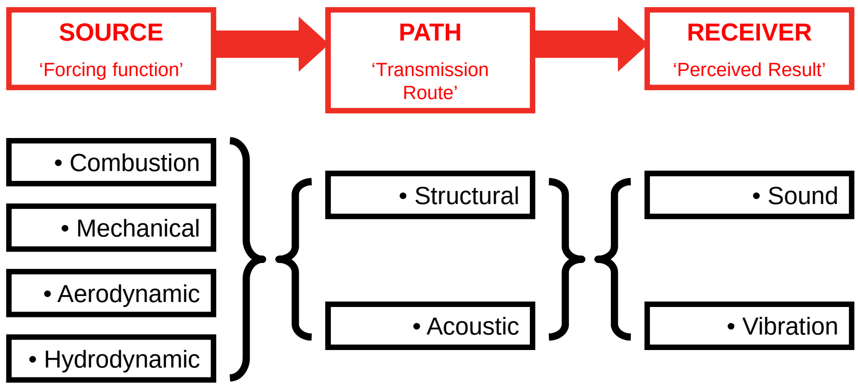
‘Drain the swamp, and all the tree stumps start to show’

Noise Reduction

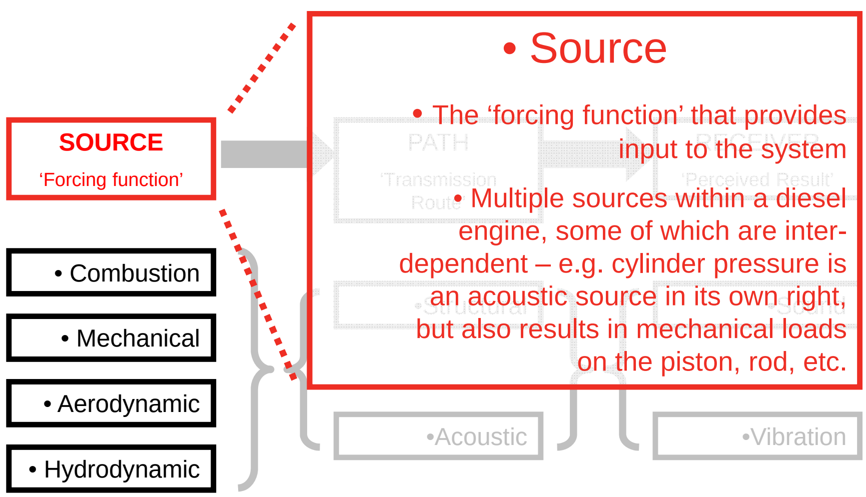
The Source – Path – Receiver Model

Source – Path – Receiver Model for (Engine) Noise

- The Source – Path – Receiver model is a useful starting point for understanding and addressing engine noise:



Source – Path – Receiver



Source – Path – Receiver

SOURCE
'Forcing function'

- Combustion
- Mechanical
- Aerodynamic
- Hydrodynamic

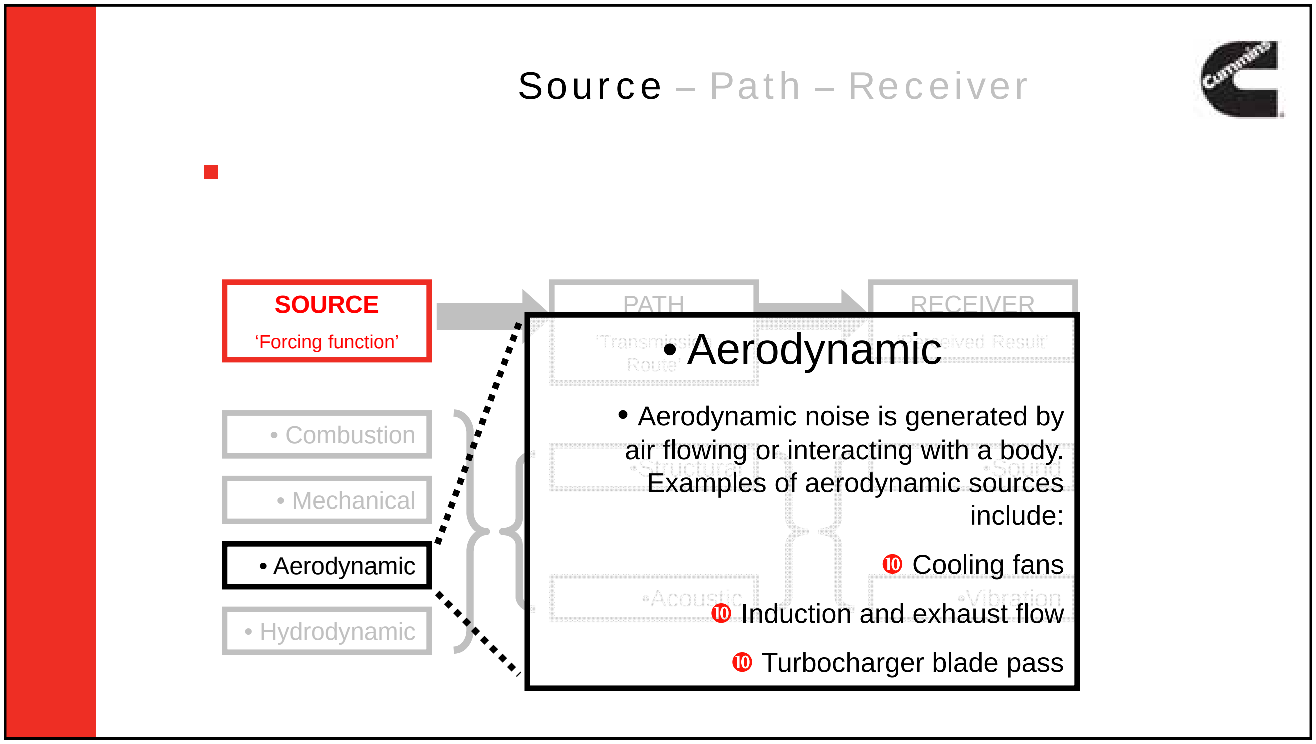
- Combustion
  - Cyclic variation in cylinder pressure is equivalent to ~ 170 dB re 20 μPa!
  - Combustion sound level and quality are affected by pressure rise rate, timing, combustion stability and variability
  - Becoming particularly important with common rail fuel systems due to lower mechanical noise
  - We'll present a separate section on this topic later in the course

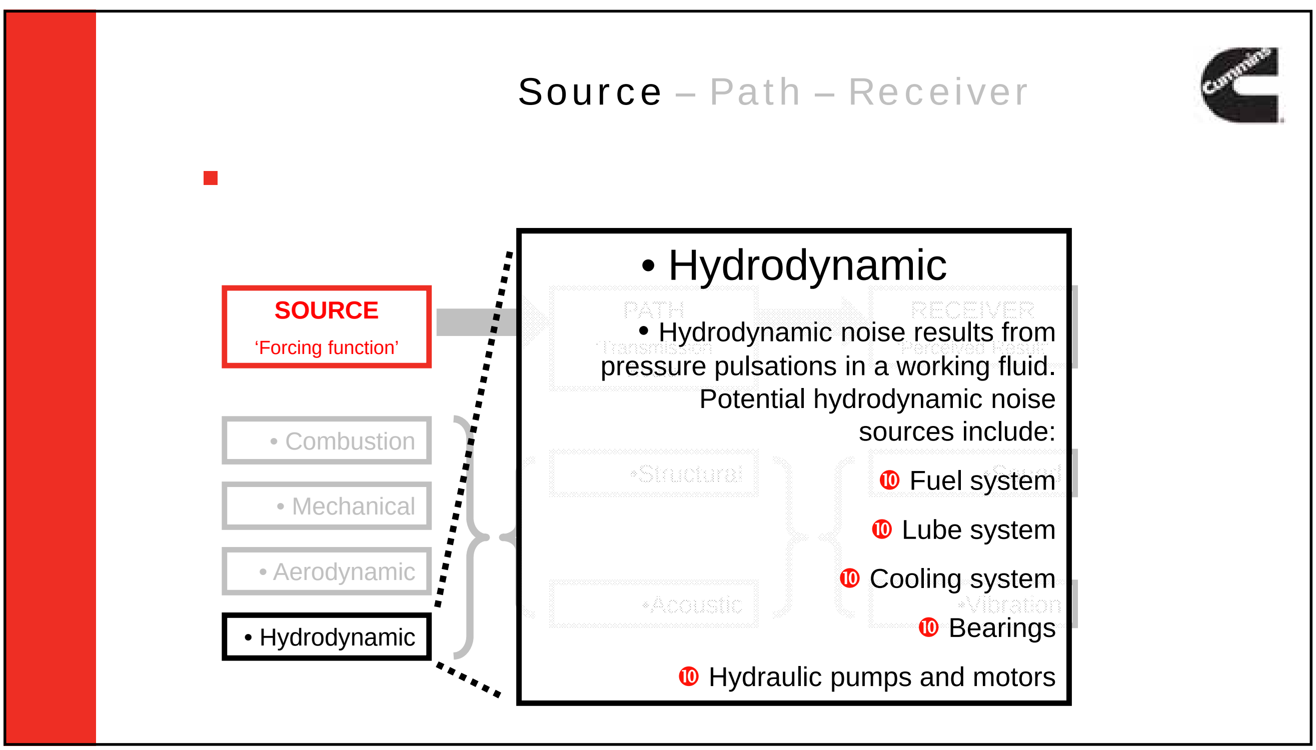
Source – Path – Receiver

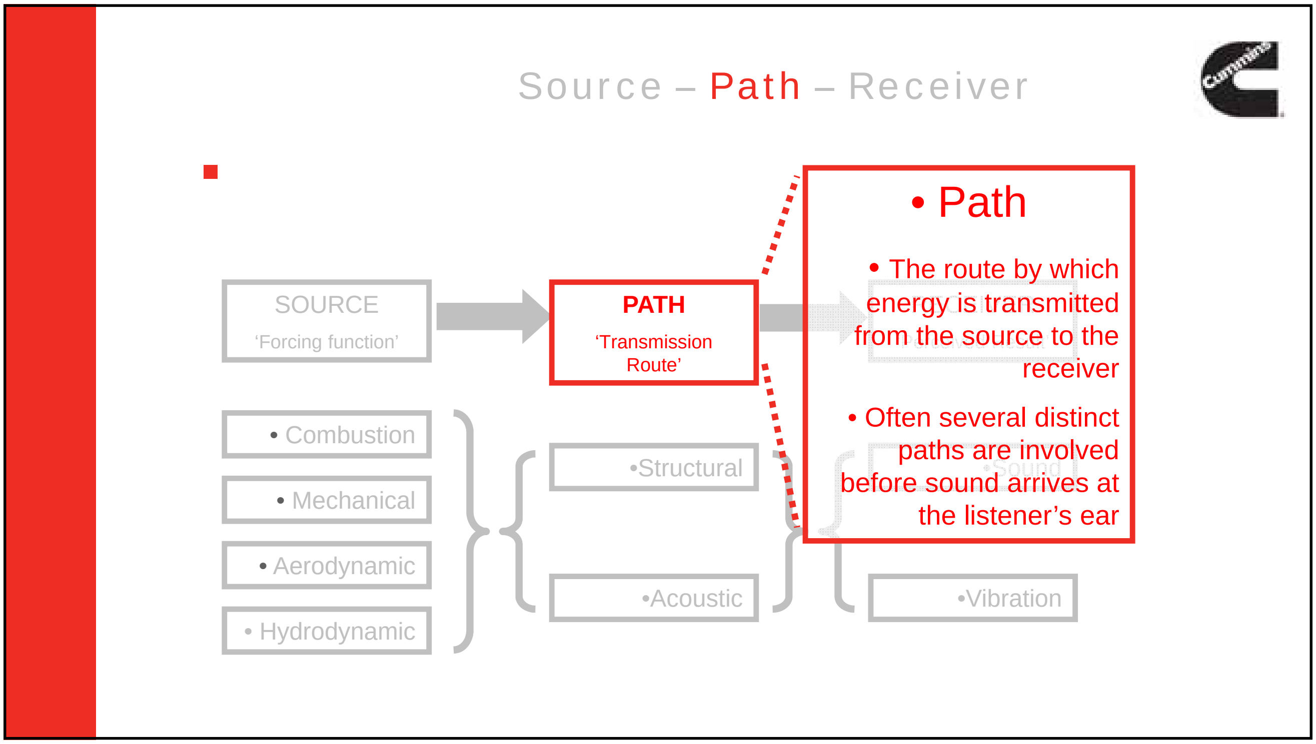
SOURCE
'Forcing function'

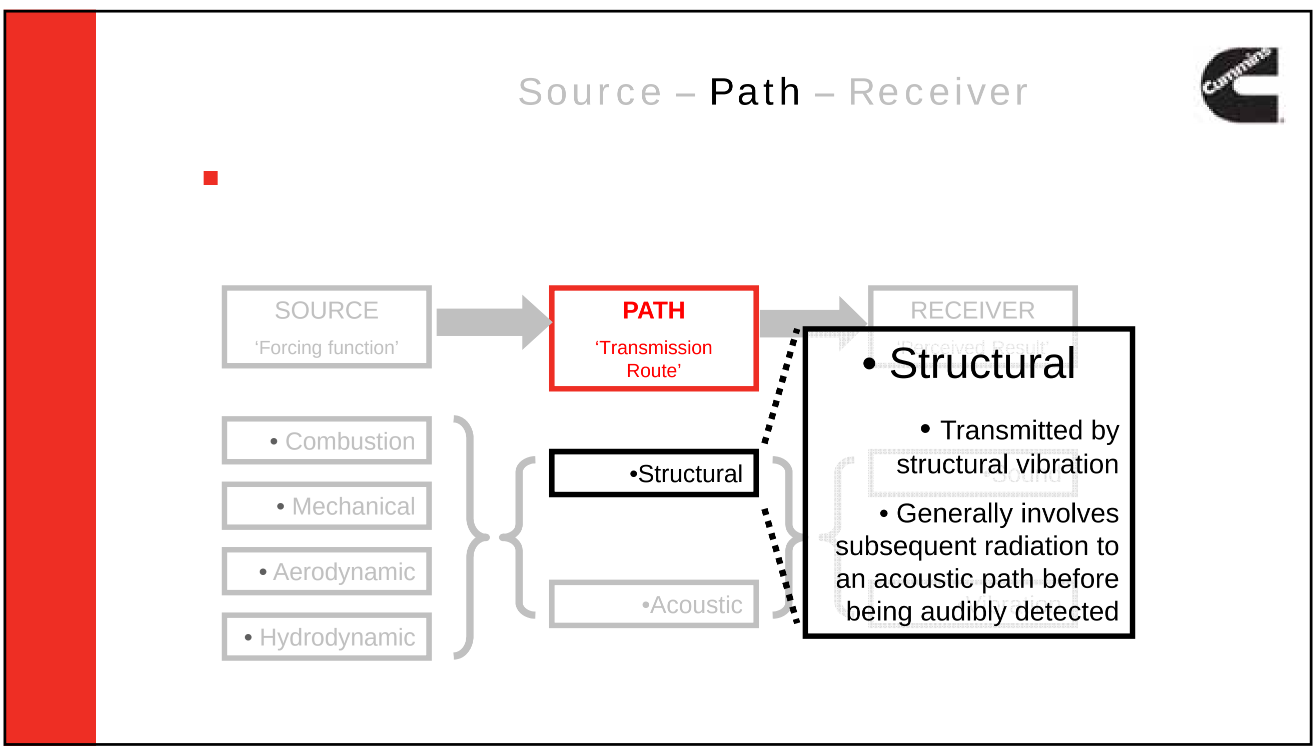
- Combustion
- Mechanical
- Aerodynamic
- Hydrodynamic

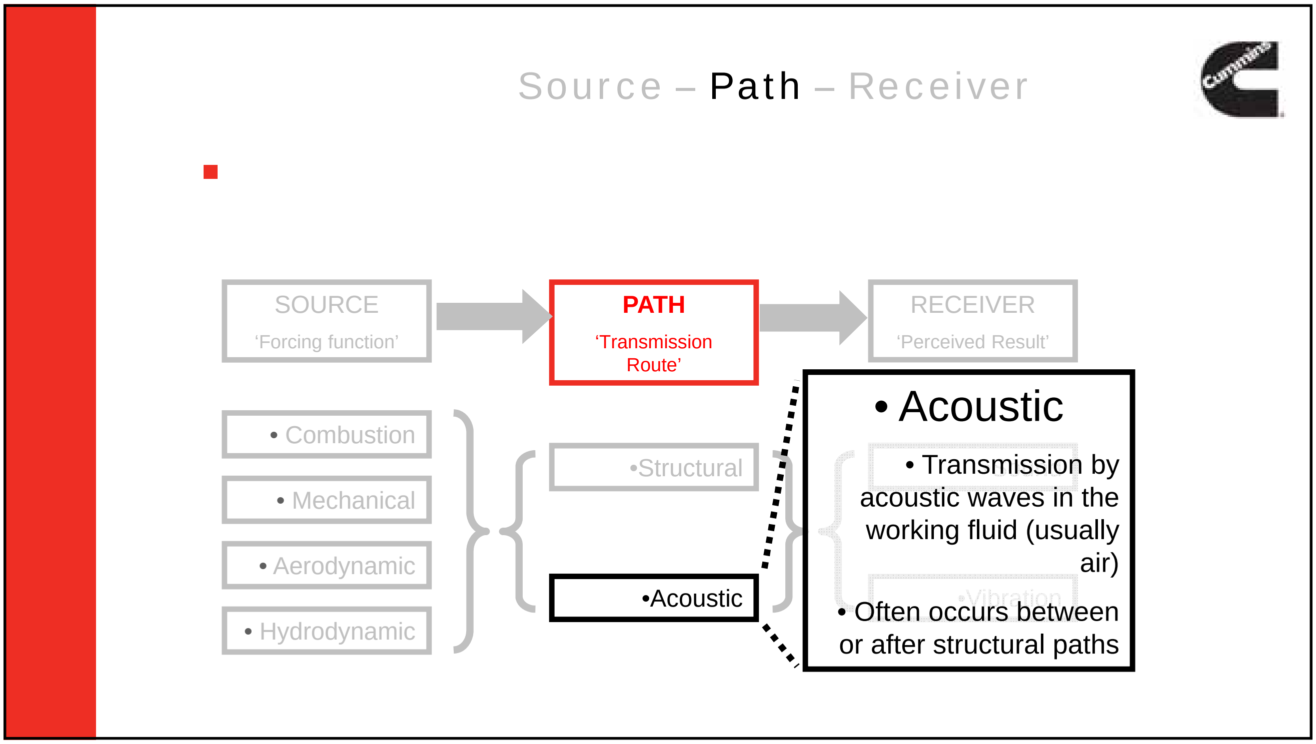
- Mechanical
  - Multiple mechanical sources in the engine and its sub-systems, including:
    - Gear impacts, piston impacts, valve train forces, imbalance forces, bearing loads, etc..
    - Some portion of mechanical noise may vary as cylinder pressure varies

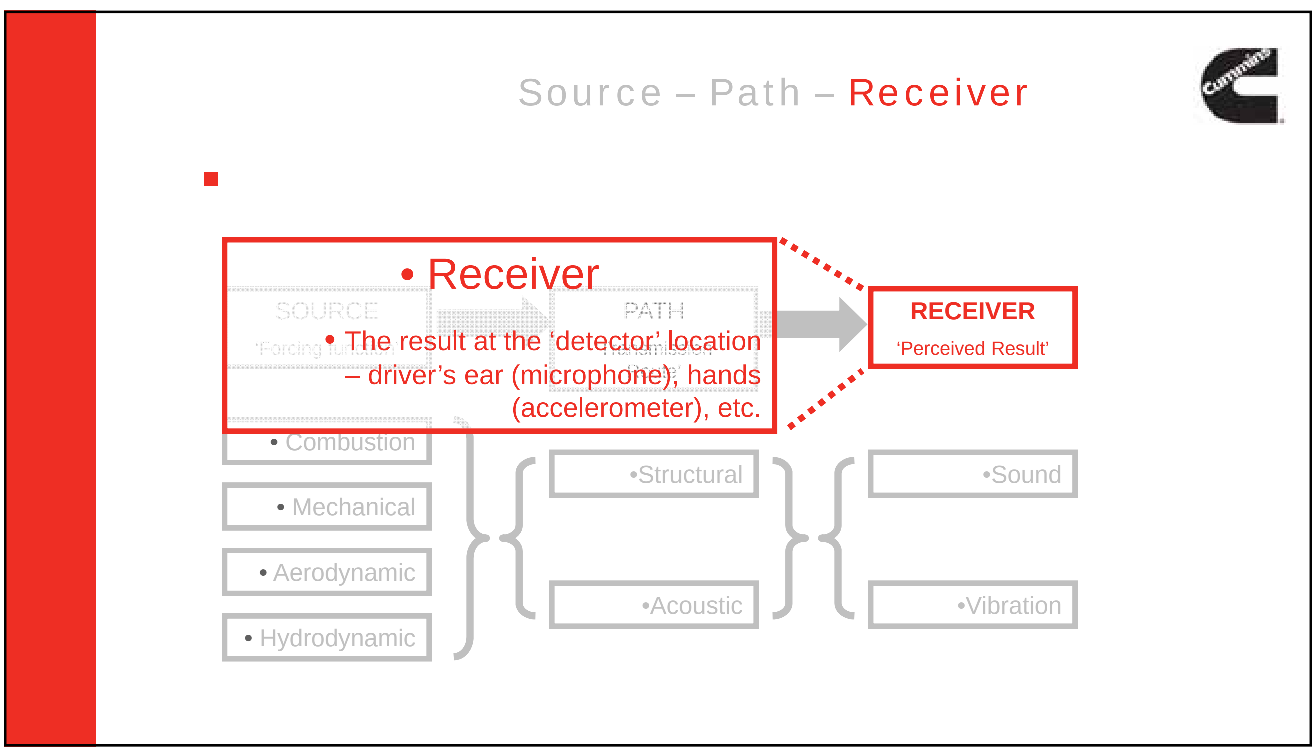

Source – Path – Receiver
SOURCE
'Forcing function'
PATH
RECEIVER
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
• Aerodynamic
• Aerodynamic noise is generated by air flowing or interacting with a body. Examples of aerodynamic sources include:
Cooling fans
Induction and exhaust flow
Turbocharger blade pass

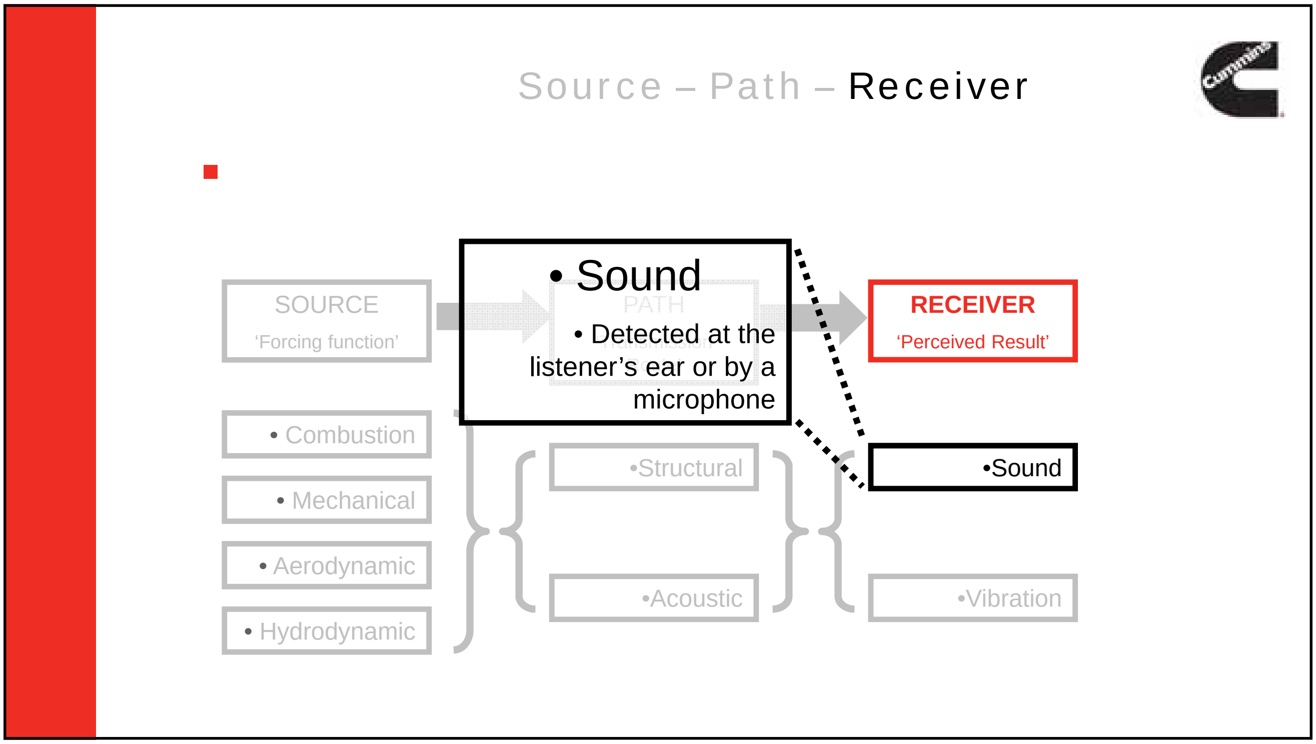

Source – Path – Receiver
SOURCE
'Forcing function'
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
• Hydrodynamic
• Hydrodynamic noise results from pressure pulsations in a working fluid. Potential hydrodynamic noise sources include:
Fuel system
Lube system
Cooling system
Bearings
Hydraulic pumps and motors

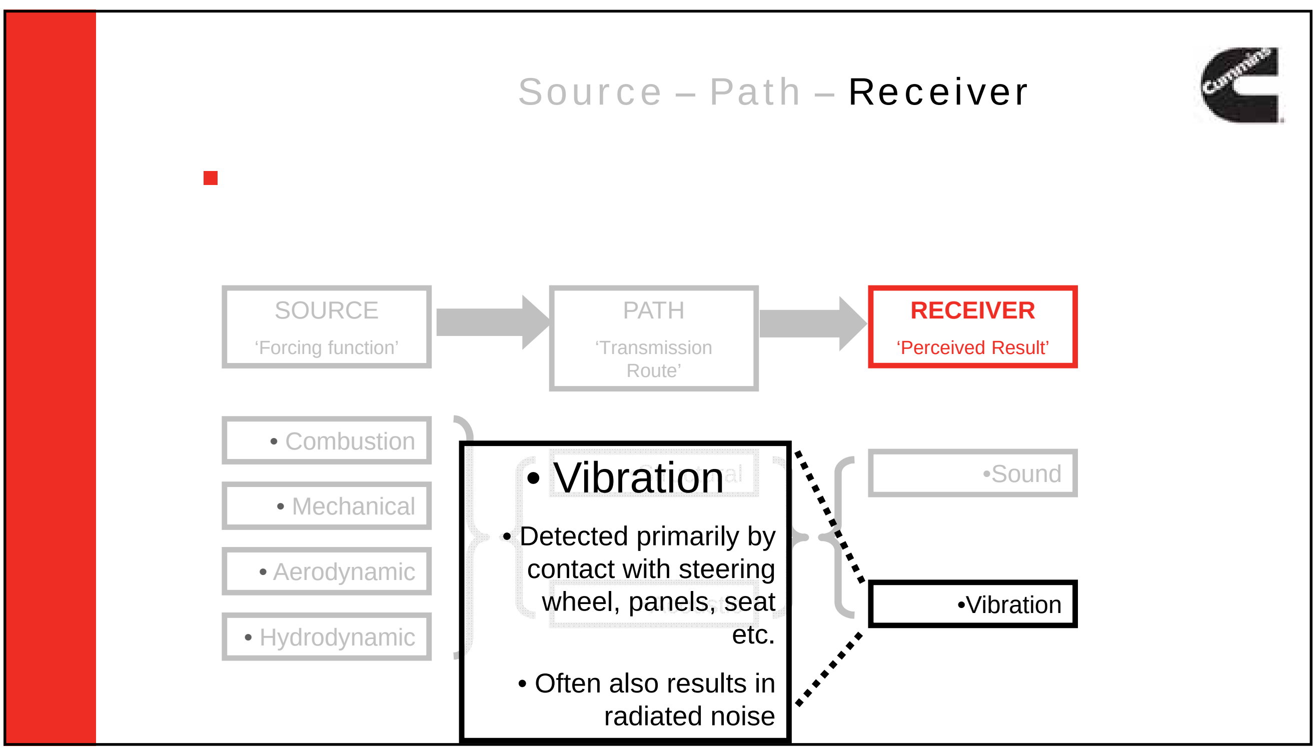

Source – Path – Receiver
SOURCE
'Forcing function'
PATH
'Transmission Route'
• Path
• The route by which energy is transmitted from the source to the receiver
• Often several distinct paths are involved before sound arrives at the listener's ear
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
•Structural
•Acoustic
•Vibration


Source – Path – Receiver
SOURCE
'Forcing function'
PATH
'Transmission Route'
RECEIVER
• Structural
• Transmitted by structural vibration
• Generally involves subsequent radiation to an acoustic path before being audibly detected
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
•Structural
•Acoustic


Source – Path – Receiver
SOURCE
'Forcing function'
PATH
'Transmission Route'
RECEIVER
'Perceived Result'
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
•Structural
•Acoustic
• Acoustic
• Transmission by acoustic waves in the working fluid (usually air)
• Often occurs between or after structural paths


Source – Path – Receiver
• Receiver
• The result at the 'detector' location – driver's ear (microphone), hands (accelerometer), etc.
RECEIVER
'Perceived Result'
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
•Structural
•Acoustic
•Sound
•Vibration


Source – Path – Receiver
SOURCE
'Forcing function'
• Sound
• Detected at the listener's ear or by a microphone
RECEIVER
'Perceived Result'
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
•Structural
•Acoustic
•Sound
•Vibration


Source – Path – Receiver
SOURCE
'Forcing function'
PATH
'Transmission Route'
RECEIVER
'Perceived Result'
• Combustion
• Mechanical
• Aerodynamic
• Hydrodynamic
• Vibration
• Detected primarily by contact with steering wheel, panels, seat etc.
• Often also results in radiated noise
•Sound
•Vibration

Source – Path – Receiver

- SOURCE 'Forcing function'
  - Combustion
  - Mechanical
  - Aerodynamic
  - Hydrodynamic
- PATH 'Transmission Route'
  - Structural
  - Acoustic
- RECEIVER 'Perceived Result'
  - Sound
  - Vibration

- The sensations of sound and vibration are closely linked – hence the concept of NVH

Noise
Vibration
Harshness

Noise Reduction

- To Reduce Noise, We Can….

Modify the Source	AND/ OR	Modify the Path	AND/ OR	Modify the Receiver
Cylinder pressure Cyclic torque Piston slap Gear impacts Gear whine Fan noise ……..etc.		Structural design Oil pan & cover materials Oil pan & cover isolation Shields & enclosures Mounts…		Rarely the preferred solution! Ear muffs or ear plugs Reduce exposure time (Turn up the radio!)….

Noise Reduction

The Source – Path – Receiver Model

Noise Reduction – Source
Basic Design Principles

- Optimize cylinder pressure shape and variation for best combustion noise tradeoff versus other parameters
- Avoid step changes in noise due to e.g. rapid pilot transition
- Minimize cyclic torque variations
- Control clearances and clearance variations (e.g., gear lash)
- Eliminate or reduce impact loads

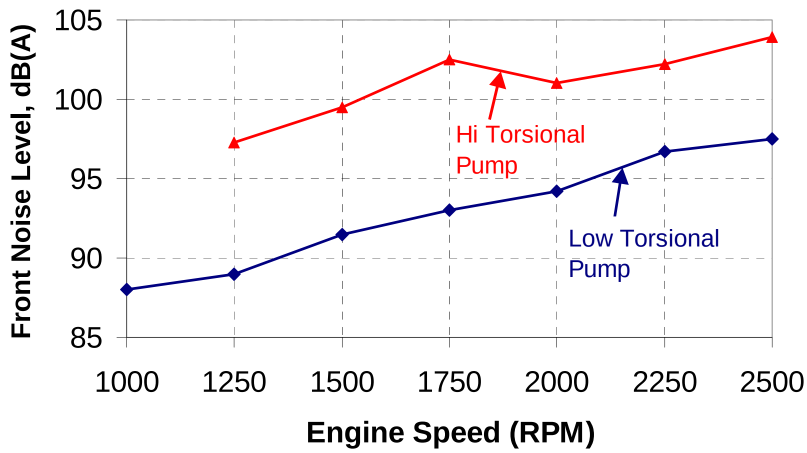
Gear Impact Reduction

High cyclic torque (relative to mean torque) causes periodic unloading/ reverse loading/ impacts of gear teeth:

- Design for the lowest number of gear meshes
  - Each mesh is an additional noise source
- Reduce alternating torque
  - Low cyclic torque fuel system/ overhead loads
  - Fuel pump damper
  - Camshaft damper
  - Rear gear train
- Increase mean torque
  - Drive constant torque loads through the gear train – used in some passenger car applications
- Reduce backlash
  - Scissor gears

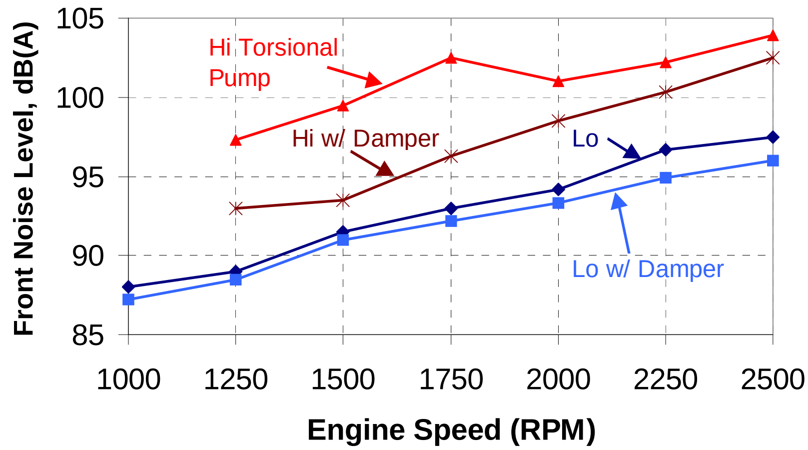
Low Cyclic Torque Fuel Systems

Example: 1m-SPL with Low- & High- cyclic torque fuel systems:



Fuel Pump Torsional Damper

Example: 1m-SPL with and without a fuel pump tuned torsional damper:



Reduced Backlash – Scissor Gears

- The scissors gear reduces backlash by applying a preload within the mesh
- Applicable to helical (below) and spur gear (right) configurations

Gear Whine

- Gear Whine – tonal noise resulting from:
  - Cyclic stiffness variation
    - Effective 'Contact Ratio' – number of teeth in mesh – varies as teeth engage and disengage
      - **Helical gears transfer loads between teeth more gradually than spur gears**
      - **Spur gears share load more uniformly if contact ratio is high**
  - Transmission Error
    - Loading
      - **Tooth profile deviates from the optimum under load**
    - Wear
      - **Wear changes tooth profile and hence load transfer**
    - Local defects
      - **Nicks, handling damage, etc. causing periodic noise**
    - Geometry Errors
      - **Manufacturing / machining errors – distortion, 'ghost' errors, etc.**
      - **Eccentricity/ tilting – due to shaft and bearing run-out, clearances**

Piston Impact Noise – 'Piston Slap'

- Piston secondary motion:
  - Piston moves laterally across the bore and tilts as a result of gas pressure and inertia loads
  - High gas loading on the combustion stroke in particular causes rapid lateral motion and a 'slap' impact with the bore
  - Influenced by operating clearances, piston and bore geometry, stiffness, thermal / mechanical distortion, pin offset, lubrication, etc.

Example: Engine Noise From Cold – Two Alternate Piston Configurations

1m 4-side average SPL immediately after starting from cold
Differences became indiscernible with the engine warm

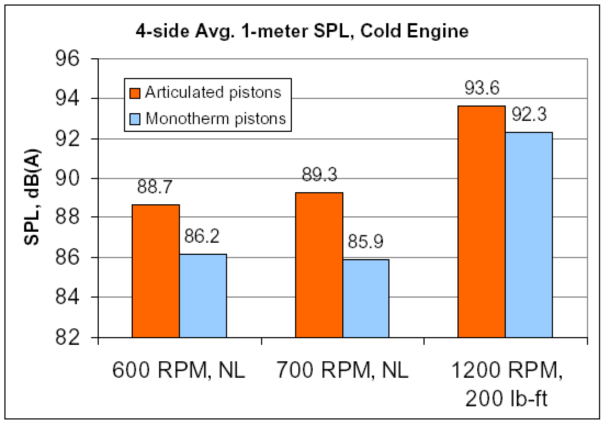
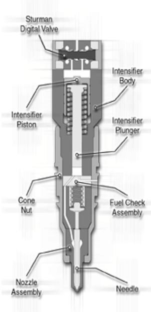
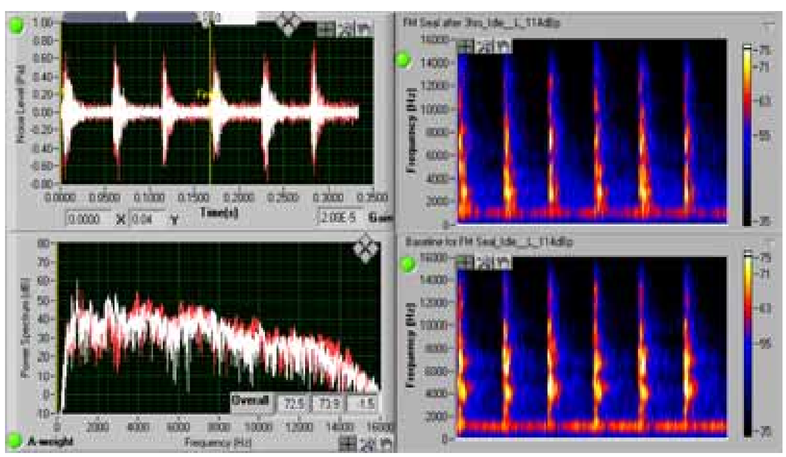


Figure 12: Overall Sound Pressure Levels, Cold Engine

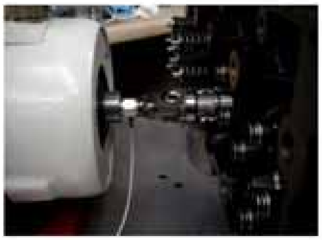
Injector Noise

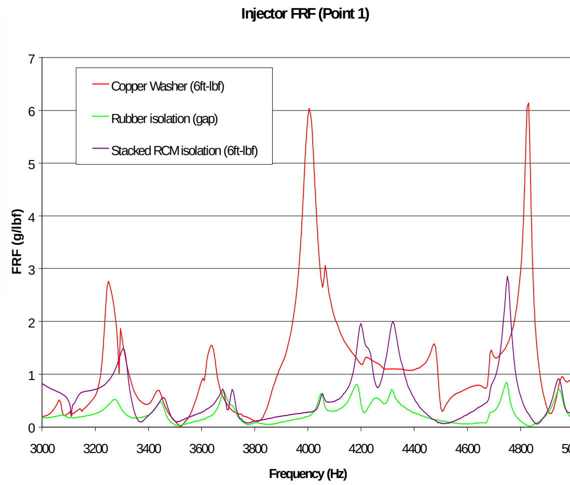




Engine noise contains a ticking due to injector operation, transmitted to and rated from the cylinder head. Isolation reduced the ticking

Injector Noise





Transmissibility rig test shows isolation provided by rubber isolator (green). Stacked washers (blue) are a more practical implementation

Fuel Systems – Mechanical Noise

- Fuel system related mechanical noise tends to be worst at high speed & load, as a result of:
  - Cyclic torque inputs to the gear train
  - Gear backlash, impacts and rattle
  - Axial vibration of helical gears
  - Cam / fuel pump gears that move much more than crank
- Mechanical noise is lower for a fuel system with:
  - Minimum torque fluctuation
  - Ability to phase torque fluctuations relative to the crank
    - ❿ Requires injection timing independent of pump timing
  - Ability to handle an isolation coupling between the pump and drive gear

Turbocharger Noise

- Turbocharger noise is not normally a significant contributor to overall noise levels, but is often a source of subjective complaints.
- Principal turbocharger noise issues are:
  - Compressor bladepass noise, normally > 8 kHz
  - "Low-order" noise, 1st, 2nd or sub-harmonic,1 - 3 kHz)
  - Turbine bladepass noise, usually on spool-down or at idle
  - VG turbos present challenges because the engine operator has less direct control of turbo speed

Accessories

- As base engine noise is reduced, other sources may start to become significant:
  - Oil pump – transmitted to and radiated by the oil pan, this is considered a perennial problem by one of our JV partners
  - Air compressor – 'ping tank'
  - Freon compressor
  - Alternator
  - Drive belts (belt squeal on shutdown is a common issue)
  - Lift pumps… etc

Cooling Fan Noise

- Increased heat rejection requires greater cooling air flow:
  - Fan Airflow $\propto$ RPM * Diameter^3
  - Fan Static pressure $\propto$ RPM^2 * Diameter^2
  - Fan Sound Power $\propto$ RPM^5 * Diameter^7 !!!
- In some applications such as mine haul trucks or gensets, the cooling fan may be the dominant noise source
  - The relative contribution can be gauged from decrease in level with fan turned off:
  - More than 3dB drop indicates that fan noise level is higher than all other sources combined

Noise Level Decrease with Fan Removed	Percentage Fan Noise Contribution
0.5	10
1	20
2	37
3	50
4	60
5	68
6	75
7	80
8	84
9	87
10	90

Noise Reduction

The Source – Path – Receiver Model

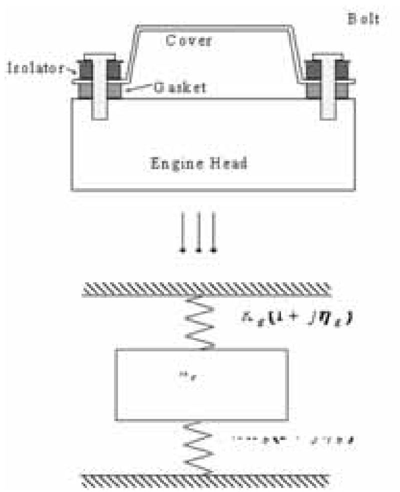
Noise Reduction – Path
Basic Design Principles

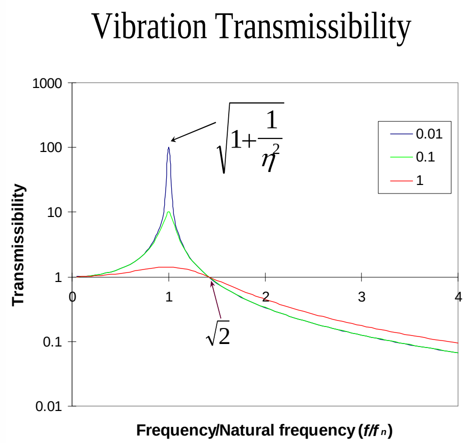
- Minimize exterior vibration for given internal forces
  - Stiff basic block structure
- Inefficient vibration energy transmission
  - Large stiffness changes across joints creates an impedance mismatch
  - Ideal combination: Stiff / Soft / Stiff
- Operate well below resonance
  - Small, stiff, high frequency external areas and components
- Or operate well above resonance
  - Large, dense, low stiffness, low freq. panels reduce radiation efficiency
- Control resonance
  - Add damping – most effective on large resonant panels
- Add shields and enclosures
  - Easier and more effective if allowed for in the initial design

Block Structure

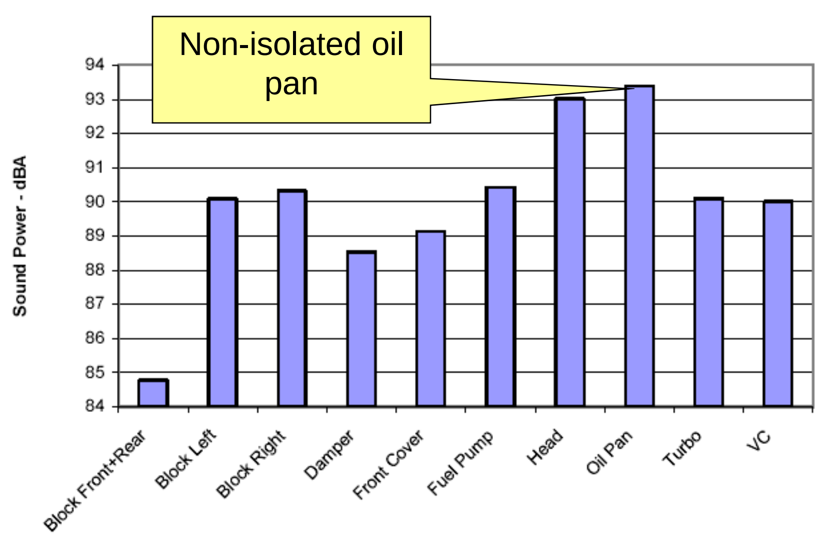
- Seek to minimize exterior vibration for given internal forces:
  - Long side skirts
  - Bedplate / Ladder Frame / Top Plate (for vee engines) to provide shear loop closure
  - Stiff main bearing bulkheads
  - Localized ribs
  - Designed-in provision for close fitting enclosures

Isolation Example – Valve Cover





Source Ranking – Oil Pan Contribution



Example: Engine Noise Source ID @ 2000rpm,125ft-lbf

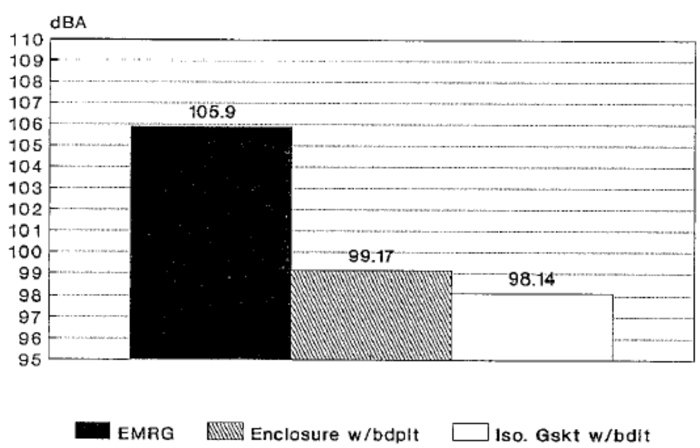
Isolation – Oil Pan

- Typical tuned for vertical natural frequency of 200-300 Hz, with a lateral frequency of ~ 100 Hz
  - Still excited by engine orders, but with low radiation efficiency and controlled by damping
  - Provides isolation for higher frequencies
    - Combustion noise
    - Block bending
    - Reduces excitation of higher order panel modes
- As good as, or better than, a pan enclosure
- Can be as durable as a 'conventional' joint
- Reduces imposed deflection stresses in pan

Effect of Oil Pan Isolation

Engine Oil Pan Sound Power
Standard Pan

Ref: CTR 0502-95-024



Standard Edge Molded Rubber Gasket

Operation Below Resonance

- Design systems and subsystems so that their natural frequency is above those of major engine orders for the operating speed range:
  - High stiffness and low mass increase resonant frequency
  - Power train bending and torsional frequencies should be as high as possible
  - Brackets, accessory attachments -
    - E.g. Some high-end passenger cars use alternators direct-mounted to the block, to avoid resonances associated with conventional bracket mounts

Operation Above Resonance

- Design panels to have principal modes with low natural frequency, below major orders for the operating speed range
- May not always be possible to drive frequencies low enough to avoid excitation, but still benefit from:
  - Low radiation efficiency
  - Avoiding strong excitation by major orders at high speed
- Applicable to:
  - Gear covers
  - Oil Pans
  - Valve covers, etc.

Panel Damping

- Reduces response at resonance, by increasing damping
- Damping material may be applied as a coating or bonded material, or integral to the part
  - Examples include constrained-layer oil pans, gear covers etc.
  - ‘Doubled walled’ gear covers use a second steel layer, spot welded to the outer layer, primarily to add damping
    - ❿ Poor design can negatively impact noise due to an increase in panel stiffness

Block Side Shields (or ‘Enclosures’)

Figure 1: Enclosure mounted on block left side

Close-fitting side shields are easier to incorporate and more effective if allowed for in the original design

Figure 2: Rear side of enclosure with fiberglass

Example of 1-m SPL
with and without Side Shields

Note that in this example, the side shield increased low frequency noise, but provided significant attenuation above 1 kHz

Sound power from this region of the block reduced from 102.1 dB(A) without the enclosure, to 97.2 dB(A) with enclosure

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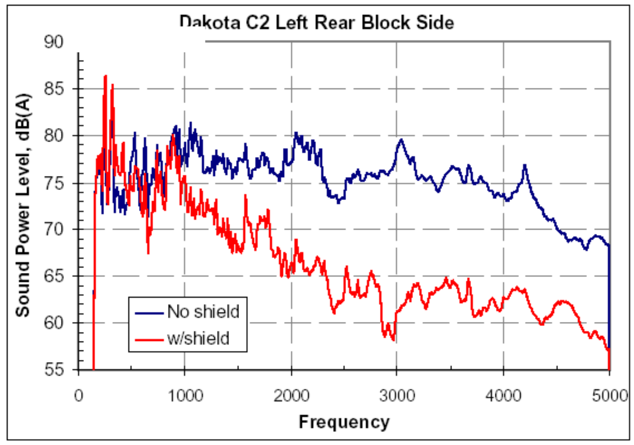

Figure 4: Sound power spectra with and without enclosures, 2100 RPM, 915 lb-ft

Side Shield Design

- Enclosure construction in the preceding example:
  - 1.5 mm thick Premix Premi-Glas 1282 as used for Signature valve cover
  - Backed by 6 mm layer of fiberglass
  - Fiberglass decouples the vibration from the block
  - Ideally, enclosures should be fully isolated from the block
    - In this case a four-point direct mount did not significantly reduce enclosure performance

Noise Reduction

The Source – Path – Receiver Model

Receiver

- Usually we cannot directly influence the receiver
  - Ear plugs or ear muffs are only feasible in a few industrial applications
- Understanding how noise is perceived is required for developing a suitable metric for measuring noise improvements / degradations
- Sound quality is becoming increasingly important
  - Recent DFSS projects include:
    - Idle noise quality
    - Annoyance of pure tones (turbochargers, gear whine)
    - Combustion noise target setting