Many Players, One Team

Noise in Hydraulic Systems and Applications

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07 March 2018
Agenda

• Introduction (General Noise Background)
• Noise in Hydraulics (General)
• Noise in Hydraulic Systems & Applications
Why do we care about noise?

- Personal Safety (hearing loss), Comfort
- Government Regulations (EU, OSHA)
- Marketing Advantage for Low Noise Products
- Loss of Business or No New Business (due to Noisy Products)
Automotive markets typically leads the Noise Trends.
Followed by Truck
Agriculture, Construction, and Industrial Markets

• Mobile Applications
  - Excavator
  - Tractor

• Industrial Applications
  - Injection Molding Machine
  - Hydraulic Press
Hydraulics Supplier NVH Goal

To provide hydraulic components & systems that exceed our customer’s expectations regarding overall noise level and sound quality. In effect, become “NVH transparent” to the marketplace.
Quiet Hydraulics – Is a “Team” effort.

• A successful noise control program requires a team effort by individuals in several areas of expertise.
• A quiet hydraulic pump does not guarantee a quiet system.
• The program calls upon the talents of:
  • The designer (both hydraulic and vehicle)
  • Fabricator of parts
  • Manufacturing or installer
  • Maintenance technicians, Service, etc.
• If any member of the team fails to do their job, it can mean failure of the entire noise control program.
Noise Generation (In General)

The excitation force could be fluid borne or mechanical.

The transfer function includes structural, acoustic, and fluid resonances. This also reflects the effectiveness or efficiency of the transmission paths.

Vibration is the result of the force and the transfer function.

Radiation Efficiency is a measure of how effective is a vibration being converted to noise.

What’s measured or predicted. This is the result.

\[
\text{Force} \times \text{Transfer Function} = \text{Vibration} \times \text{Radiation Efficiency} = \text{Sound Pressure or Power}
\]
What do we hear? (Sound ??) (Noise ??)

• Sound and/or Noise is divided into:
  • Overall Level
    • What we can measure.
      • Sound Pressure, Sound Power
  • Sound Quality
    • The perception or psychoacoustics of noise.
    • Which can be measured but is subjective.
### Changes in Sound Pressure Level

<table>
<thead>
<tr>
<th>Change in SPL (dB)</th>
<th>Percent Change</th>
<th>Change in SPL (dB)</th>
<th>Percent Change</th>
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<tbody>
<tr>
<td>1</td>
<td>12%</td>
<td>-1</td>
<td>-11%</td>
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<tr>
<td>2</td>
<td>26%</td>
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<td>6</td>
<td>100%</td>
<td>-6</td>
<td>-50%</td>
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<tr>
<td>7</td>
<td>124%</td>
<td>-7</td>
<td>-55%</td>
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<tr>
<td>8</td>
<td>151%</td>
<td>-8</td>
<td>-60%</td>
</tr>
<tr>
<td>9</td>
<td>182%</td>
<td>-9</td>
<td>-65%</td>
</tr>
<tr>
<td>10</td>
<td>216%</td>
<td>-10</td>
<td>-68%</td>
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# Changes in Sound Power Level

<table>
<thead>
<tr>
<th>Change in SWL (dB)</th>
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<tr>
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<td>5</td>
<td>216%</td>
<td>-5</td>
<td>-68%</td>
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<td>6</td>
<td>298%</td>
<td>-6</td>
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<td>401%</td>
<td>-7</td>
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<td>531%</td>
<td>-8</td>
<td>-84%</td>
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<td>694%</td>
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<tr>
<td>10</td>
<td>900%</td>
<td>-10</td>
<td>-90%</td>
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</table>
Sound Quality

• What customers really want:

  • Pleasant sound
  • Sound which suggests power and strength
  • 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.
Reservoir Details

- Baffles to separate return line from outlet line
- Filler pipe with filter
- Magnetic drain plugs at low point(s)
- Clean-out plate
- Baffles to prevent cascading
- Outlet line strainer
- Fluid level above pump inlet
- Sight gauge
- Large surface area for cooling
- Capacity of 2-3 times pump flow
- Filtered breather cap
- Filtered breather cap
Fluid Bulk Modulus:

Easy5 #18 (SAE 10W)
Trapped air = 3%

Bulk Modulus (psi)
Pressure (psi)
Temperature (F)

Fluid Bulk Modulus:
Air in Hydraulic Fluid

- Air Bubbles Expand
- Air Bubbles Implode
- Leaky Fitting
- Erosion
Air in Hydraulic Fluid

Vapor Bubbles Form

Restriction

Vapor Bubbles Impplode

Erosion
Air in Hydraulic Fluid

Fluid velocity, due to excessive pump speed, is higher than the pump inlet can accommodate.
Valveplate Cavitation

Figure 15-6  Piston pump valve plate erosion caused by aeration or cavitation
Air in Hydraulic Fluid

• **Entrained Air** — Air in the form of bubbles. Has large effect on bulk modulus (affects pump performance, noise, efficiency….). If the amount of dissolved air in the oil is lower than the solubility limit, entrained air becomes dissolved air.

• **Dissolved Air** — Has minimal effect on bulk modulus. If the amount of dissolved air exceeds the solubility of the oil, dissolved air will become entrained air. If the amount of dissolved air is less than the solubility limit and the oil is exposed to air, then air will penetrate the oil and become dissolved air.

• **Solubility Limit** — The solubility limit of oil is a function of pressure. Thus, as a system fluctuates in pressure, the amounts of entrained and dissolved air in oil can fluctuate. If the system is periodically exposed to air, the total amount of air in the oil can vary with time.
Pump Inlet Pressure Loss

Minimum Inlet Pressure During Pumping Cycle

Location in Pump

Potential for Dissolved Gas to Become Entrained.

Inlet Pressure

Solubility Limit

Hose Bends
Pump Inlet
Piston
Entrained Air Example:
Bore Pressure Rise Rate

ID #61 Valveplate Low-to-High Pressure Transition

Overshoot

Pressure Rise Rate (dP/dt)

Pressure Transition
Piston Pump Noise and Vibration Path

- **Pump (Forcing Function)**
  - Internal Component Dynamics
    - Flow/Pressure Ripple
      - Fluid Lines and Line Dynamics
      - Vibration to Structure Through Mounts, Clamps and Accessories
      - Airborne Noise from the Structure and Lines
      - Attenuators or Resonators
  - Housing
    - Vibration to the structure
    - Airborne Noise from the Housing
  - Airborne Noise from the Structure
Noise Transmission and Generation

- In hydraulic systems noise is transmitted in three ways:
  - Fluid-borne noise
  - Structure-borne noise
  - Airborne noise

- Note: It’s important to understand which source (transmission path) is dominant.
Hydraulic Systems Noise Flow Chart

- Internal Forces
  - Fluid Borne Noise
  - Structure Borne Noise
  - Air Borne Noise

Air Sound
Fluid-Borne Noise

- Noise that is created by the pump as pressure ripple, pressure waves, and uneven flow characteristics (vibrations) in the fluid lines and transmitted to anything attached to the fluid lines.

  - Fluid line clamps, clips, or mounts.
  - Motors, actuators, valves.
Noise Generation (Fluid Borne)

- The excitation force is due to the flow/pressure ripple from the pump.

Excitation from the fluid enters the structure of the application from the hose or tube via the supports and excites the structure.

The excitation includes all harmonics of the source.

Vibration is the result of the force and the transfer function.

At this point, the vibration is in the structure and propagates through the structure at the speed of sound of the material.

Radiation efficiency is a measure of how effective is a vibration being converted to noise.

What’s measured or predicted. This is the result.
Piston Pump Pressure Ripple Source

ID #61 Valveplate Low-to-High Pressure Transition

- **Overshoot**
- **Pressure Rise Rate (dP/dt)**
- **Pressure Transition**
Pump Pressure Ripple
Fluid Borne Noise

- Motor
- Cylinder
- Manifold
- Hose/Tube
- Vibration Isolation Mount
- Pressure Ripple
- Vibration Isolation Mounts
Hydraulic Hose:

- Think of a hydraulic hose as similar to a Chinese Finger Puzzle.
Hydraulic Line / Hose Configuration

Worst
Bad
Better
Best

Preferred Short Line Configuration
Wilkes & McLean makes suppressors similar to the Pass-Through Gas Charged Filter Shown above.
Structure-Borne Noise

• Any vibration from the pump that is transmitted, not only through the pump body, but through the application structure as well.

• Typically at pumping frequency and multiples of pumping frequency.
Noise Generation (Structure Borne)

The excitation force is mechanical

The transfer function includes structural paths.
- Engine Block
- Gear Box
- Frame
- Supports / Struts
- Panels

Vibration is the result of the force and the transfer function.

Radiation Efficiency determines the amount of noise is generated given some amount of vibration.

Radiation efficiency varies based on shape of the source (geometry), frequency, deflection pattern, and excitation (mechanical, airborne or fluid borne).

What’s measured or predicted.
This is the result.
Structure Borne Noise

- Motor
- Cylinder
- Manifold
- Pump
- Hose/Tube Vibration Isolation Mount
- Axial Vibration
- Vibration Isolation Mounts
Mounting Plate Dynamics:
Proper Installation is key to a Quiet System

Pump and Motor/Engine on Subplate, Isolated from Stiff Foundation/Frame
Air-Borne Noise

- Noise that is transmitted from the surface of the pump through the medium of the air to the receiver (our ear).
  - Operator
  - By-Stander / Pass-by
Noise Path (Air Borne)(Operator)

The noise source could be a time varying amplitude and varying amplitude as a function of frequency.

The transfer function takes into account the path from the source to the cabin.

If the source is within a full or partial enclosure the effects of the enclosure will also be included in this transfer function. (Hood, Side Panels, Shields, Radiator, etc.)

The enclosure will have a general amplifying effect, but it could also include absorptive material; which will be frequency dependent.

This transfer function will take into account the effectiveness of the noise going through the cabin walls and window, but also takes into account the acoustic leakage through door seals, window seals, leakage around holes in the cabin for wires and hoses.

What’s measured or predicted.

This is the result.
Noise Path (Air Borne)(By-stander / Drive-By)

The noise source could be a time varying amplitude and varying amplitude as a function of frequency.

The transfer function takes into account the path from the source to the by-stander / drive-by microphones.

If the source maybe within a full or partial enclosure. The enclosure will have a general amplifying effect, but it could also include absorptive material; which will be frequency dependent.

Acoustic leakage of the enclosure is taken into account here.

This transfer function will take into account the effectiveness of the noise going through components on the application: (Hood, Side Panels, Shields, Radiator, etc.)

A direct line of sight will allow higher noise level.

For Drive-by noise measurements, the direct line sight maybe only for a few seconds.

What’s measured or predicted.

This is the result.
Air Borne Noise

Motor

Cylinder

Manifold

Hose/Tube Vibration Isolation Mount

Pump

Vibration Isolation Mounts
Noise Source in an Enclosure:

- What is the absorption coefficient of the enclosure?
- What is the directivity index?
- Echo radius?
- Acoustic Leakage?
- Ref: Wallin, et al. 2011
Enclosures (It’s not always easy!)

Rule of Thumb:
A 1% hole in an enclosure will reduce the performance of the enclosure by 50%.
Steering Control Unit: Where Does the Noise Come From?

- Noise Transmission Paths
- Steering Column Shaft
- Steering Column Supports
- Mounting Bolts
- Vehicle Cab Floor
Steering Control Unit Applications

- Mount rubber isolators between the SCU and Cab floor
- Add Rubber grommets underneath mounting bolt heads

This Noise Isolator is Available from Eaton—
Part Number 208-1017-002

Lower End Type 3 (Ref.)

82.6 [3.25] Dia.

See Note Below

61.0 [2.40]

Upper Shaft End EJ (Ref.)

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Understanding the Noise Sources

- Assume we have three noise sources:
  - Structure Borne 70 dBA
  - Airborne 74 dBA
  - Fluid Borne 77 dBA
- The total sound pressure level from these 3 sources would be?

\[
SPL_{Total} = 10 \log \sum 10^{SPL_n/10}
\]

\[
= 10 \log (10^{70/10} + 10^{74/10} + 10^{77/10})
\]

\[
= 10 \log (10^{7.0} + 10^{7.4} + 10^{7.7})
\]

\[
= 79.3 \text{ dB}
\]
Understanding the Noise Sources

• Suppose we reduced the Airborne source from 74 dB to 71 dB: (- 29%)
  • We would have: 70dB + 71dB + 77 dB.
  • The new total sound pressure level from these 3 sources would be?

\[
SPL_{Total} = 10 \log \sum 10^{\frac{SPL_n}{10}}
\]

\[
= 10 \log \left( 10^{\frac{70}{10}} + 10^{\frac{71}{10}} + 10^{\frac{77}{10}} \right)
\]

\[
= 10 \log (10^{7.0} + 10^{7.1} + 10^{7.7})
\]

\[
= 78.6 \, dB
\]

• A reduction of 0.7 dB (- 8%)
Understanding the Noise Sources

- Next we reduced the Fluid Borne source from 77 dB to 74 dB. (-29%)
  - We would have: 70 dB + 71 dB + 74 dB.
- The new total sound pressure level from these 3 sources would be?

\[
SPL_{Total} = 10 \log \sum 10^{SPL_n/10}
\]

\[
= 10 \log (10^{70/10} + 10^{71/10} + 10^{74/10})
\]

\[
= 10 \log (10^{7.0} + 10^{7.1} + 10^{7.4})
\]

\[
= 76.8 \text{ dB}
\]

- A reduction of 1.8 dB (-19%)
Vehicle Noise Sources

- Engine / Muffler
- Fan
- Hydraulic System (Accessories: Gears, Chains, Vibrating Parts)

Total Vehicle Noise

Application #1
Application #2
Application #3
Application #4
Noise Analysis

Application #4
Order Analysis

\[
Order = \frac{(freq) \times (60)}{RPM}
\]

- Order = Number of cycles per revolution.
  - Identify Components (9th, 18th order is piston pump)
- Frequency (Hertz or cycles per second)
- 60 (seconds per minute) make the units work out
- RPM (revolution or cycles per minute)
Noise Source Identification

- Engine (combustion) (four cylinder) (2290 rpm) (two pulses per rev)
- Muffler (combustion frequencies and harmonics) (cavity modes)
- Engine to pump gear set (41:29)
- Piston Pump (9 pistons) (3238 rpm)
- Gear Pump (13 tooth) (3238 rpm)
- Fan (1.35:1 ratio) (7 blades) (3091 rpm)
- Final drive (32:12)
- Gear box (10:39) (10:37)
- Piston Motor
  - Motors had 9 pistons (4772 and 4733 rpm)
- Chain ratio (12:32)
Application # 4

A WEIGHTED
110.00

SPECTRUM 1

dB ENG. UNITS
REF=2.00E-005

FREQ= 0.0
MAG= -156.02

TOTAL 99.528
50.000

Left Operator's Ear WOT High Speed Straight

Gear Box Gear Mesh

Gear Pump

Piston Pump

Fan

Final Drive

Engine

Piston Motor

FREQUENCY (Hz) 4005.0

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Noise Reduction:

• By-stander / Pass-by noise
  • European Noise Directive
  • Drive-by Noise

• Operator Ear Noise
  • Overall level
  • Sound Quality
Combine harvester
Combine harvester:

- Pumps are in the rear of the machine:
  - Airborne path most likely isn’t the dominant path for in-cabin noise, but maybe for by-stander or drive-by.

- Drive motor is just below the cabin:
  - Airborne noise maybe more of a concern, especially during roading conditions.

- Fluid borne paths via the hose supports/clamps could excite the many lightly damped panels and shields. Fluid borne vibration into the application frame/structure could be an efficient transmission path.

- Vibration isolation of the steering control unit, column, shaft, and shrouds are required for minimal contribution from the steering control unit.
Skid Steer Loaders

• Basically you’re sitting right over the pumps so airborne noise from the pumps is a concern.
• The pumps are basically in an enclosure. Component noise from the sources are most likely amplified within the confined space.
• Effective acoustic sealing between the noise source(s) and the cabin is critical.
• Hose/tube isolation. Within the confined cavity, hoses can expand when under pressure and contact the structure leading to an effective transmission path.
• Manifolds/valves can be an effective transmission path. May consider vibration isolation of manifolds; if found to be an effective transmission path.
• Hydraulic resonators, especially for the auxiliary circuits.
• Panel modes of the structure could create effective speakers.
• Acoustic treatment within the cabin.
Industrial Applications

- The same noise identification, transmission paths, and noise reduction technics also apply to industrial applications.
- The concerns are operator ear noise level and overall manufacturing plant noise levels per OSHA.
Questions

• For any questions, concerns, or issues with this presentation contact:
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  • Ph: 952-937-7244