Many Players, One Team

Noise in Hydraulic Systems and Applications

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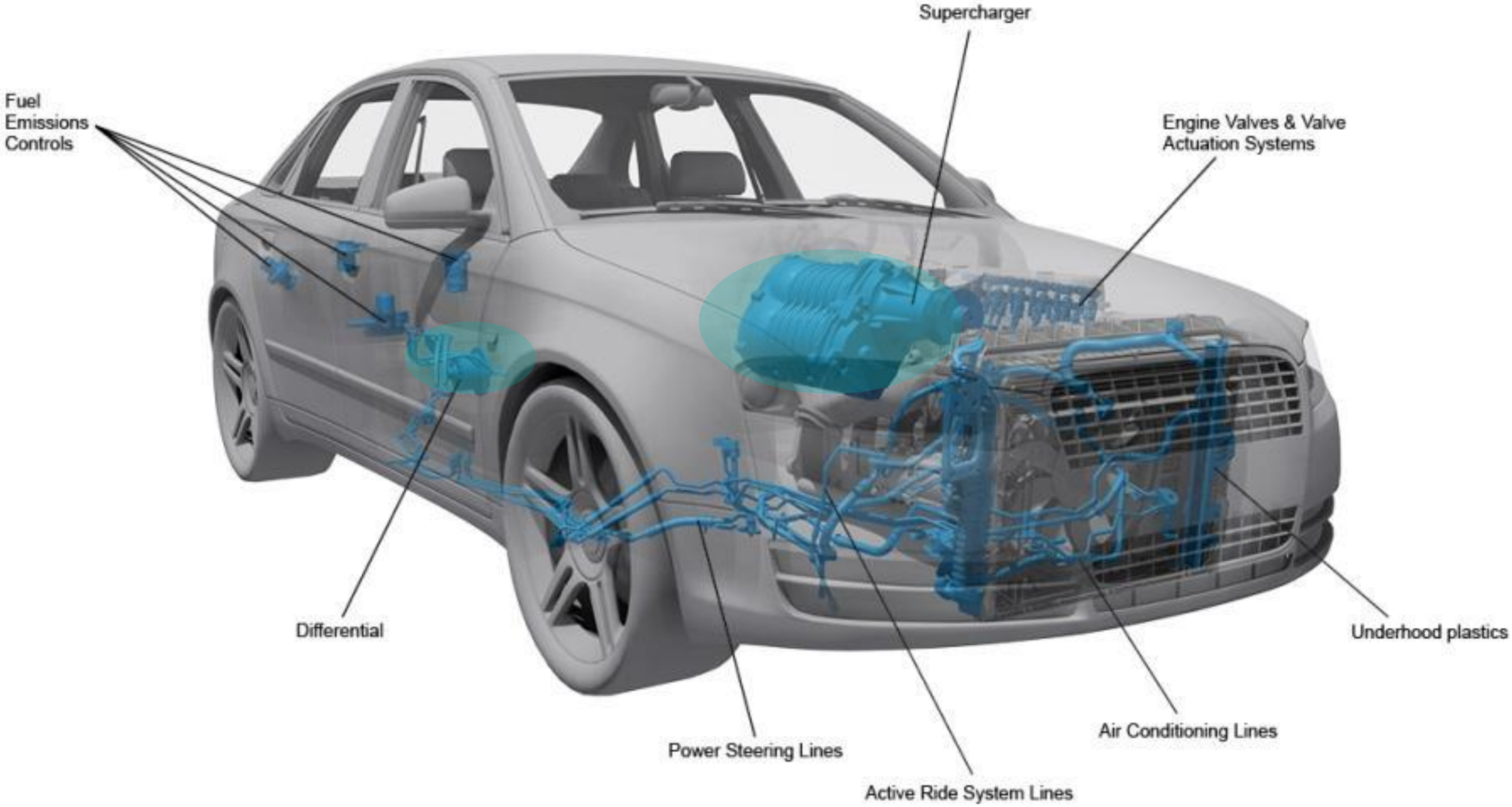
Agenda

- Introduction (General Noise Background)
- Noise in Hydraulics (General)
- Noise in Hydraulic Systems & Applications

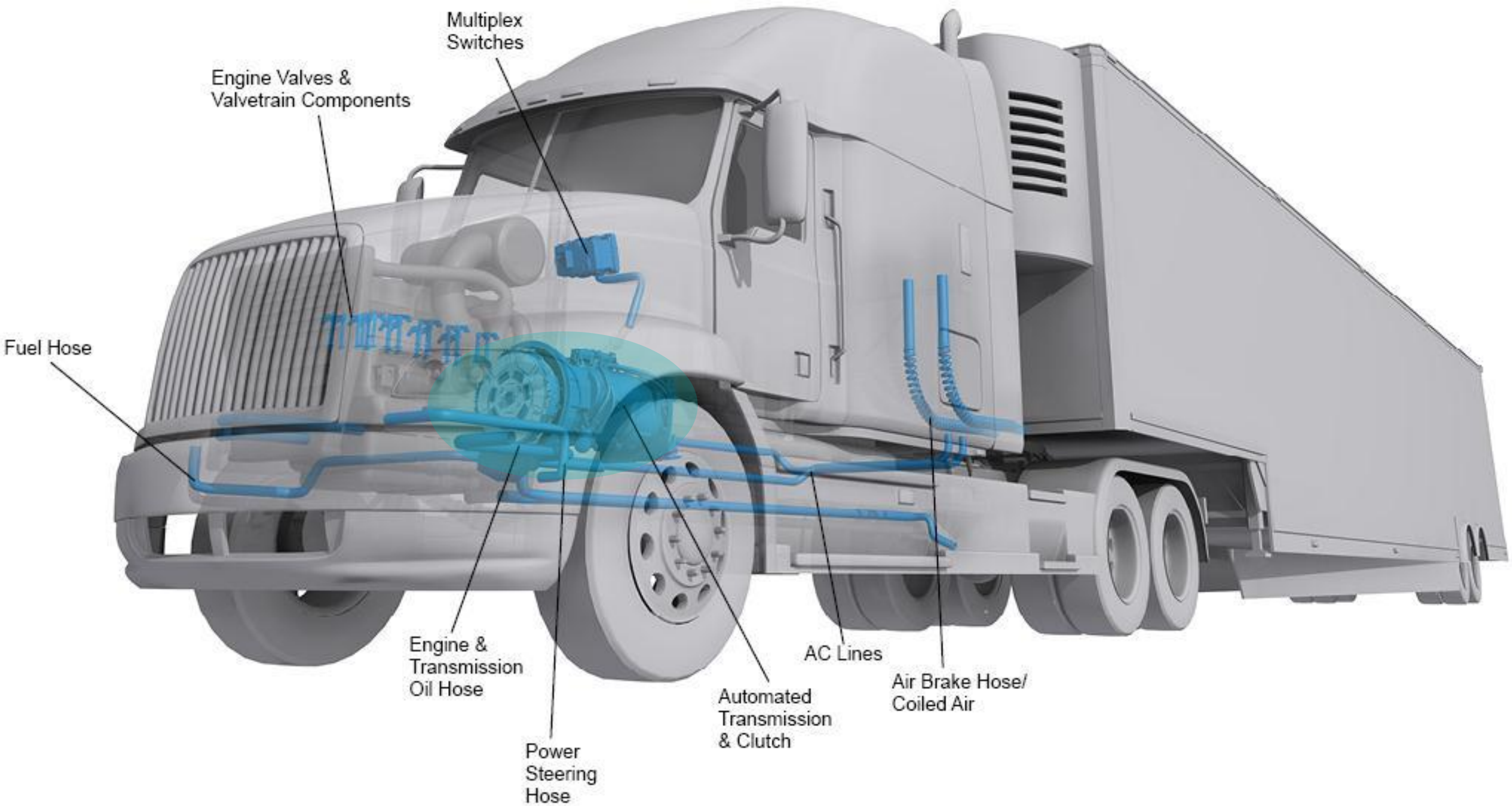
Why do we care about noise?

- 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.

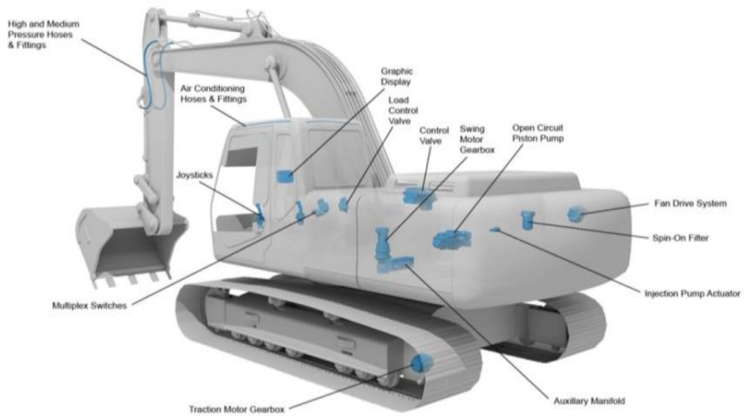


Followed by Truck

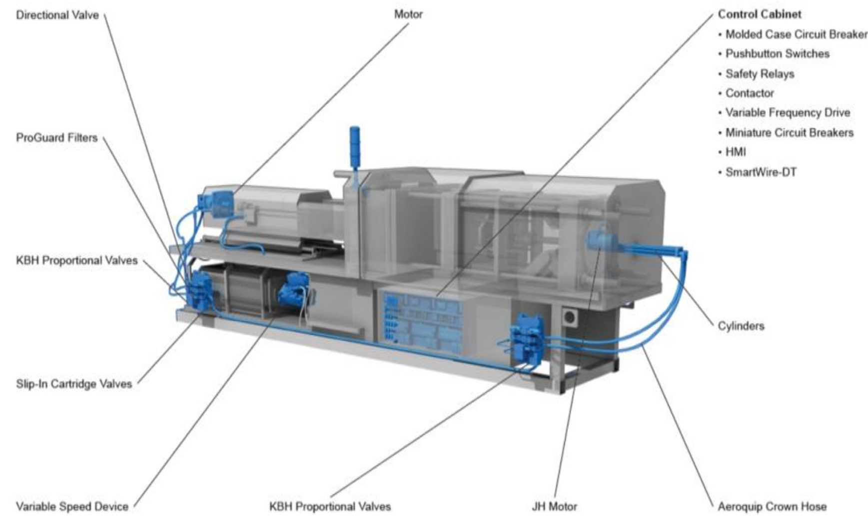


Agriculture, Construction, and Industrial Markets

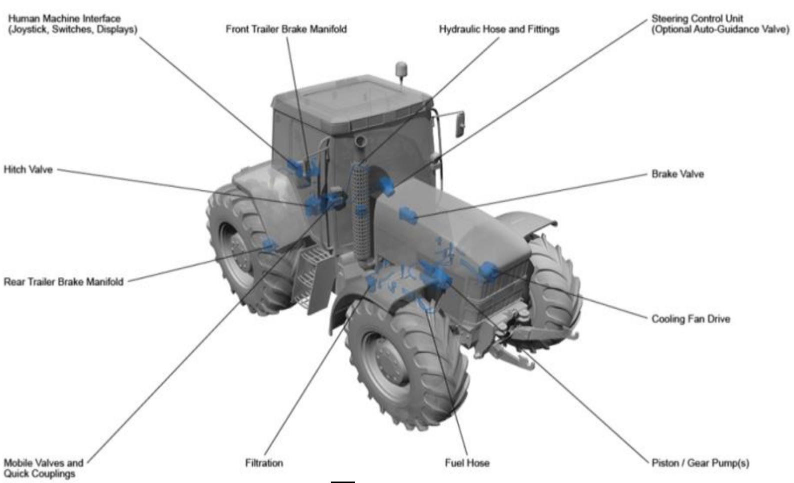
- Mobile Applications
- Industrial Applications



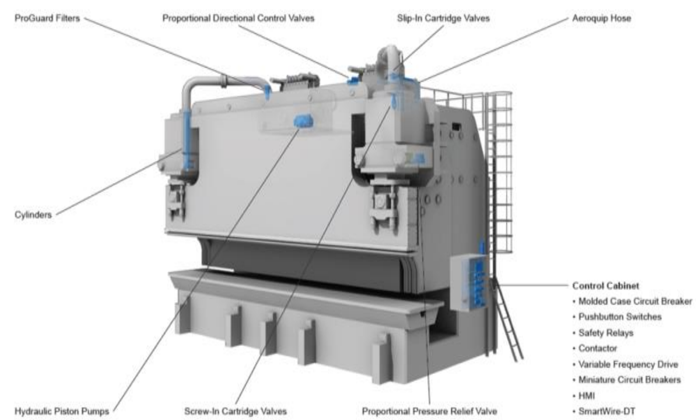
Excavator



Injection Molding Machine



Tractor



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.

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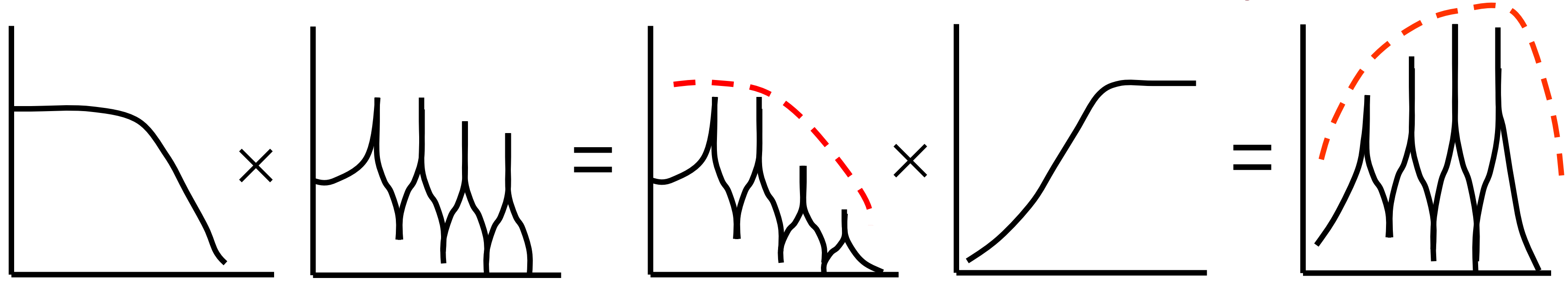
Noise Generation (In General)

Force | Transfer Function | Vibration | Radiation Efficiency | Sound Pressure or Power



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.

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 psycoacoustics of noise.
    - Which can be measured but is subjective.

Changes in Sound Pressure Level

Change in SPL (dB)	Percent Change	Change in SPL (dB)	Percent Change
1	12%	-1	-11%
2	26%	-2	-21%
3	41%	-3	-29%
4	58%	-4	-37%
5	78%	-5	-44%
6	100%	-6	-50%
7	124%	-7	-55%
8	151%	-8	-60%
9	182%	-9	-65%
10	216%	-10	-68%

Changes in Sound Power Level

Change in SWL (dB)	Percent Change	Change in SWL (dB)	Percent Change
1	26%	-1	-21%
2	58%	-2	-37%
3	100%	-3	-50%
4	151%	-4	-60%
5	216%	-5	-68%
6	298%	-6	-75%
7	401%	-7	-80%
8	531%	-8	-84%
9	694%	-9	-87%
10	900%	-10	-90%

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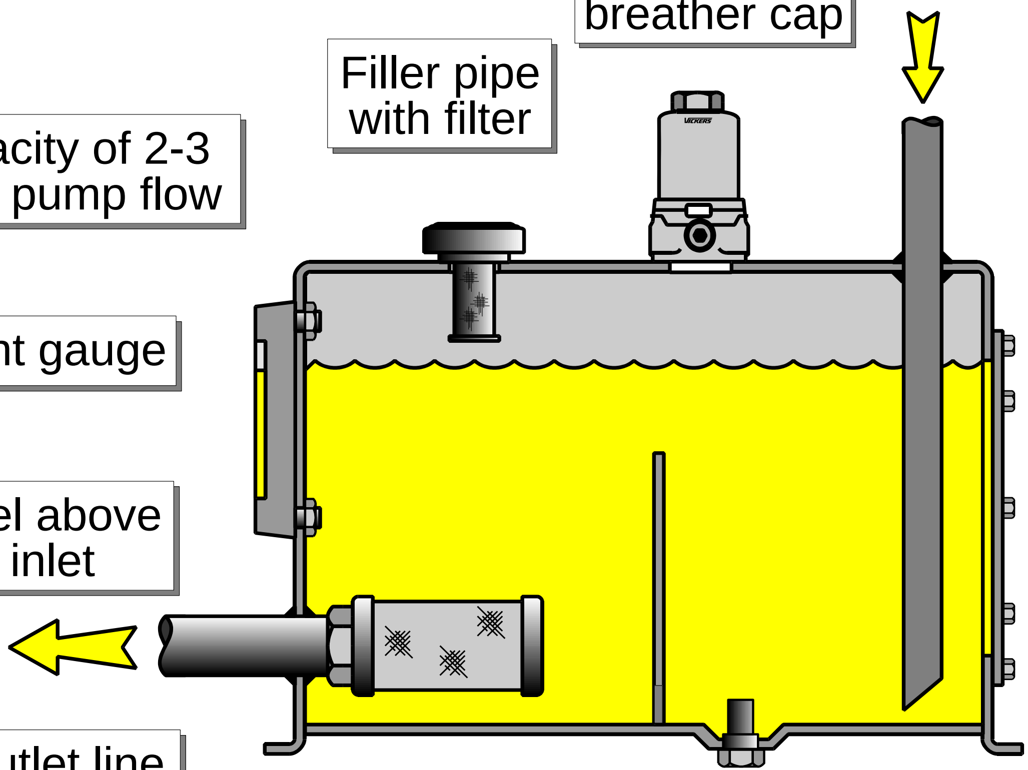
Sound Quality

- 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



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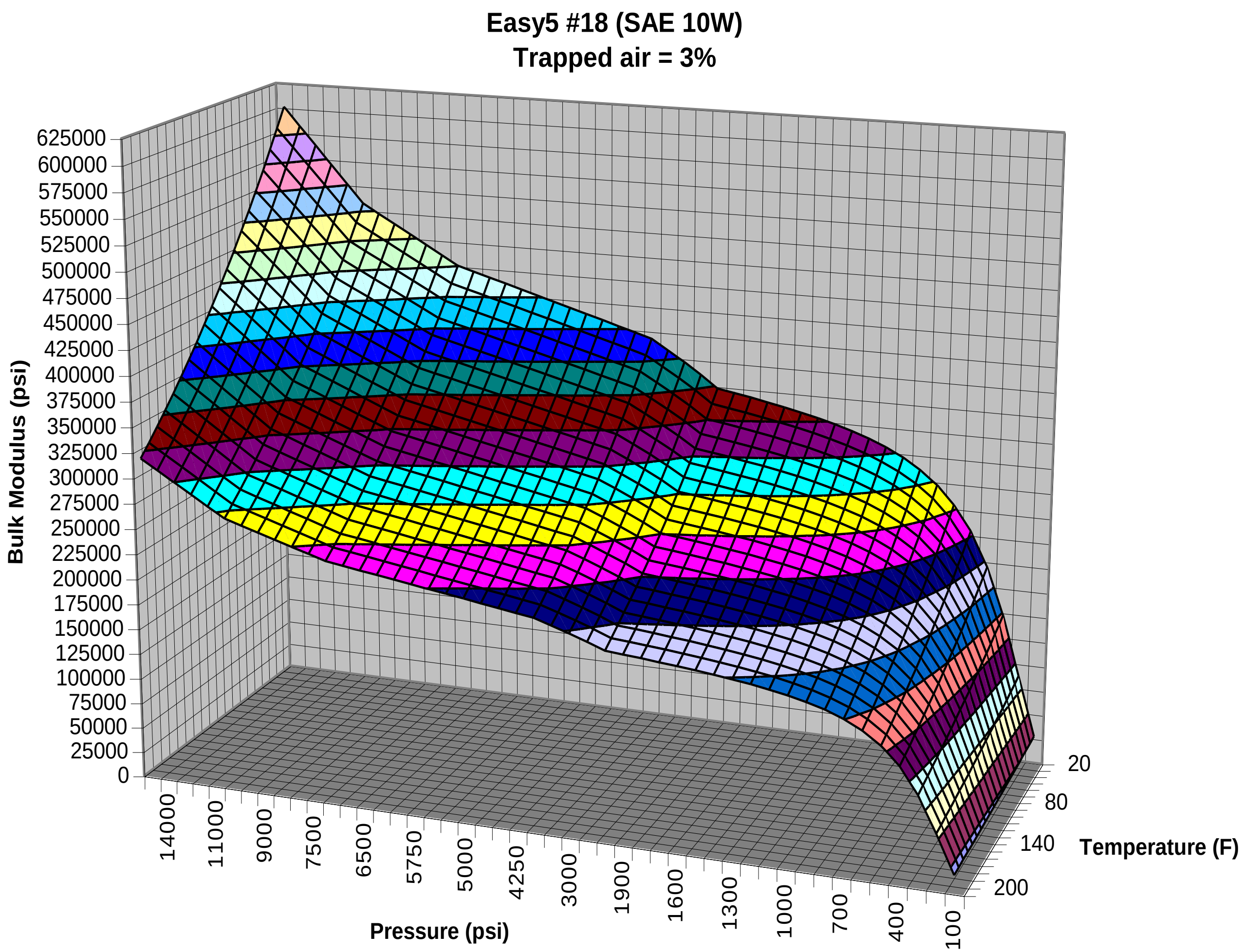
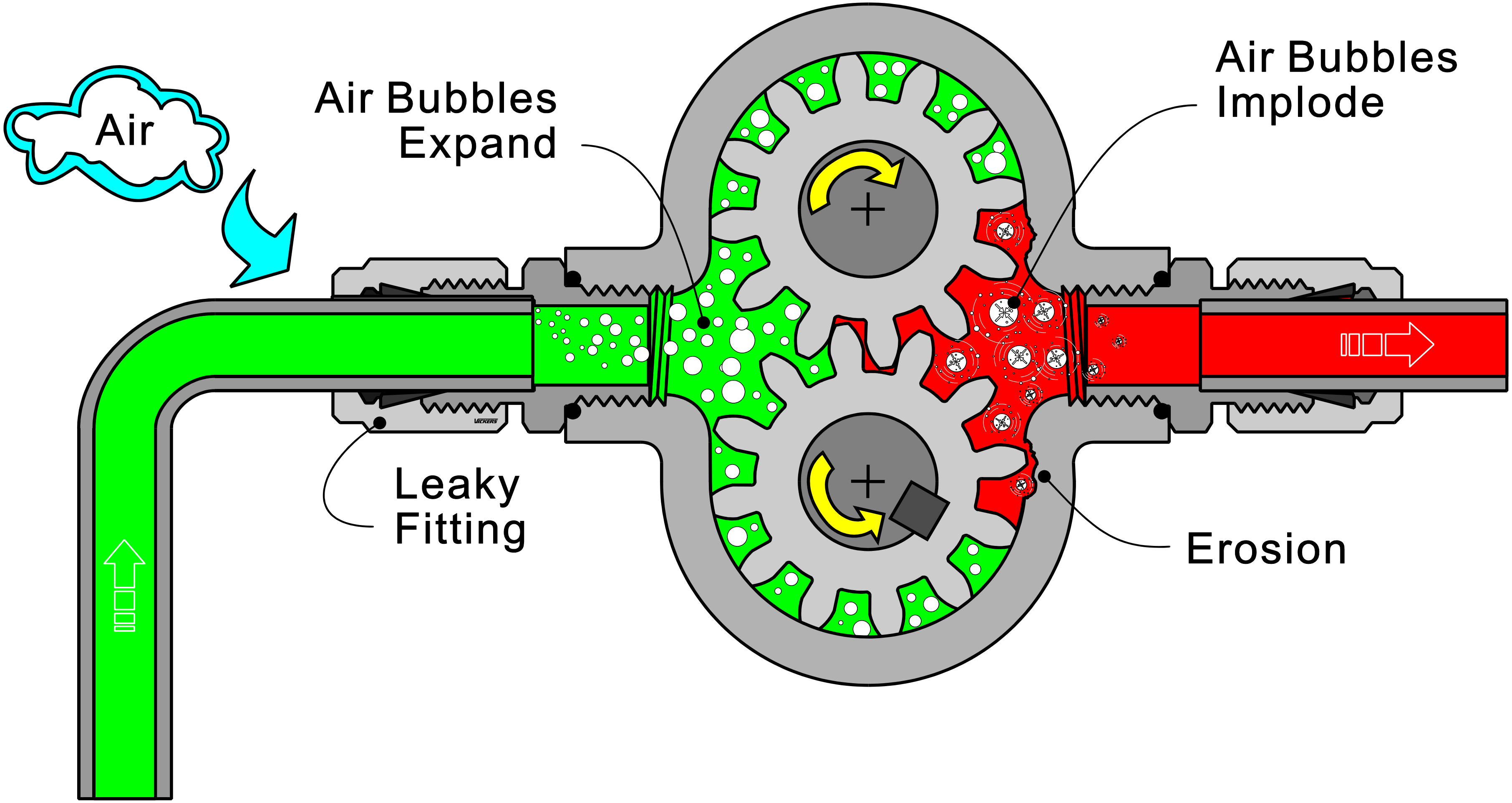
Fluid Bulk Modulus:



Air in Hydraulic Fluid



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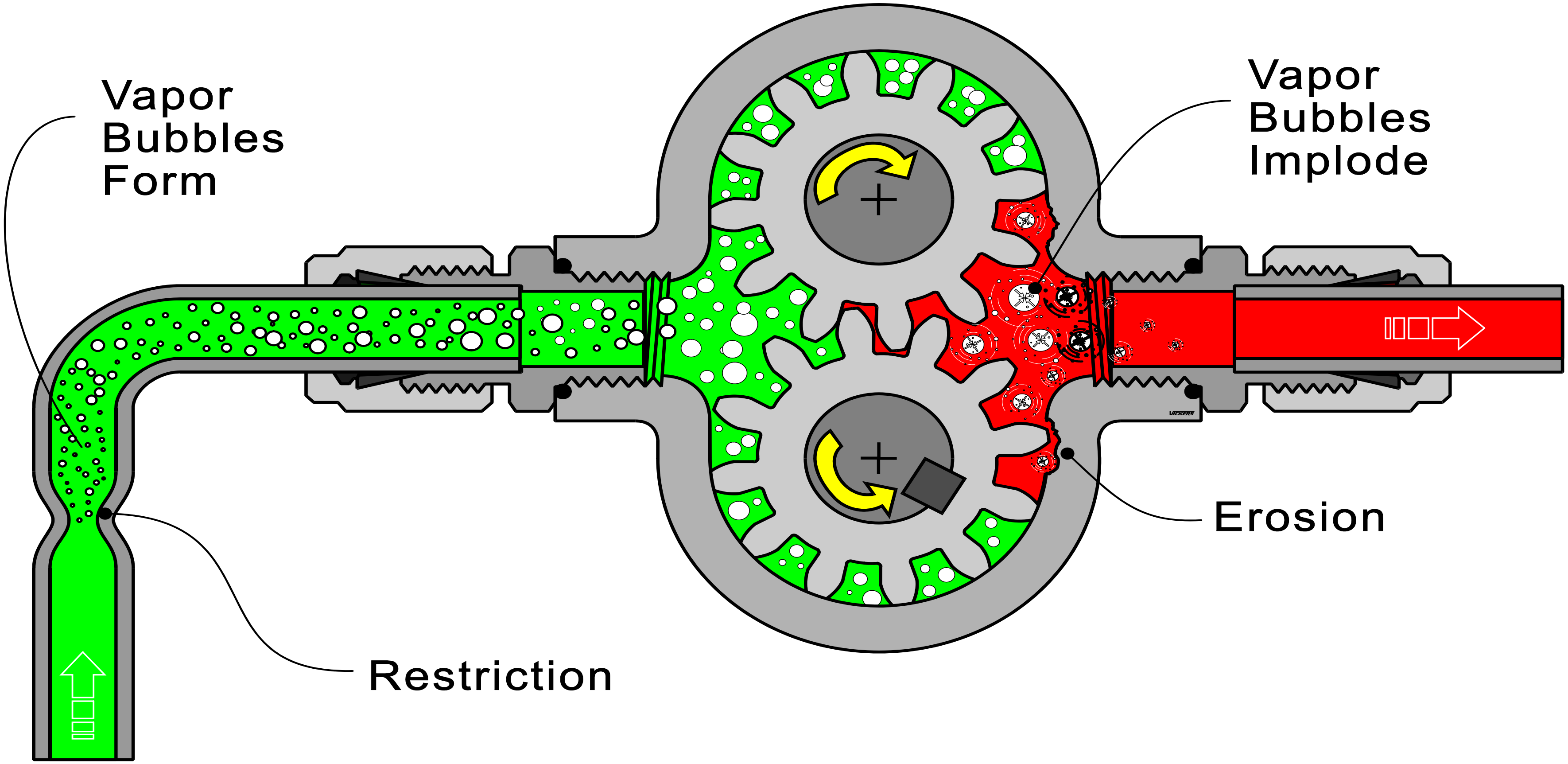
Air in Hydraulic Fluid



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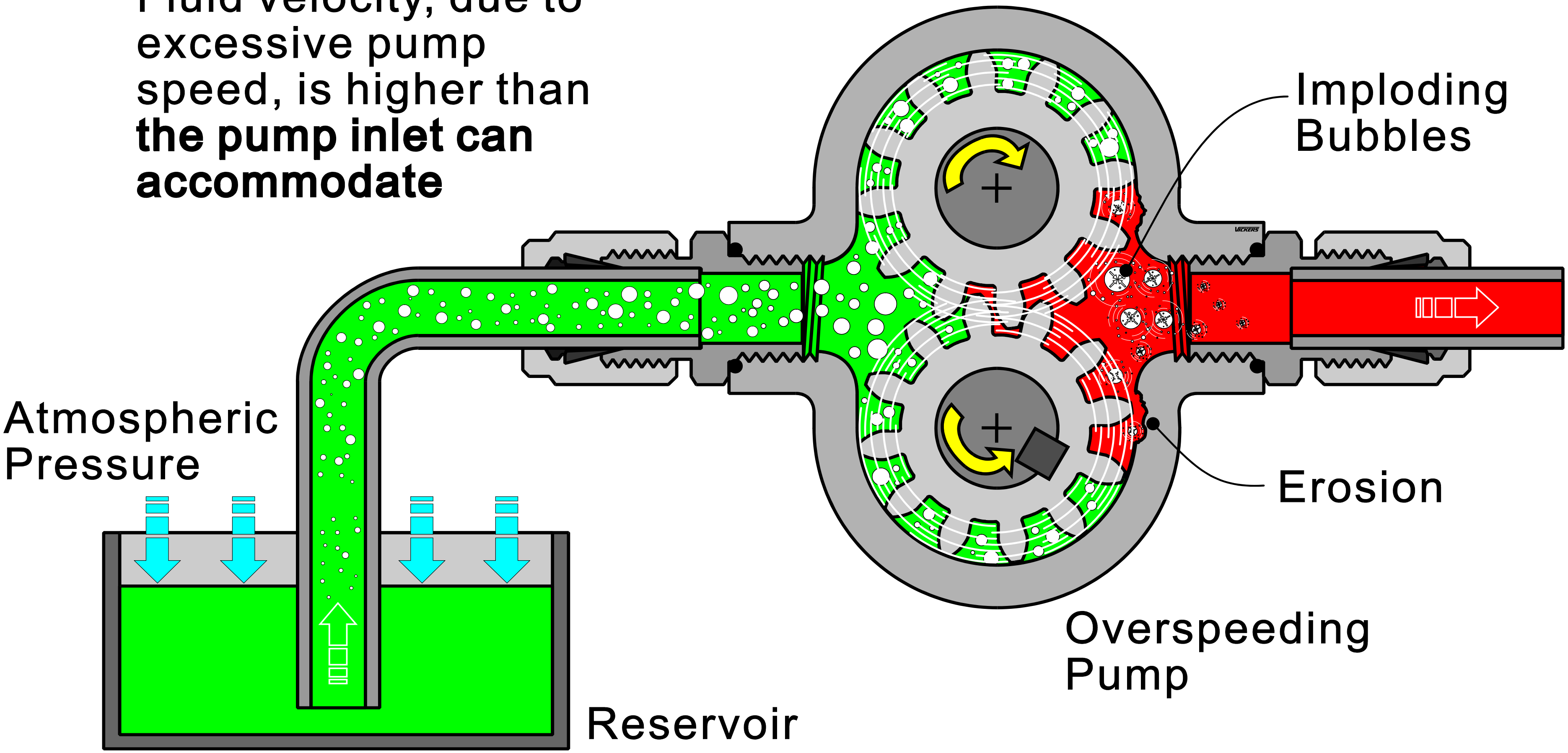
Air in Hydraulic Fluid

Fluid velocity, due to excessive pump speed, is higher than **the pump inlet can accommodate**



Valveplate Cavitation

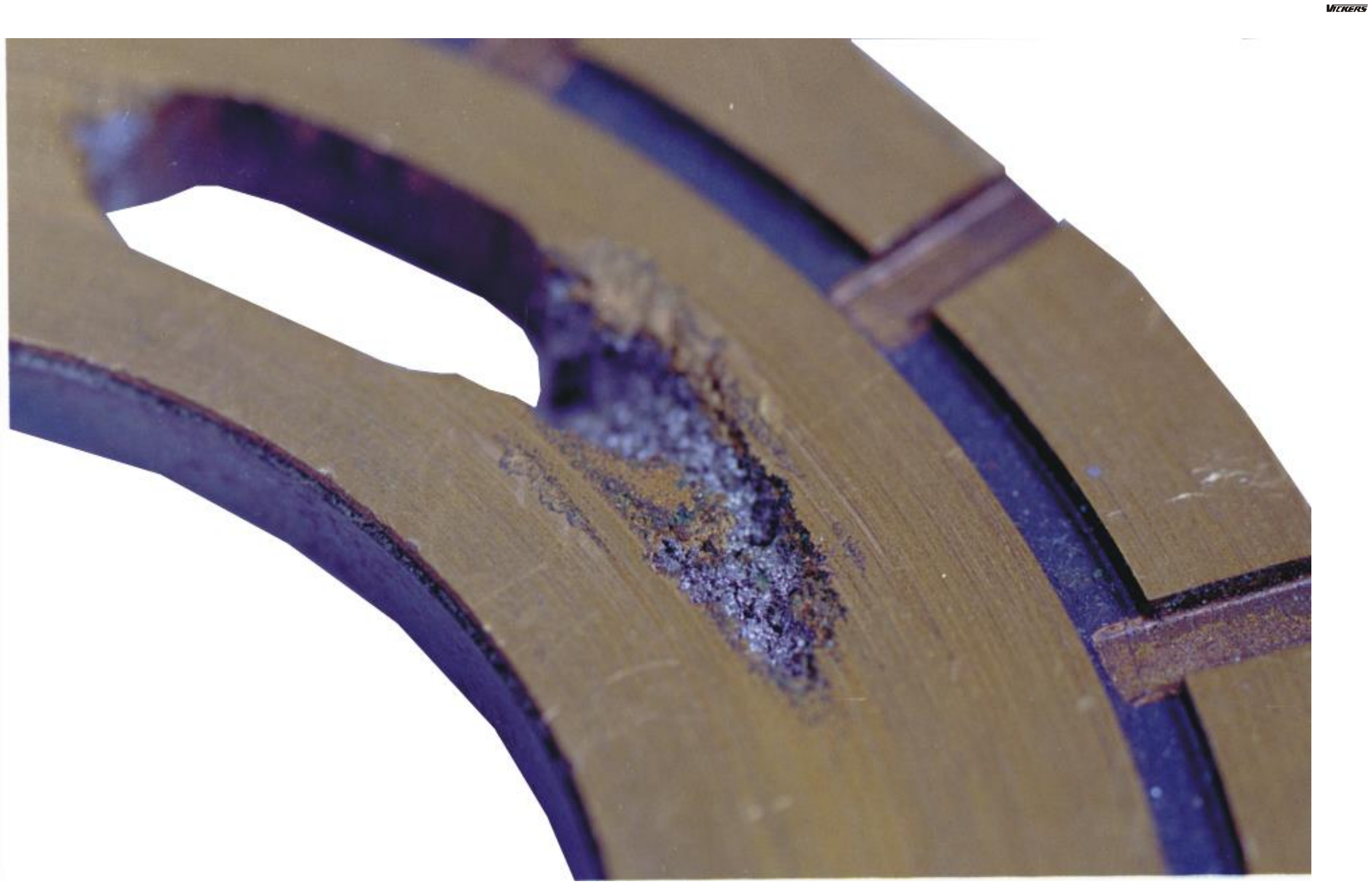


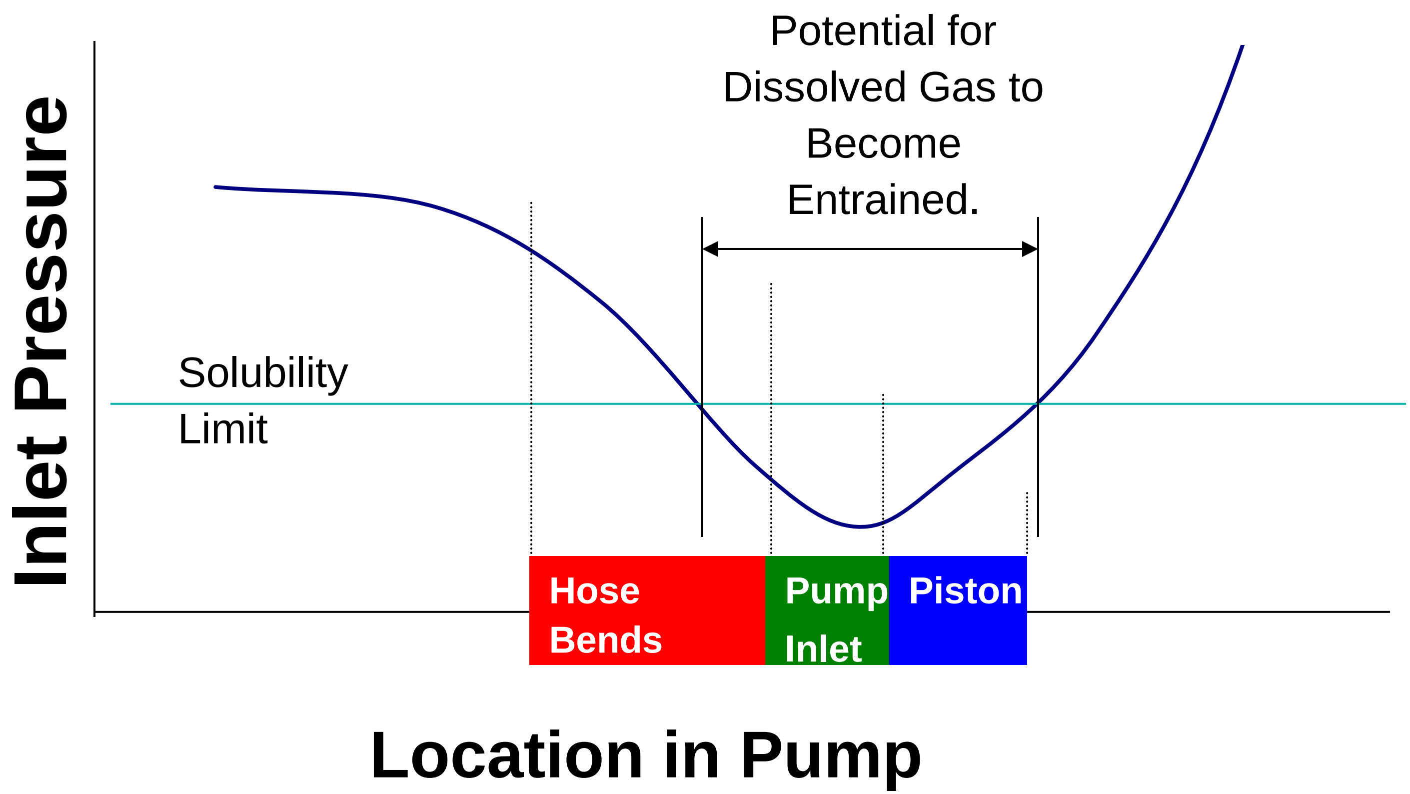
Figure 15-6 Piston pump valve plate erosion caused by aeration or cavitation

Air in Hydraulic Fluid

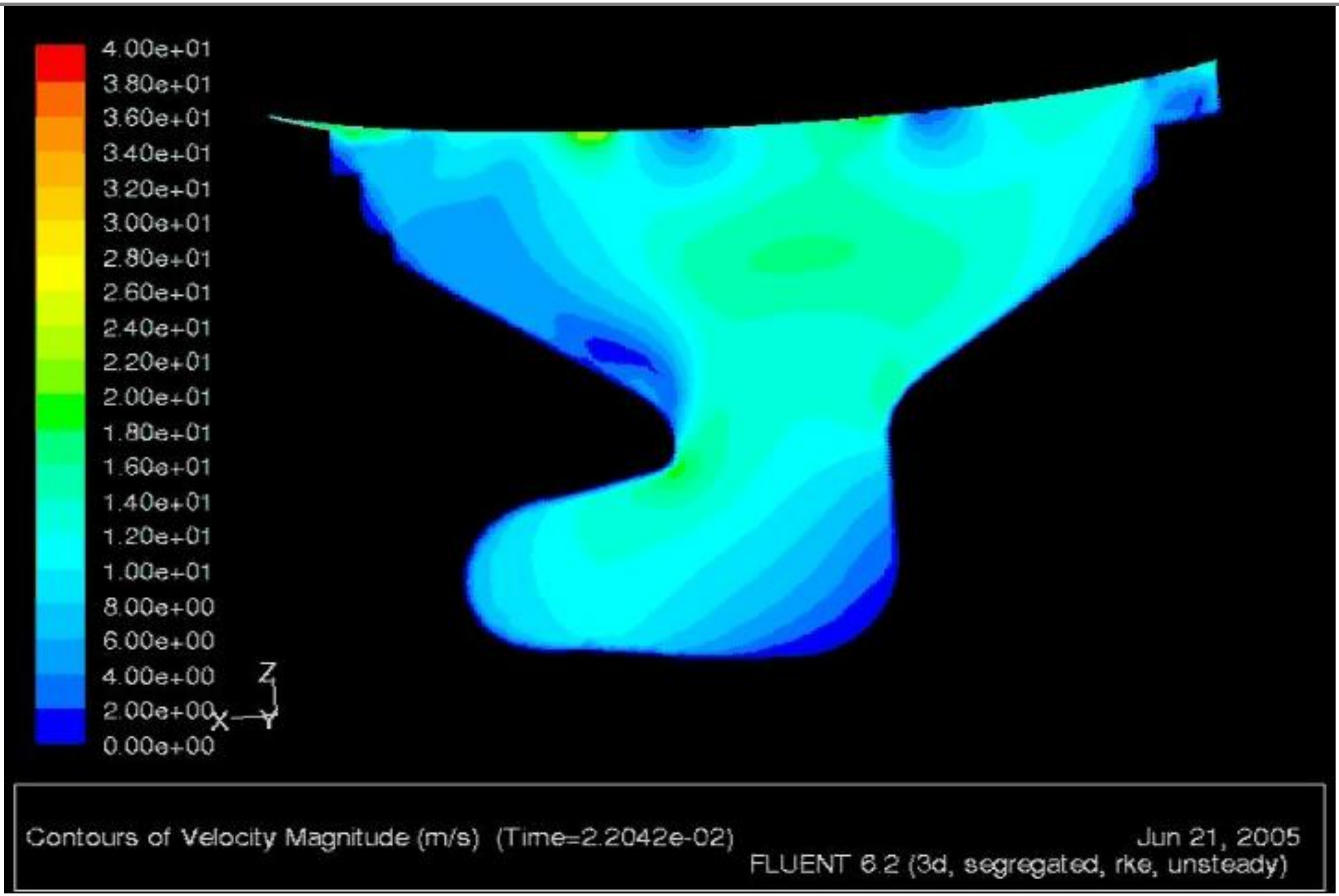
- Entrained Air – Air in the form of bubbles. Has large effect on bulk modulus (affects pump performance, noise, efficiency….) If the amount of dissolved air in the oil is lower than the solubility limit, entrained air becomes dissolved air.
- Dissolved Air – Has minimal effect on bulk modulus. If the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

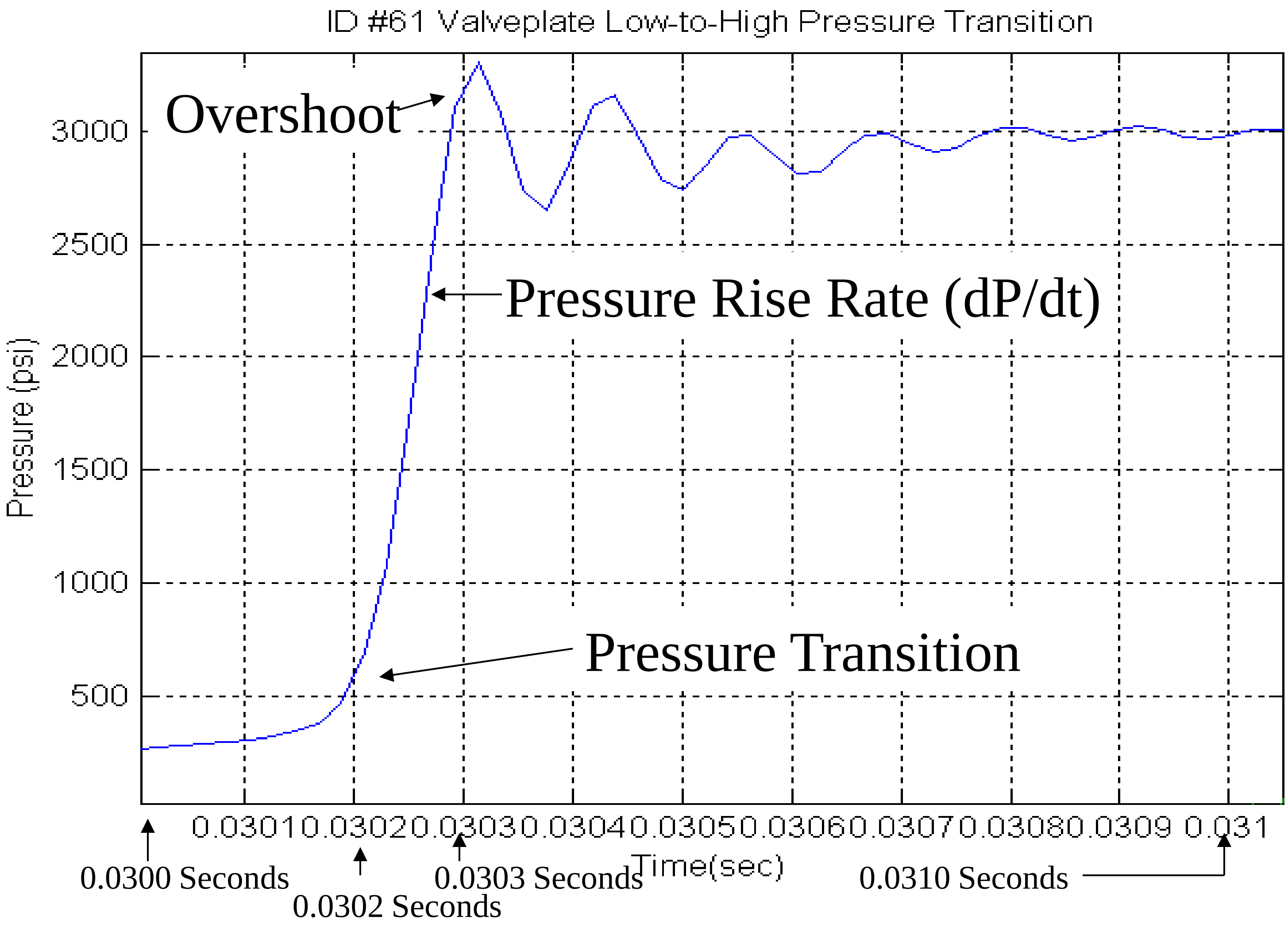
Minimum Inlet Pressure During Pumping Cycle



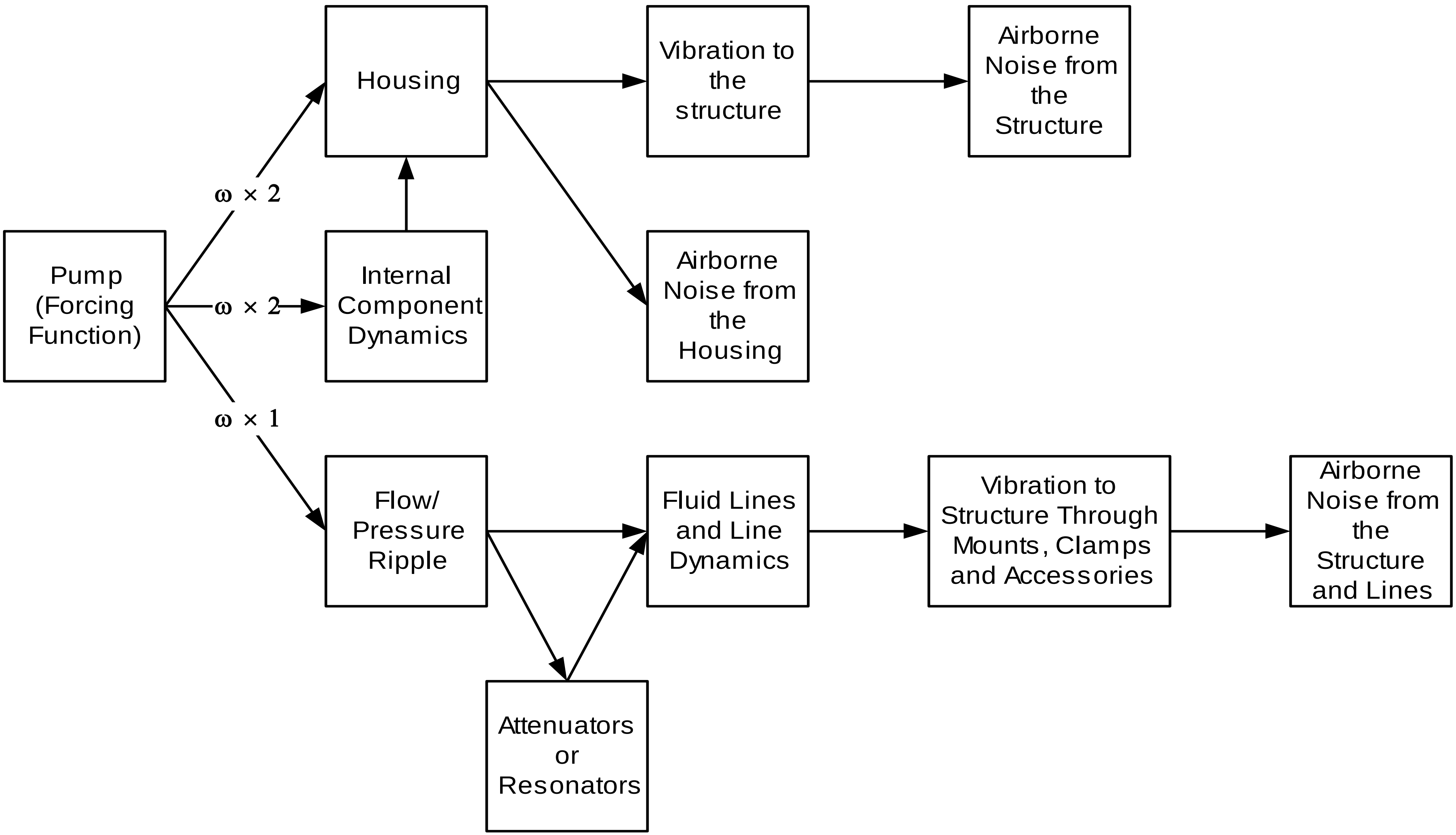
Entrained Air Example:



Bore Pressure Rise Rate



Piston Pump Noise and Vibration Path

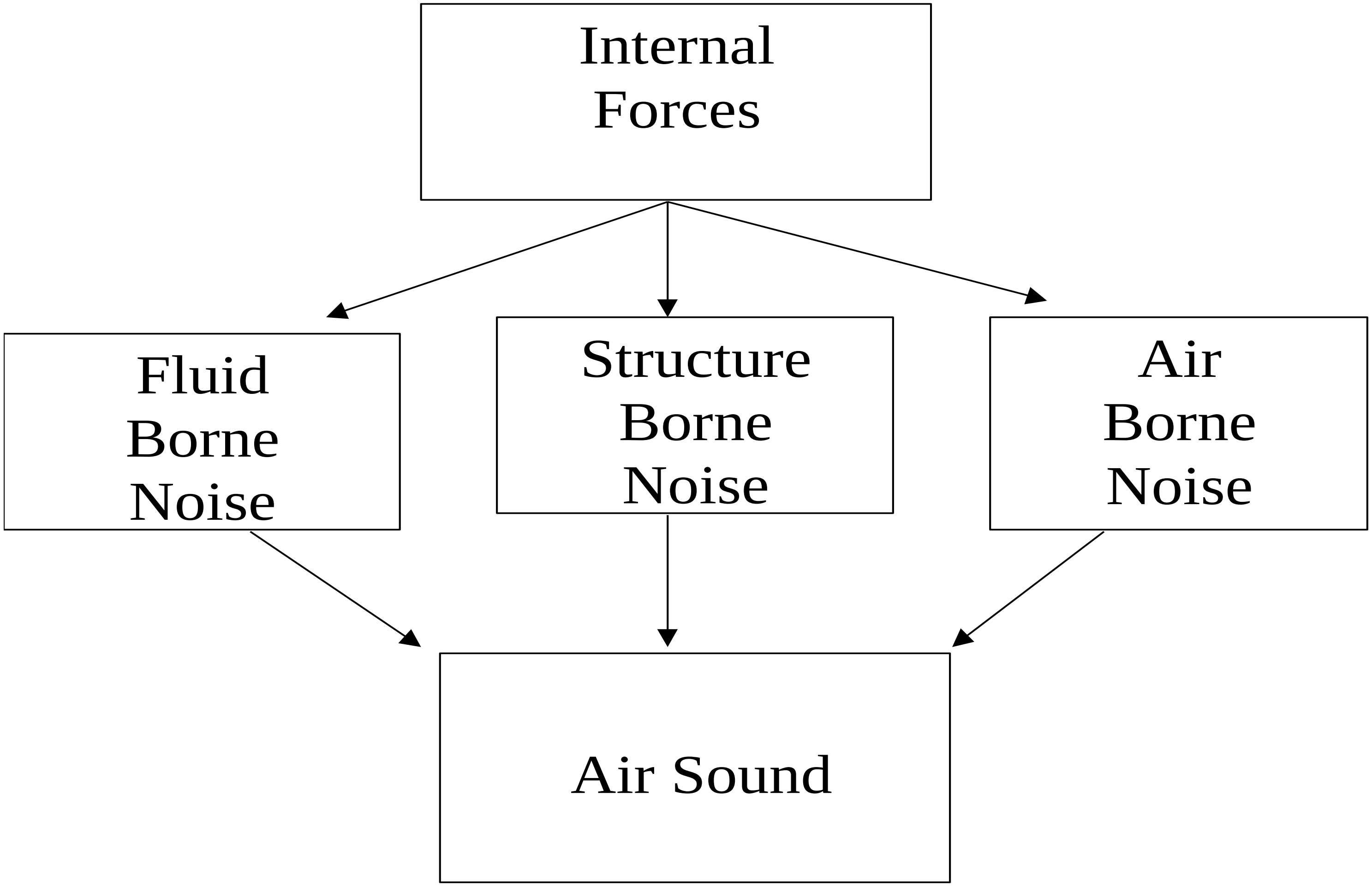


Noise Transmission and Generation

- 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.

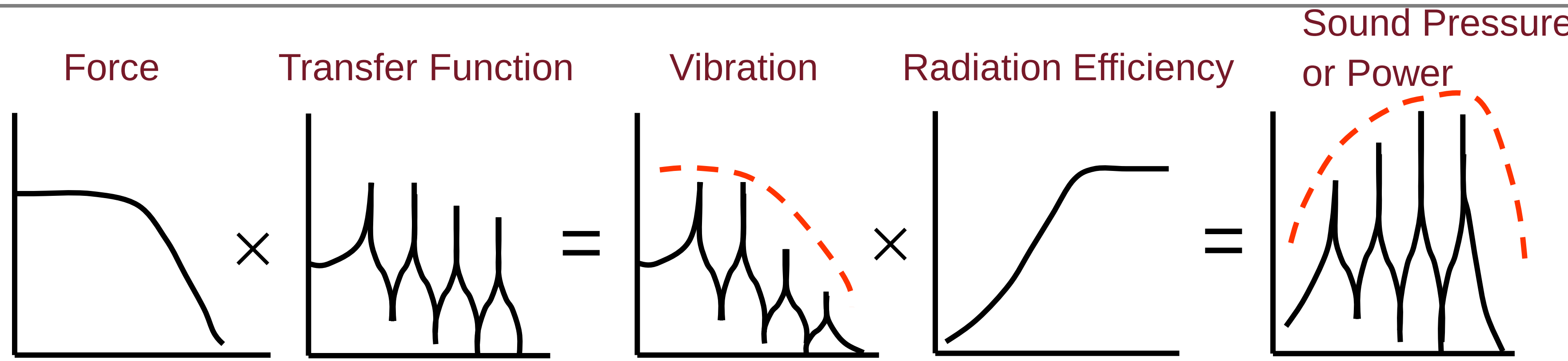
Hydraulic Systems Noise Flow Chart



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.

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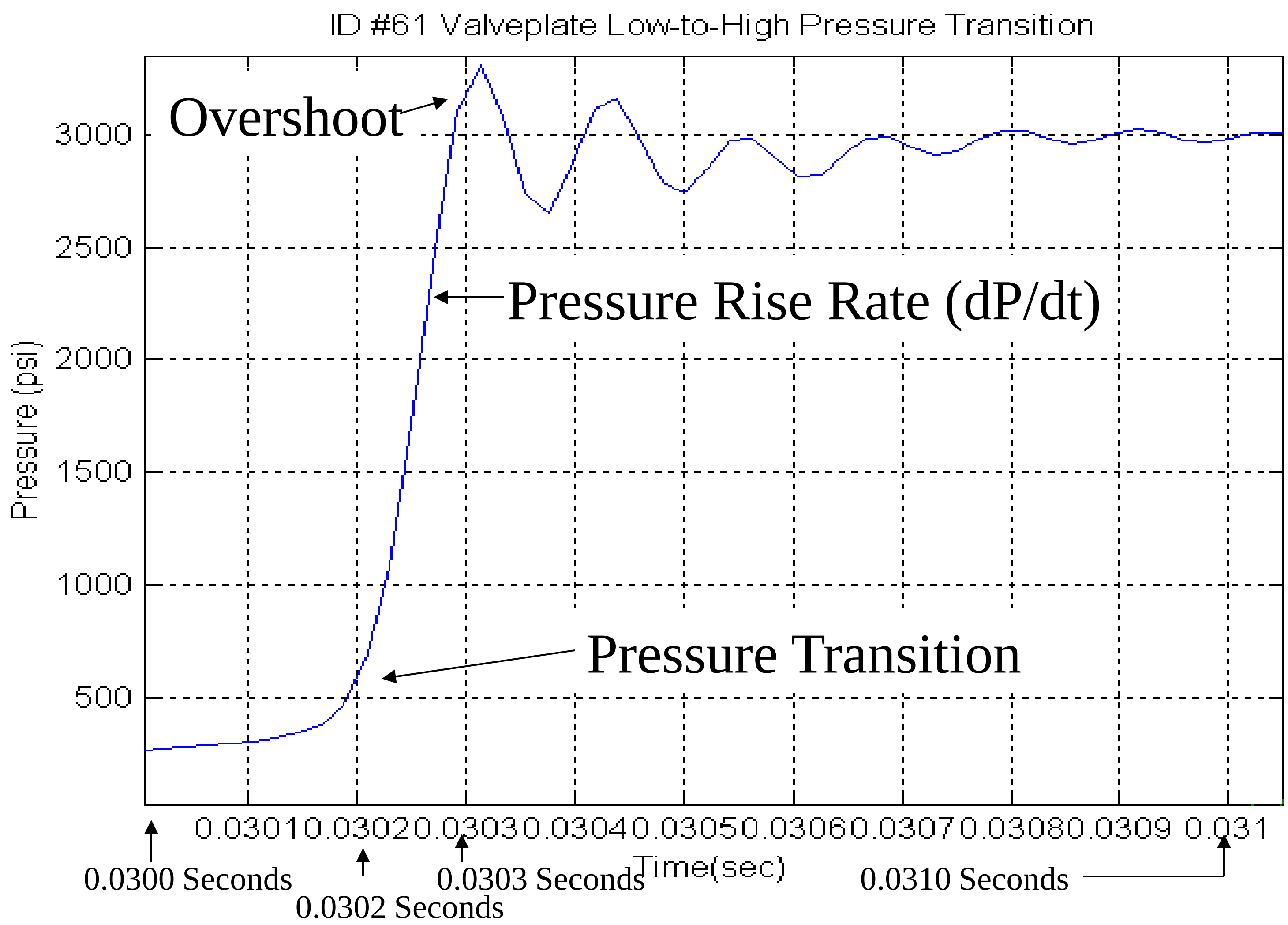
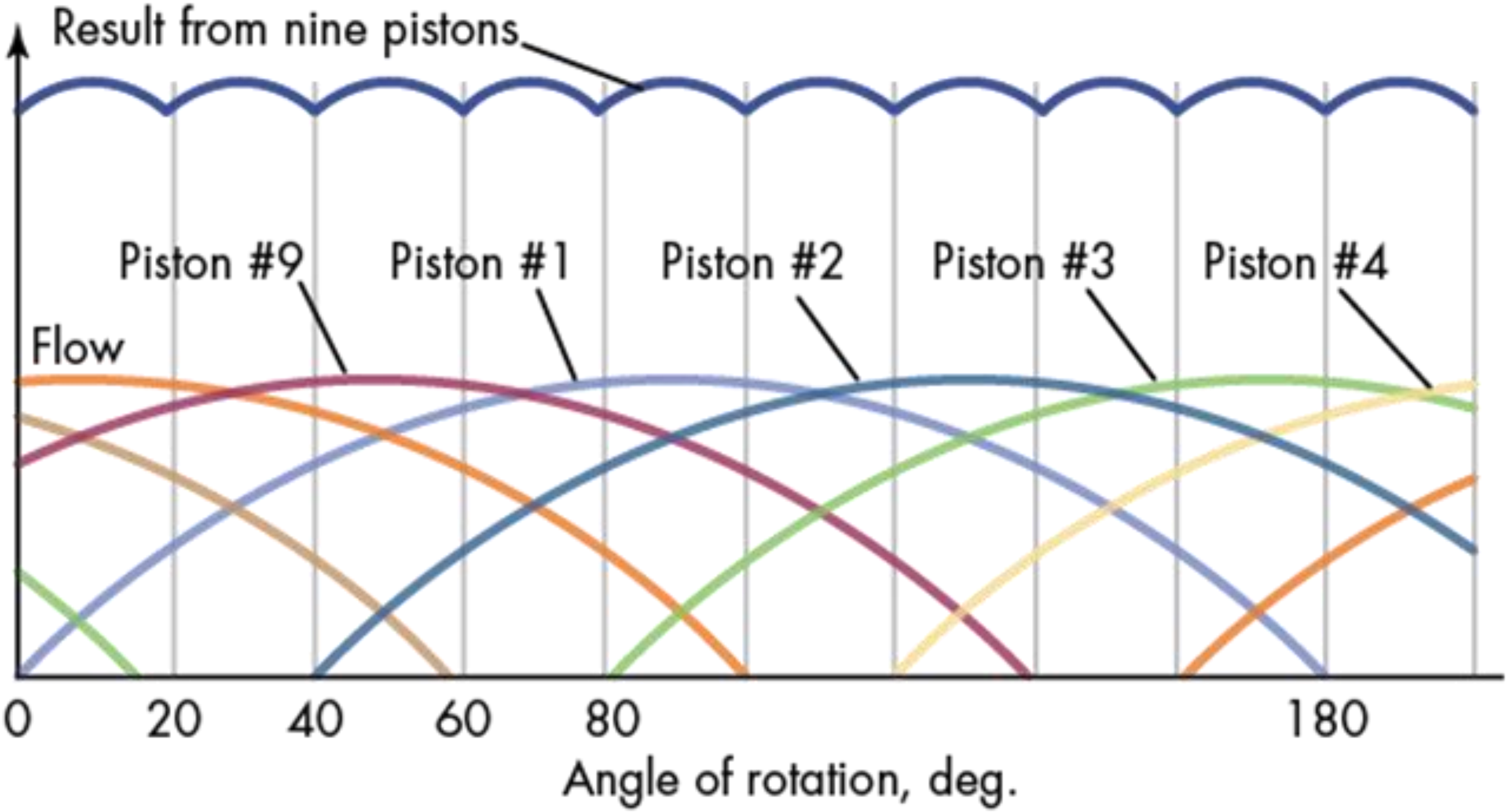
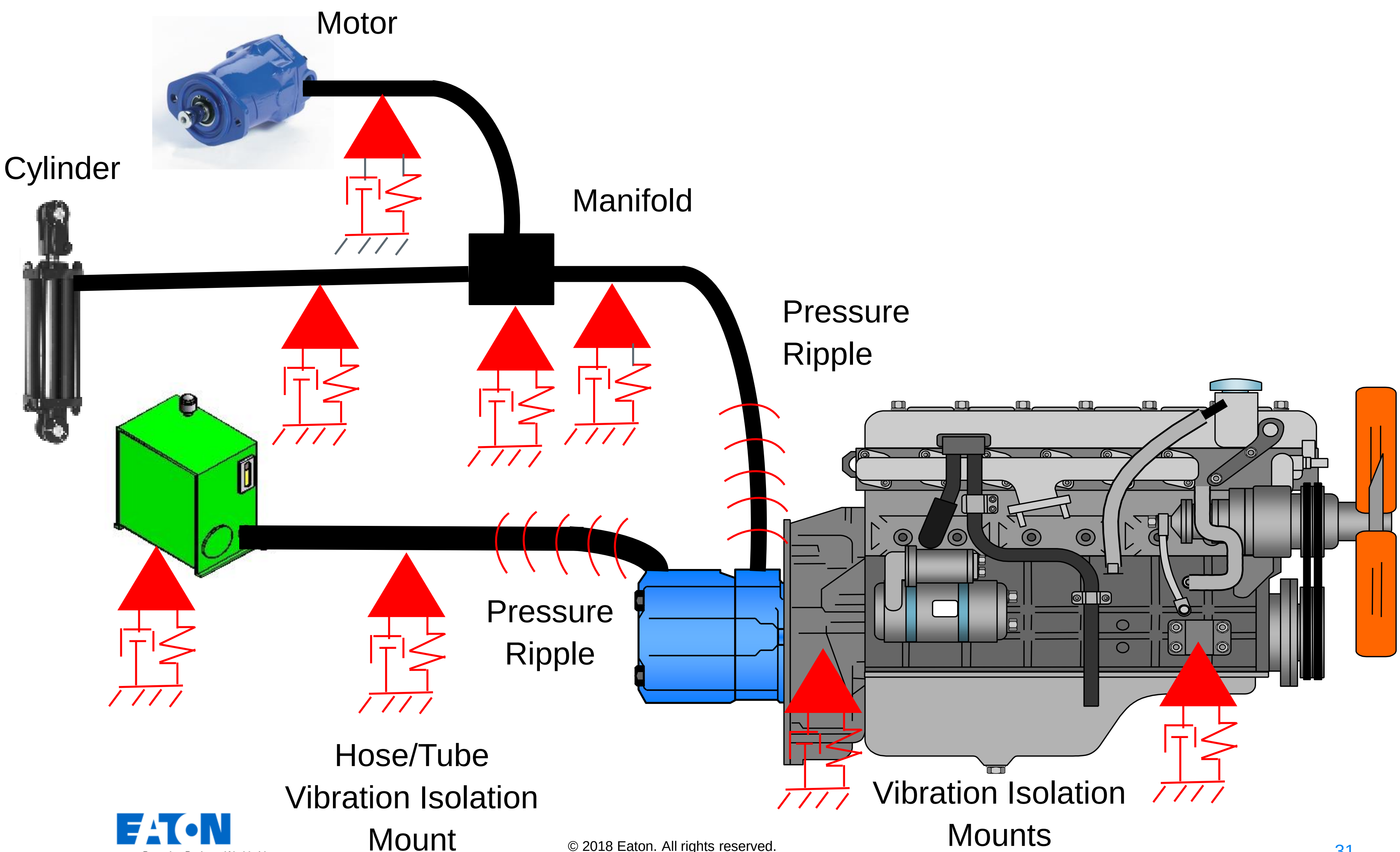
Piston Pump Pressure Ripple Source



Pump Pressure Ripple



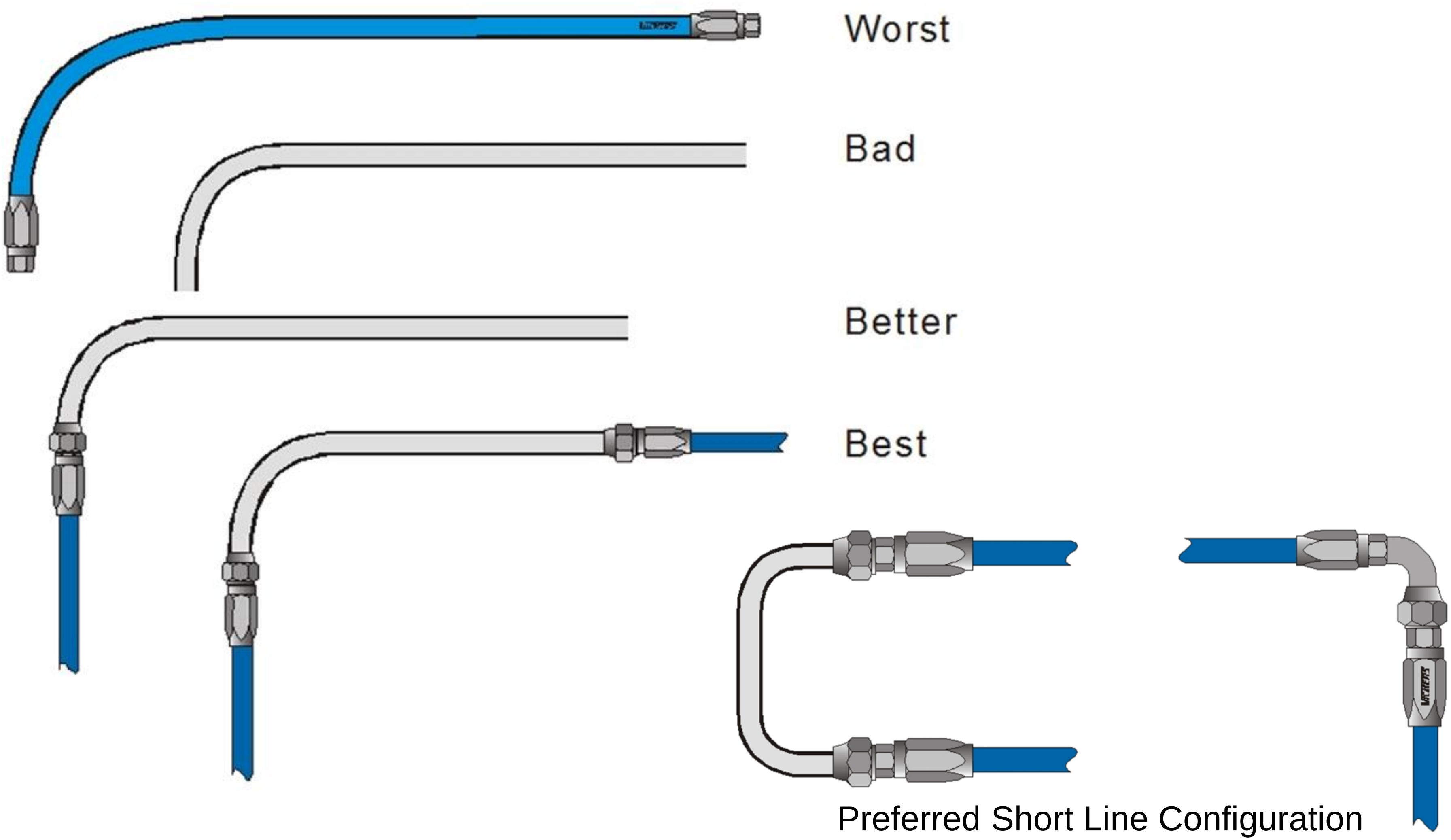
Fluid Borne Noise



Hydraulic Hose:

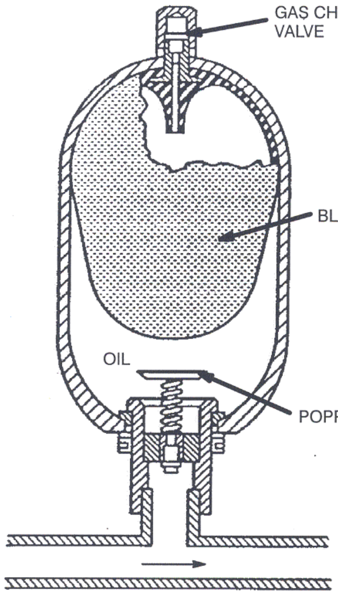
- Think of a hydraulic hose as similar to a Chinese Finger Puzzle.

Hydraulic Line / Hose Configuration

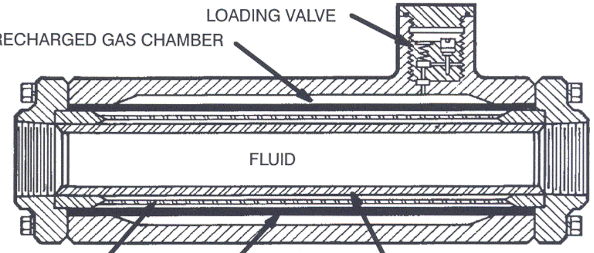


Preferred Short Line Configuration

Pressure Ripple Surppressor

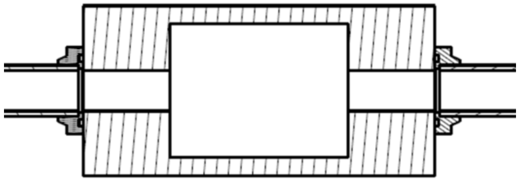


SIDE BRANCH ACCUMULATOR



PASS–THROUGH GAS CHARGED FILTER

Wilkes & McLean makes suppressors similar to the Pass-Through Gas Charged Filter Shown above.

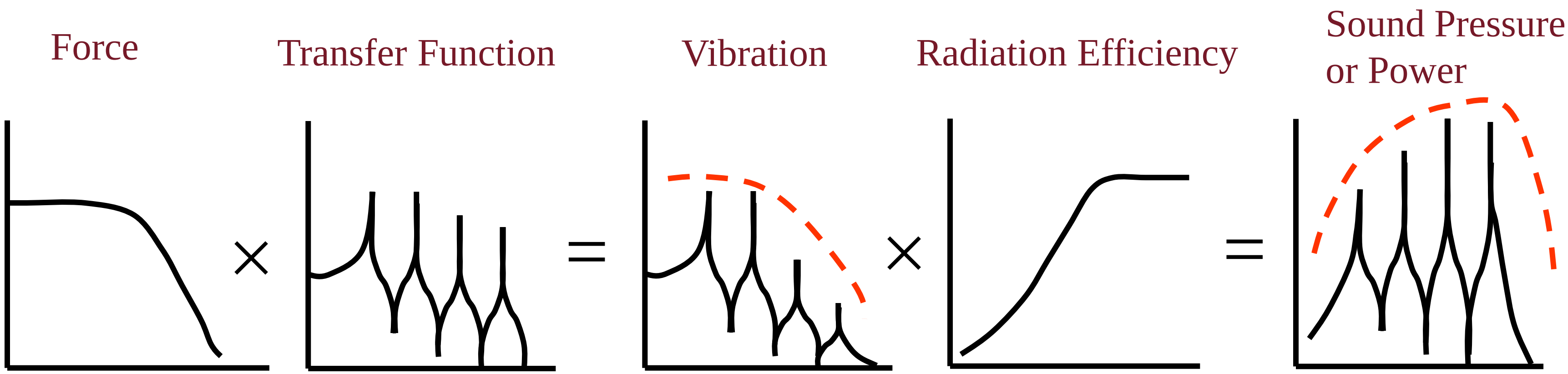


Structure-Borne Noise

- 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.

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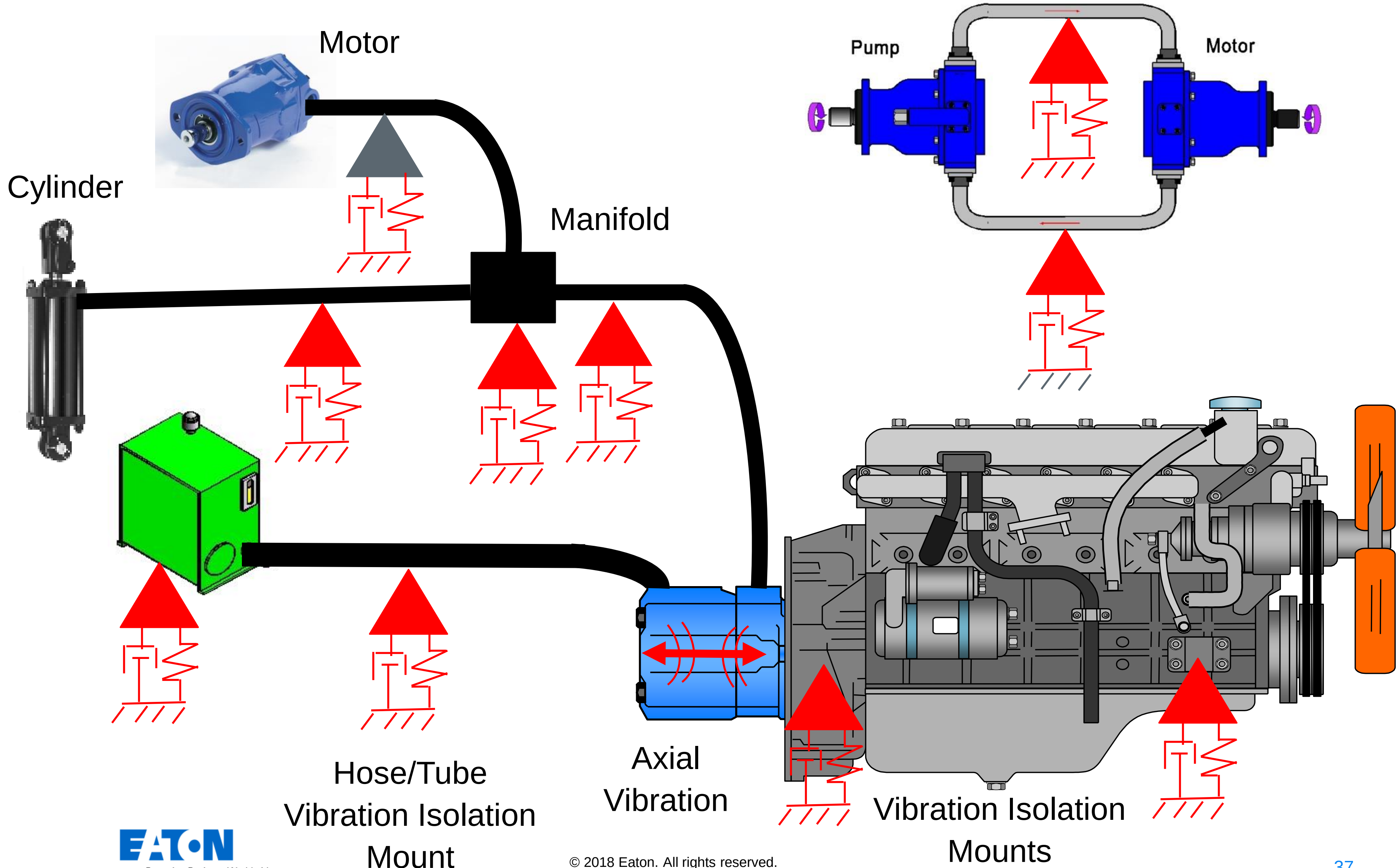
Structure Borne Noise



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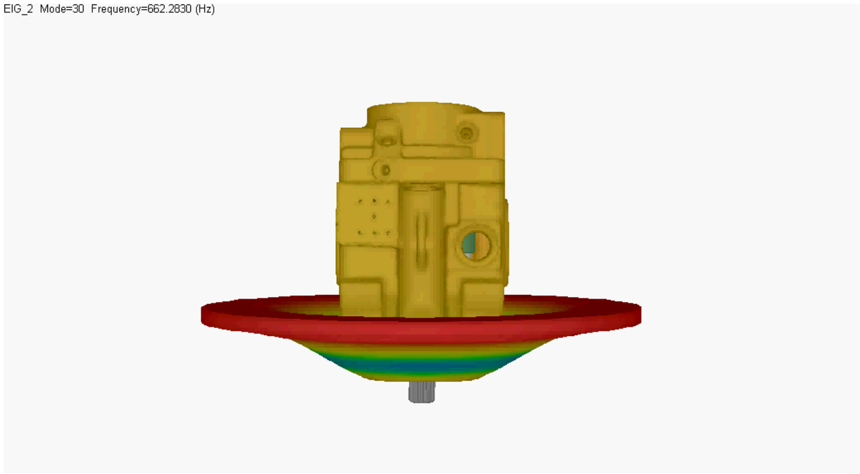
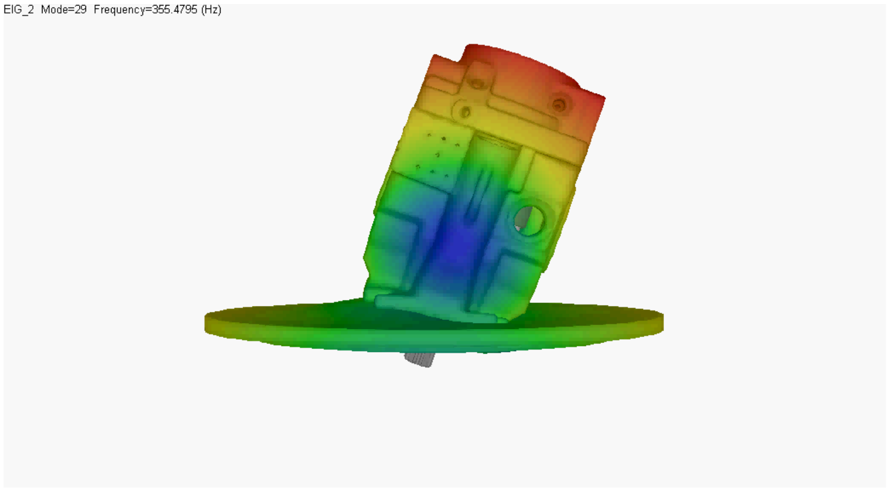
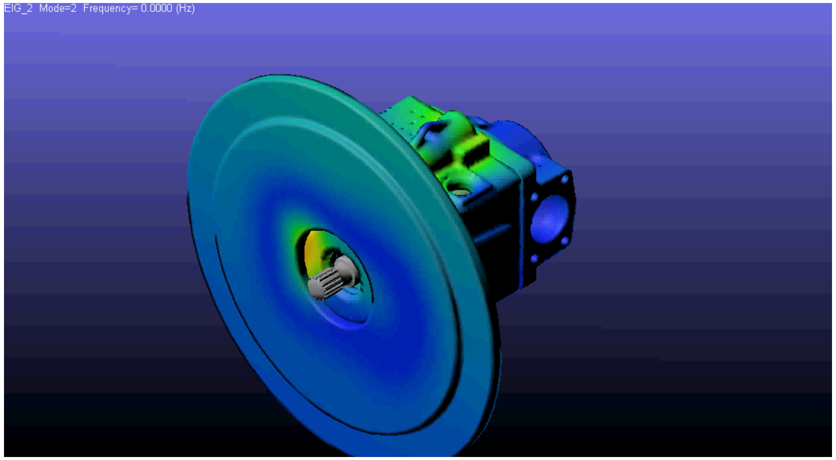
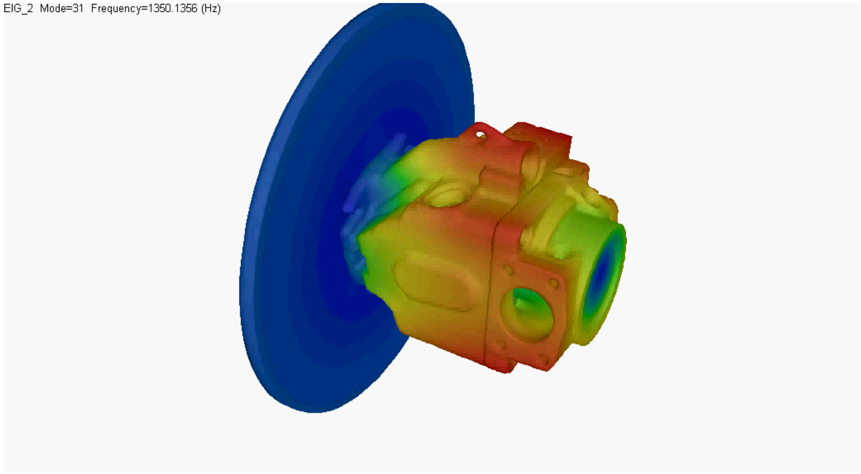
Mounting Plate Dynamics:









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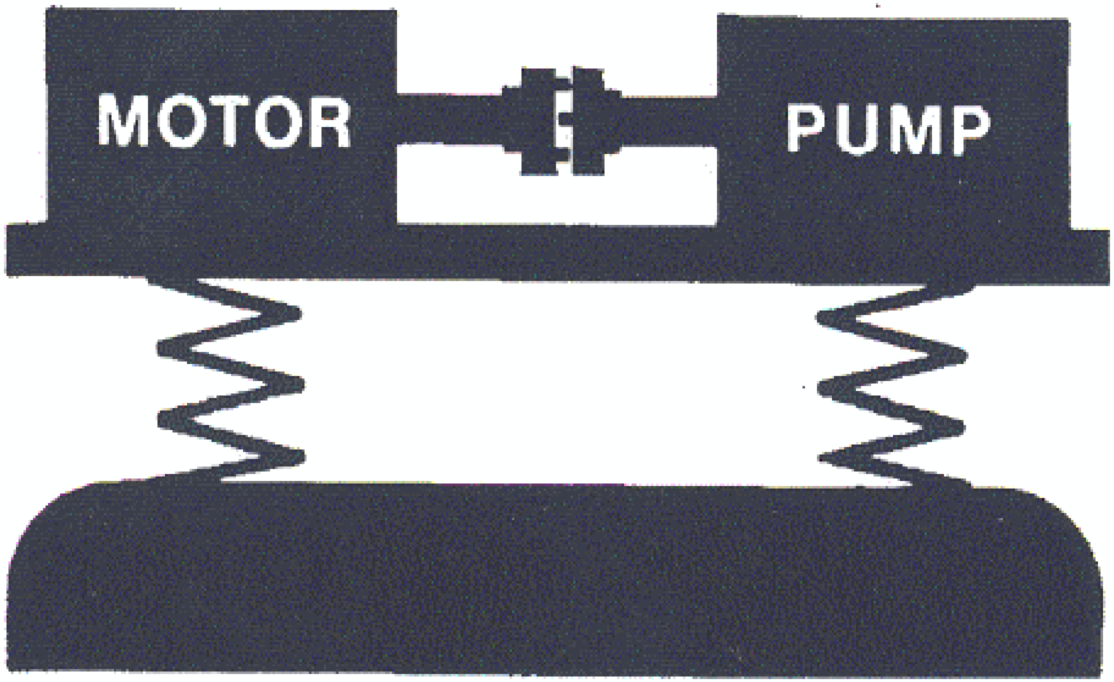
Proper Installation is key to a Quiet System



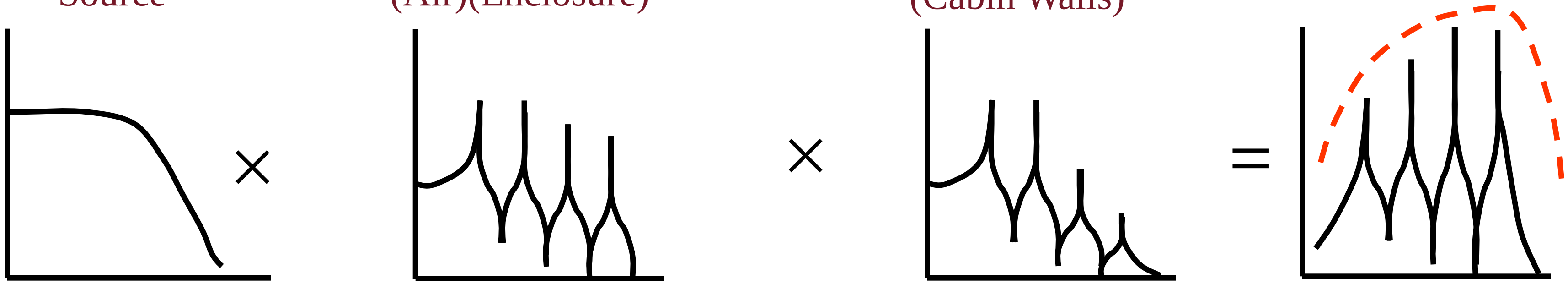
Pump and Motor/Engine on Subplate, Isolated from Stiff Foundation/Frame

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)

Noise Source | Transfer Function (Air)(Enclosure) | Transfer Function (Cabin Walls) | Sound Pressure or Power



Noise Source

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

Transfer Function (Air)(Enclosure)

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.

Transfer Function (Cabin Walls)

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.

Sound Pressure or Power

What's measured or predicted.

This is the result.

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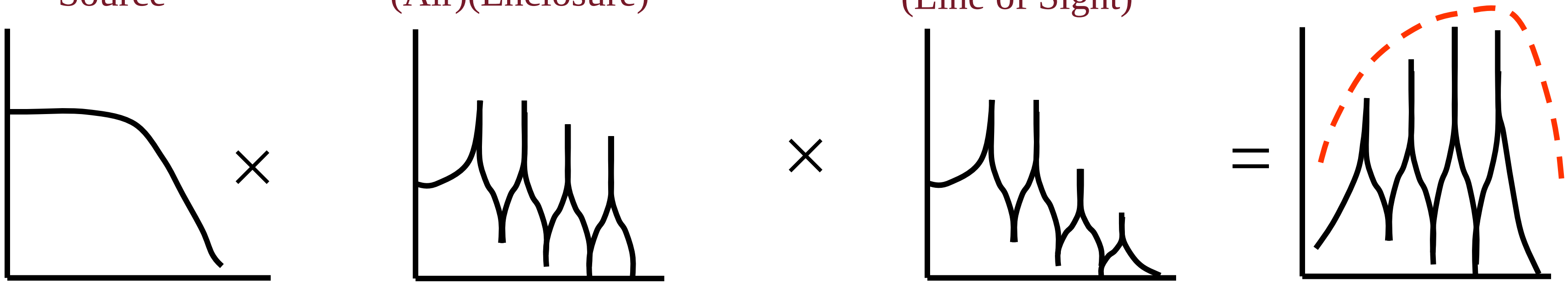
Noise Path (Air Borne)(By-Stander / Drive-By)

Noise Source | Transfer Function (Air)(Enclosure) | Transfer Function (Line of Sight) | Sound Pressure or Power



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.)

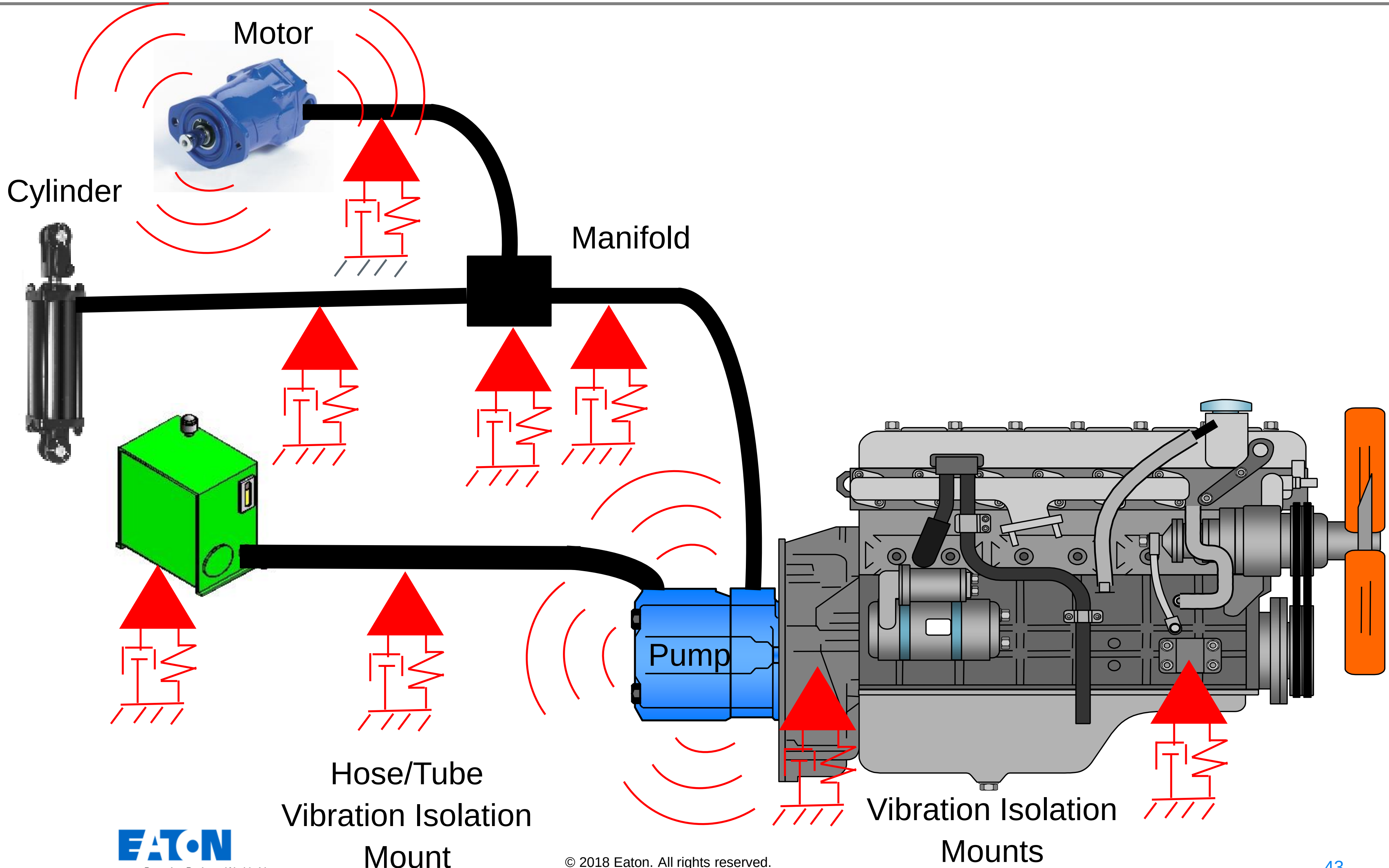
A direct line of sight will allow higher noise level.

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

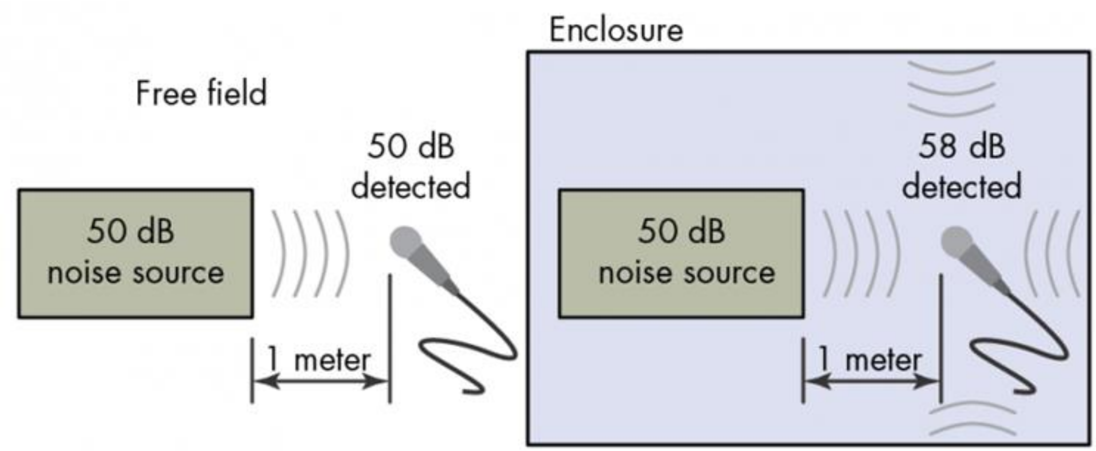
What's measured or predicted.

This is the result.

Air Borne Noise



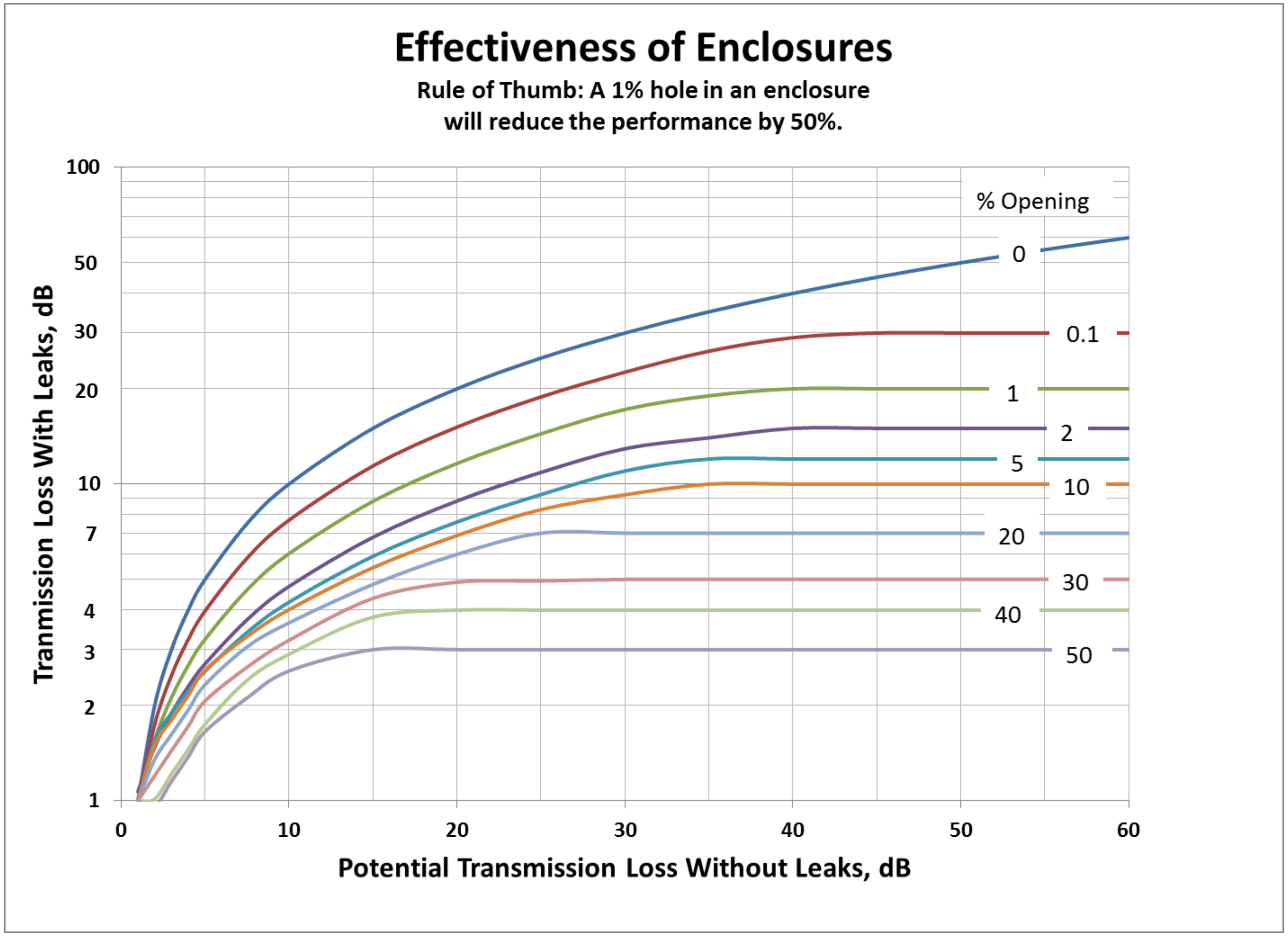
Noise Source in an Enclosure:



- What is the absorption coefficient of the enclosure.
- What is the directivity index?
- Echo radius?
- Acoustic Leakage?

- Ref: Wallin, et al. 2011

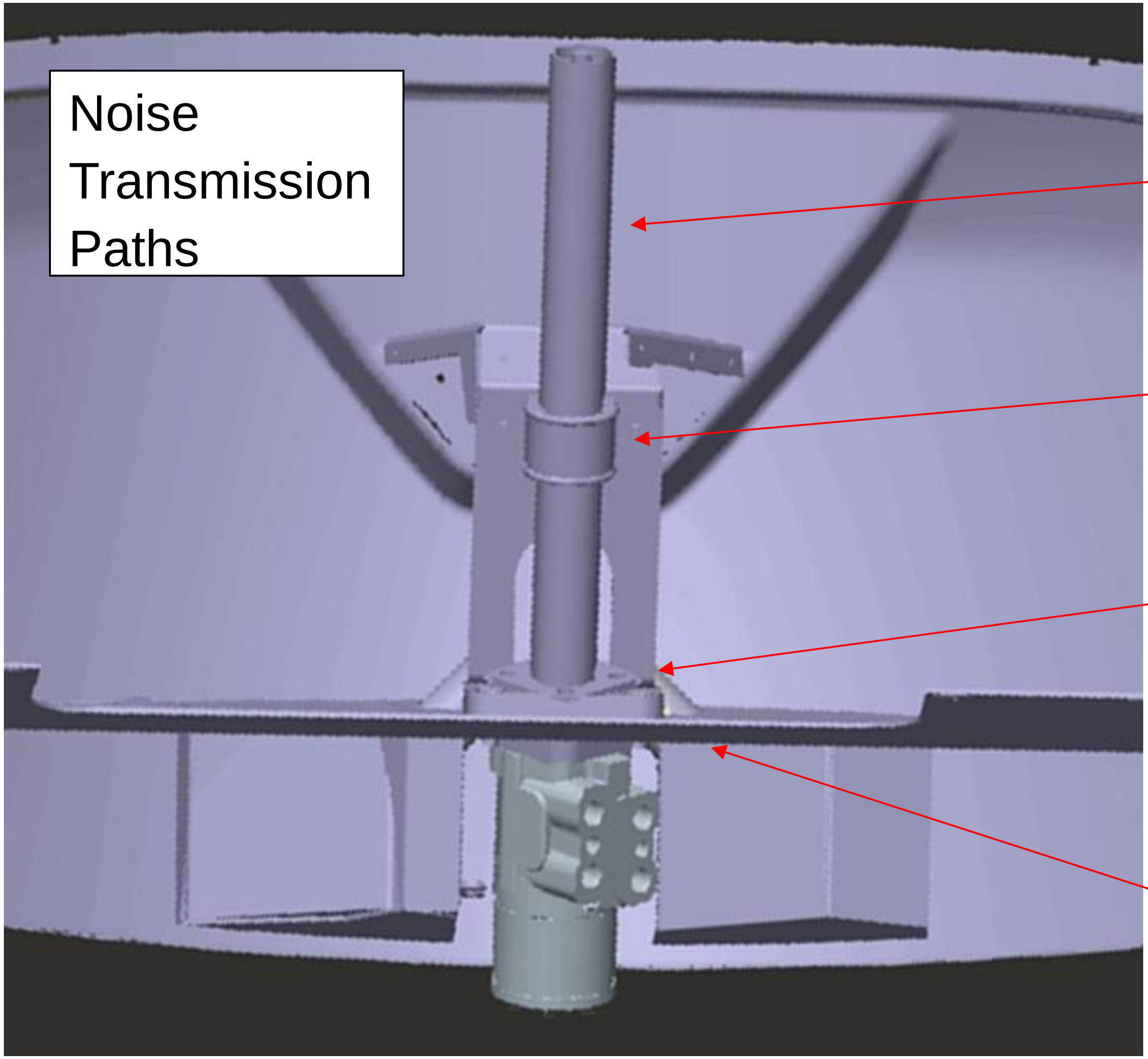
Enclosures (It's not always easy!)



<u>Rule of Thumb:</u>

A 1% hole in an enclosure will reduce the performance of the enclosure by 50%.

Steering Control Unit:
Where Does the Noise Come From?



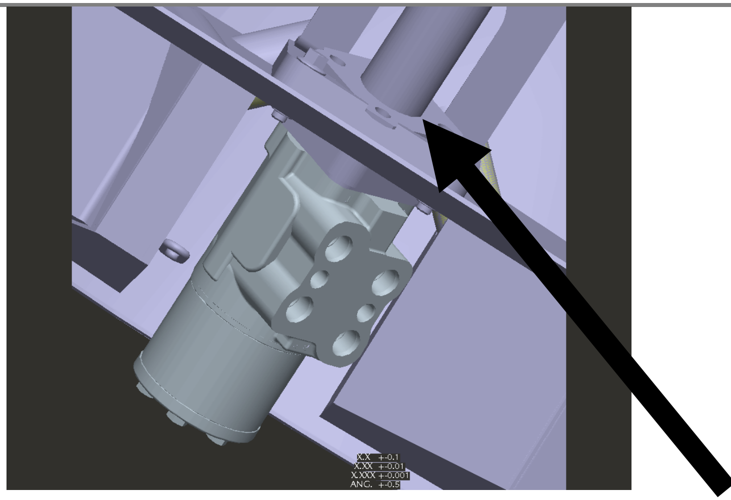
Steering Column Shaft

Steering Column Supports

Mounting Bolts

Vehicle Cab Floor

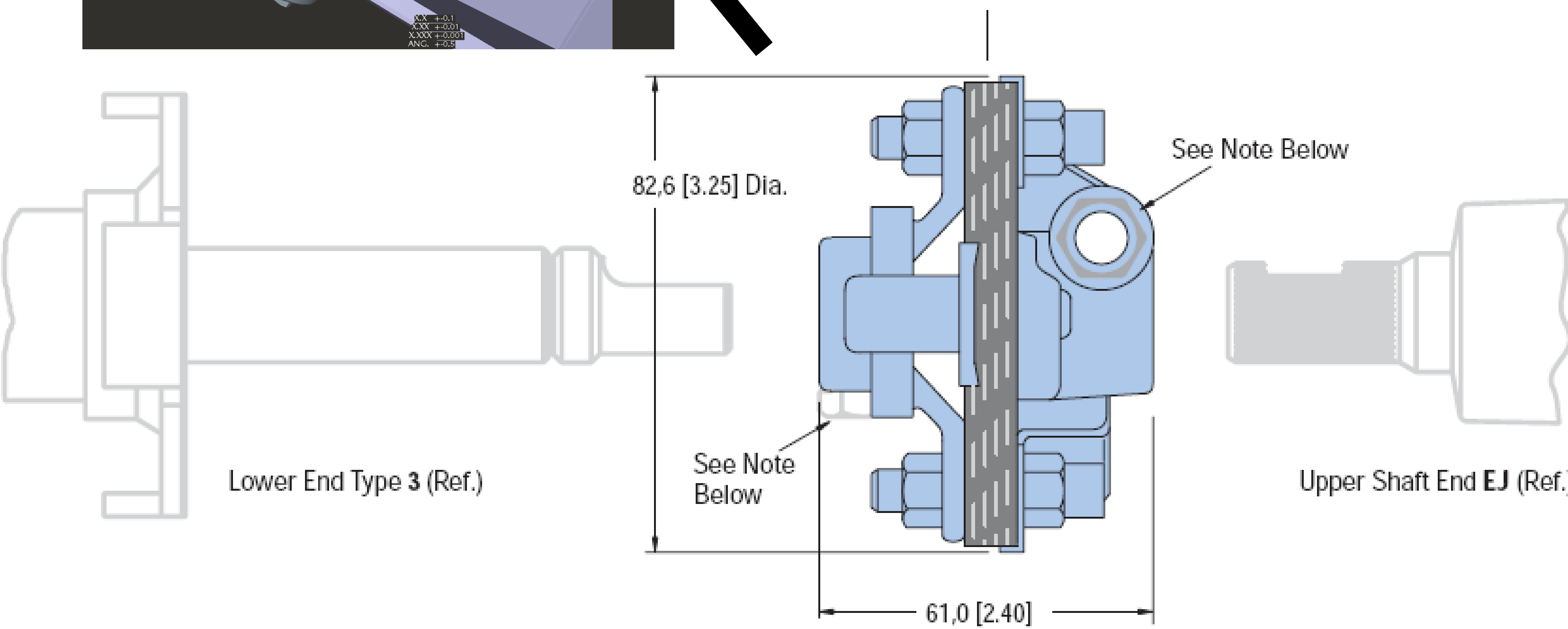
Steering Control Unit Applications



- 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



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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?

$$SPL_{Total} = 10\log \Sigma\, 10^{SPL_n/10}$$

$$= 10\log\left(10^{70/10} + 10^{74/10} + 10^{77/10}\right)$$

$$= 10\log\left(10^{7.0} + 10^{7.4} + 10^{7.7}\right)$$

$$= 79.3\,dB$$

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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?

$$SPL_{Total} = 10 \log \Sigma 10^{SPL_n / 10}$$

$$= 10 \log (10^{70/10} + 10^{71/10} + 10^{77/10})$$

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

$$= 78.6\, dB$$

- 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: 70dB + 71dB + 74 dB.
- The new total sound pressure level from these 3 sources would be?

$$SPL_{Total} = 10\log\Sigma 10^{SPL_n/10}$$

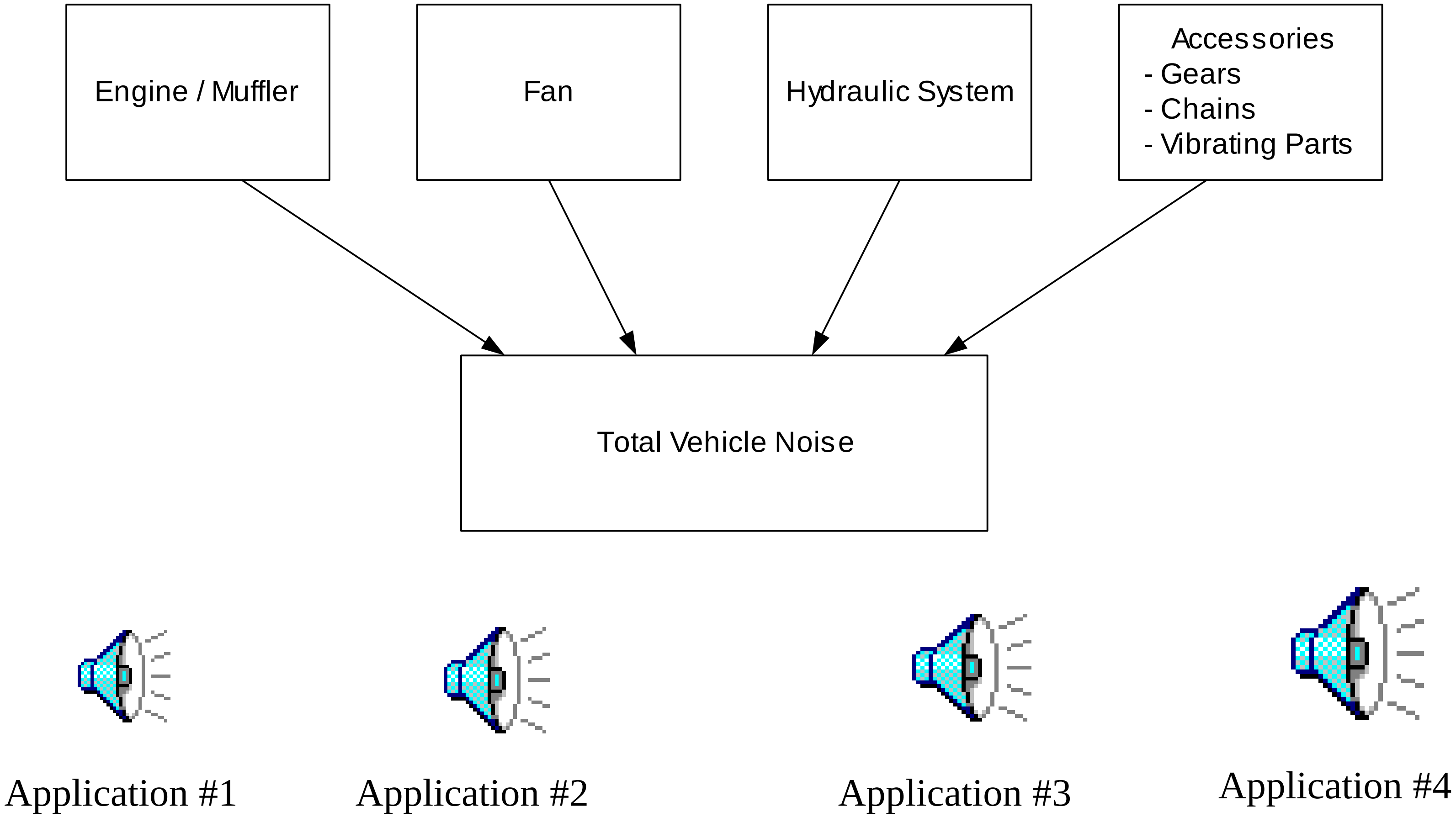
$$= 10\log(10^{70/10} + 10^{71/10} + 10^{74/10})$$

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

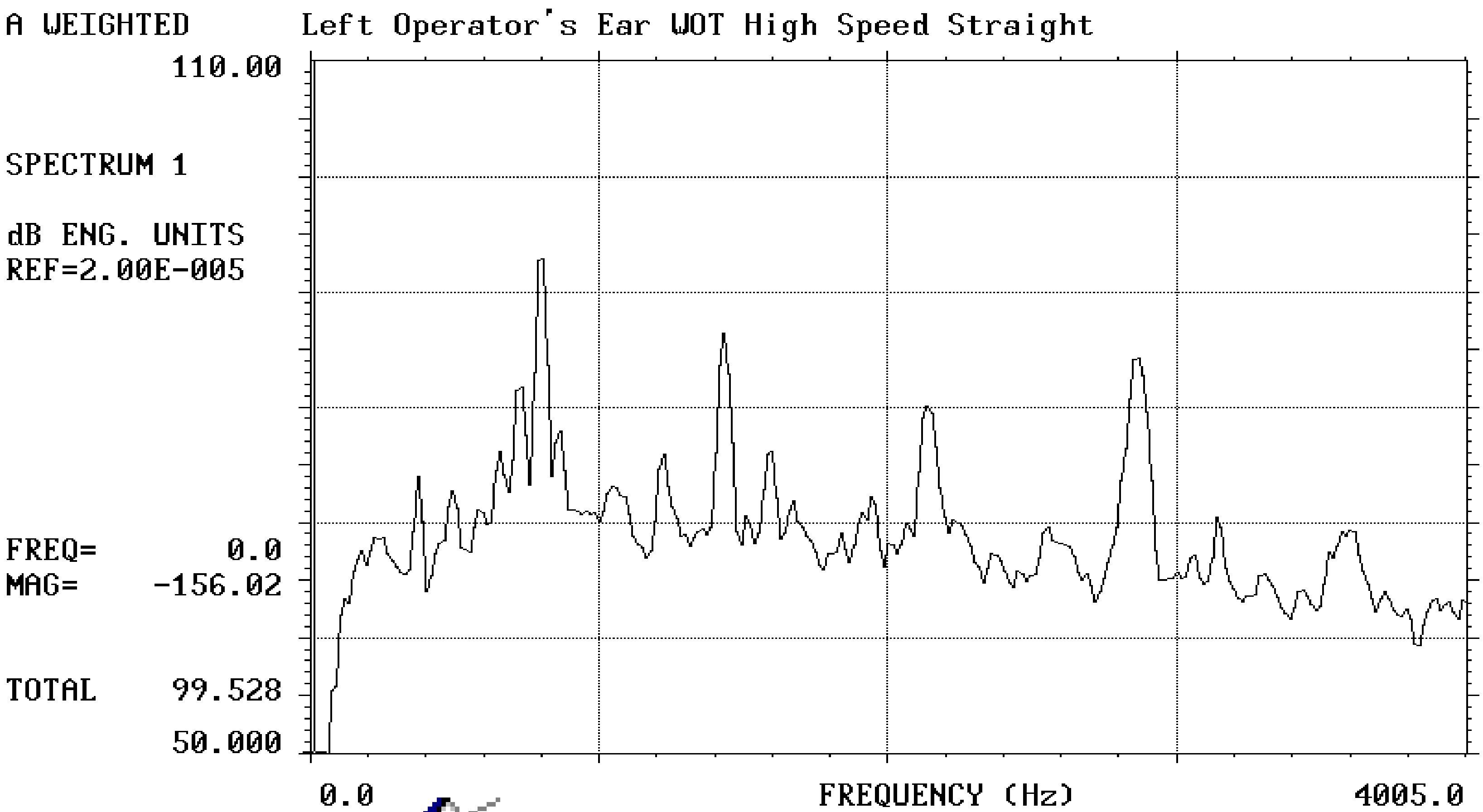
$$= 76.8\,dB$$

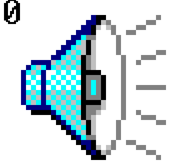
- A reduction of 1.8 dB (- 19%)

Vehicle Noise Sources



Noise Analysis





Application #4

Order Analysis

$$Order = \frac{(freq)*(60)}{RPM}$$

- 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)

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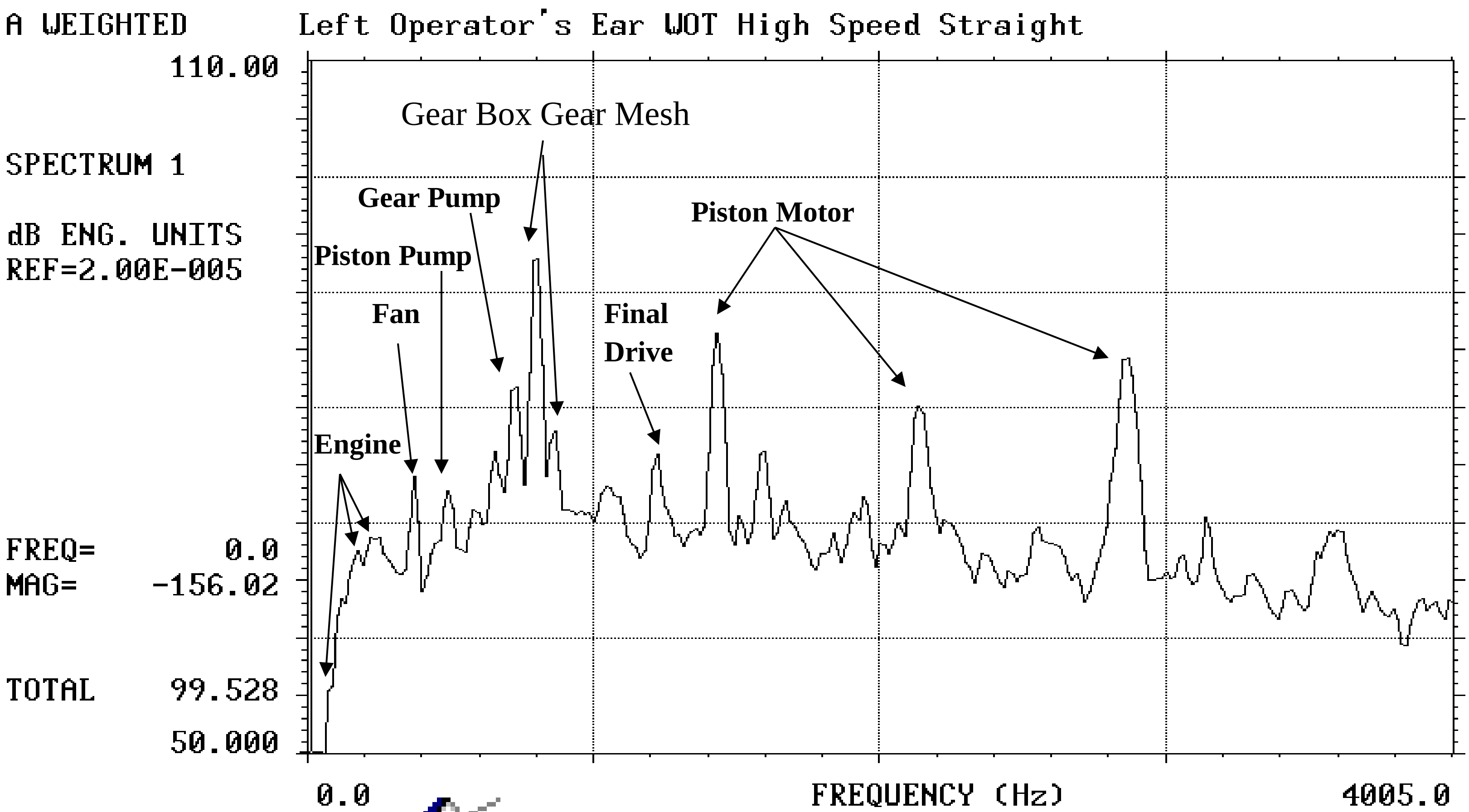
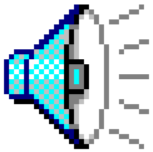
Application # 4

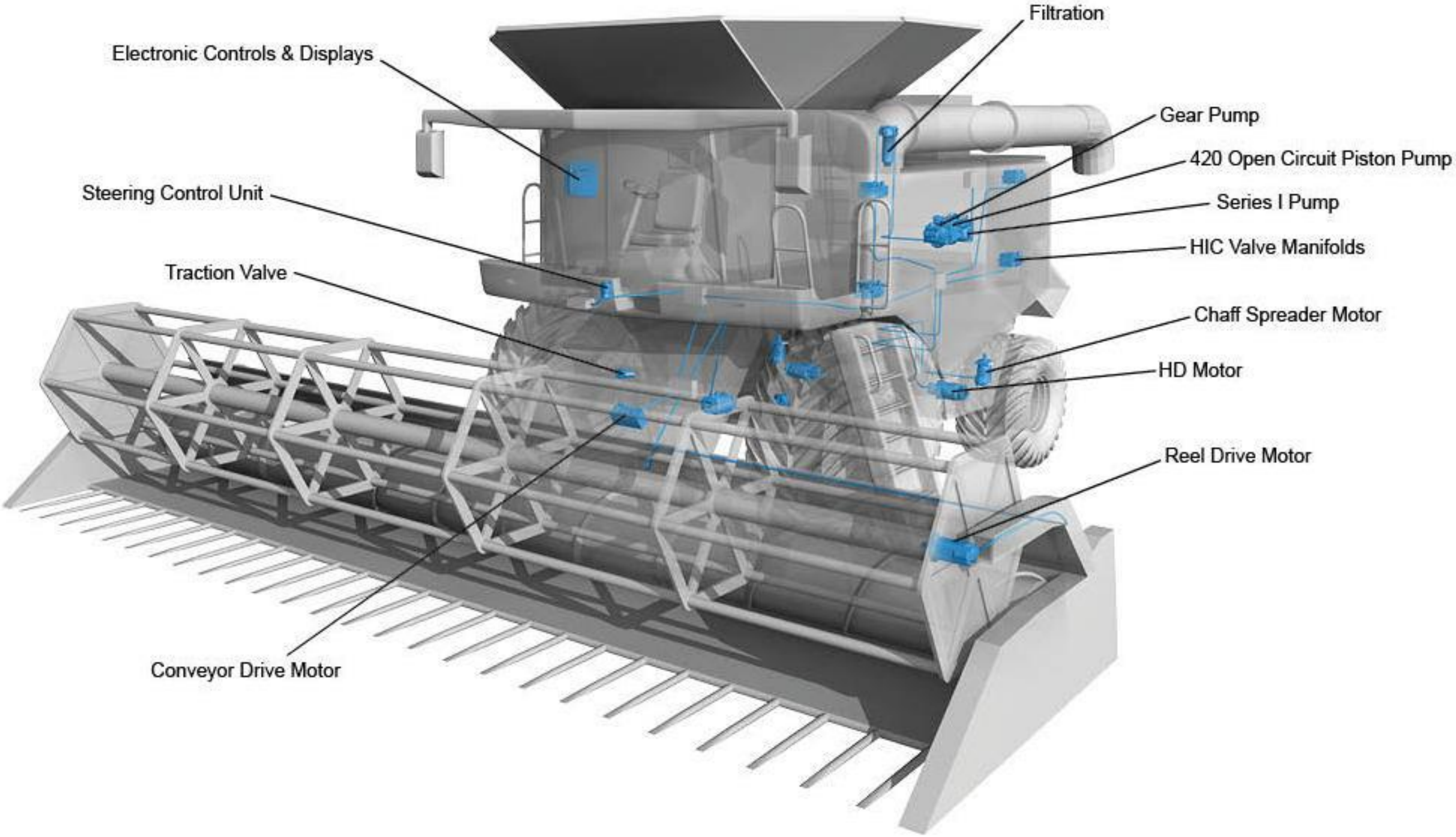




Noise Reduction:

- 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.

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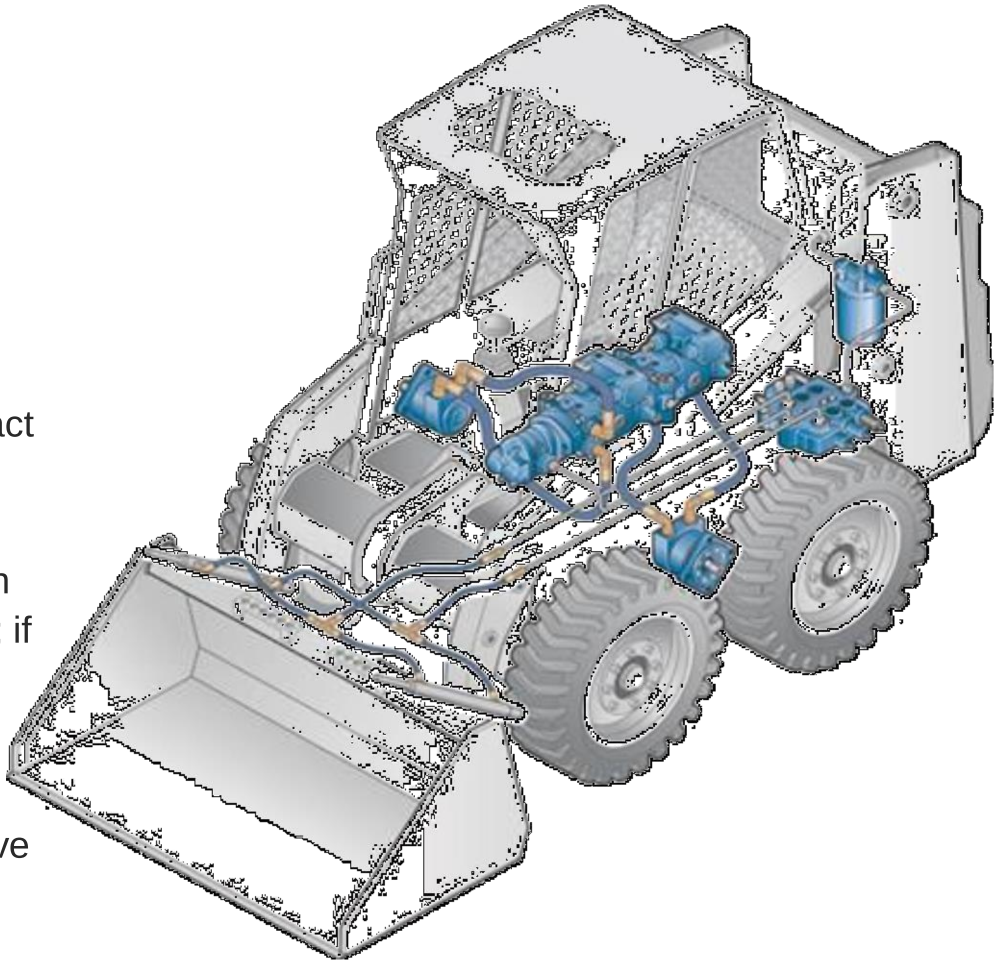
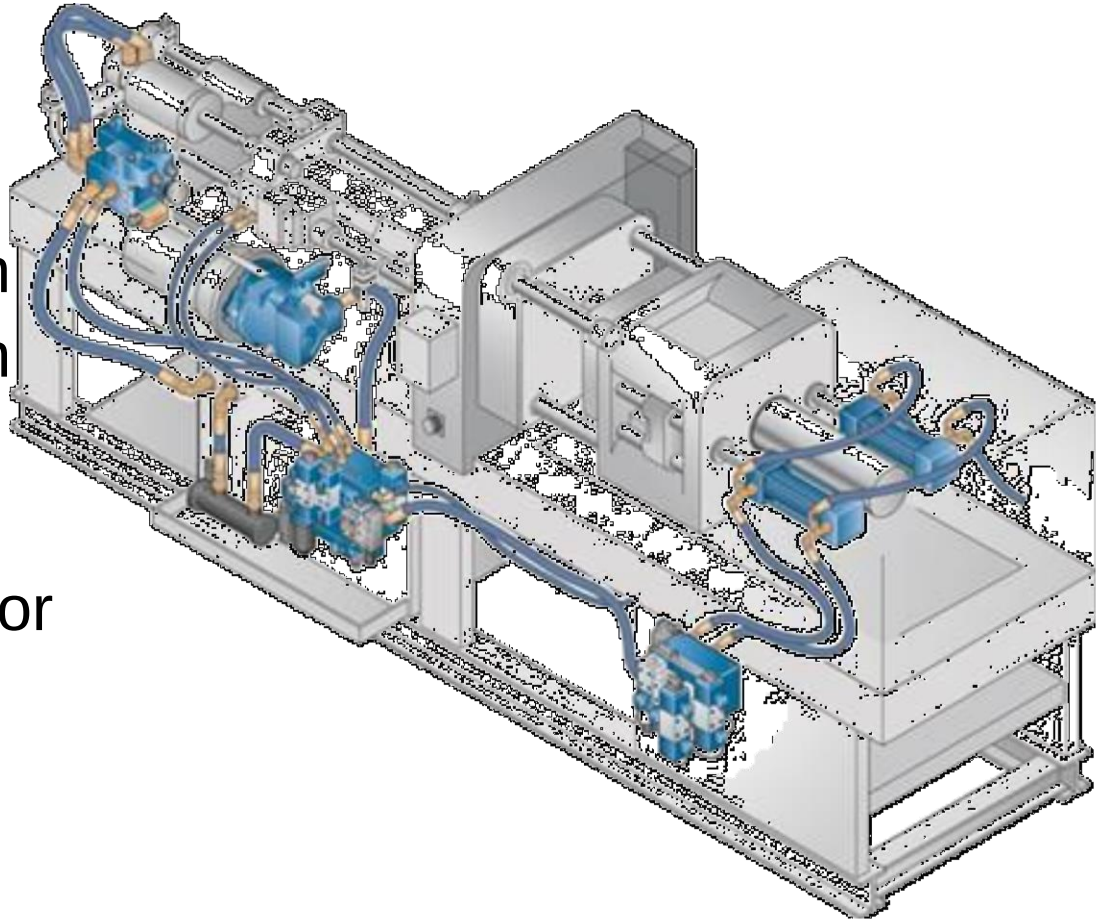
Skid Steer Loaders

- 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

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