3.11 NOISE FROM GEAR DRIVES

Rajendra Singh - *The Ohio State University*

Given that gears are used to adjust speed and transmit power, their whine and rattle noise may never be eliminated altogether. Still, efforts to improve gear and system design—and associated manufacturing methods, as well—exhibit promise to achieve meaningful inroads in gear noise abatement.

The Ohio State University's Raj Singh spoke about gear-associated noise issues. Gears are a $50 billion industry globally, with applications ranging from the transportation arena (automobiles, off-road vehicles, helicopters, and submarines, for example) to industrial equipment (including construction machinery, power plants, wind turbines, and automation actuators) to consumer products (such as tools, hair clippers, toys, and even baby swings).

Gears will never be silent, Singh said, given their primary function of transmitting power. About a decade ago, the American Society of Mechanical Engineers (ASME), in collaboration with organizations such as General Motors, Boeing, and the U.S. Army, developed a 20-year vision that included the goal of reducing gear noise while increasing speed and power.

The two major types of gear noise problems, as summarized in Figure 3.11-1, are whine—the primary focus of Singh's presentation—and rattle. Gear noise is generally a function of load and speed, and quieting gear whine noise becomes more difficult as the range of power density increases. Conversely, rattle noise (generating vibro-impacts) is associated with very light loads and clearances. Mechanical design and tooth modification are closely associated with gear noise reduction, as is the manufacturing process. Very few gears have been designed and manufactured to be ultra-quiet, Singh said.

The speaker next discussed the example of a simple gear pair. Looking at sources, mainly vibrational sources (or mechanical sources) are seen at the gears' interface. The transmission error is a deviation from the kinematic conjugacy[2] of the order of a micron, which can create significant noise. Given a one micron displacement amplitude at 1000 Hz, an almost 100 dB noise level may be generated with perfect sound radiation surfaces.

In high-precision machinery, Singh pointed out, micron level accuracy is relevant in terms of manufacturing errors and elastic deflections. Gear whine noise at mesh frequencies is primarily a structure-borne path involving the gear bodies, the shaft, the bearings, the casings, and the mounts, which affect gear noise by amplification and diffusion of energy throughout the system. Ultimately, at the receiver, significant noise is observed at the gear mesh frequencies and associated sidebands.

Some fundamental academic lessons about vibration isolation may not apply, Singh said, because compliant bearing caps, flexible casings, and ill-designed shafts and bearings might actually enhance motions or forces at the source. A geared system can be highly nonlinear with significant interactions taking place within it.

Given a simple gear pair, the presenter said, a system-oriented model can go from the gear sources to sound pressure. For example, contact mechanics codes can be used to help identify sources in terms of transmission error, mesh stiffness variation, and sliding friction.

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[2] A list of gear nomenclature is provided at: https://en.wikipedia.org/wiki/List_of_gear_nomenclature

A calculation code can provide the internal gear mesh and bearing forces, and then forces or motions can be transmitted to the casing; bearing transfer properties are relevant in this regard. Usually, the bearings are rolling element types, except in some cases of heavy equipment with a hydrodynamic bearing or similar mechanism. Casing dynamics and mount properties are also relevant for predicting sound pressure for a geared system. With respect to planetary gears or a multi-mesh geared system, it can be more challenging to develop a mathematical model, given multiple sources, paths, and other interactions.

Singh next spoke about NASA gear pairs—gears designed for research and experimental work for helicopter transmission design. Figure 3.11-2 shows shaft displacements, in the line of action (LOA) and off line of action (OLOA), as a function of torque. The gears are designed to be quiet in terms of the transmission error, at the design load of 600-pound-inch torque, for example, and the vibration level is relatively minimal. This assumes only one source (transmission error), however. But when this source is minimized, other noise sources such as the sliding friction arise. With vibration sources and paths well defined, determination of sound radiation becomes easier.

Sound pressure level for any gear pair is a function of torque. As multiple sources start to enter, the dip in the vibratory displacement vs. torque is usually not visible in terms of the noise vs. torque curve.

Gear design is vital—for example, going from spur gears to helical gears and considering the high-contact ratio gears. And micro-geometry modifications (in terms of the profile and lead) may be the most important factors. For instance, profile modifications such as tip relief can be a tremendous help in gear design. So when someone wants quieter gears designed, Singh said, fundamental design and gear contact patterns are among the factors considered.

Manufacturing restrictions can make some designs impossible to achieve and some error inevitable. Engineers may have little influence on the manufacturing side, Singh said, but the introduction of a quieter design—even where significant resonances and dynamic interactions within the system render conventional vibration control solutions useless—represents the “holy grail” design.

Singh spoke next about gear rattle, which is compared with gear whine in Figure 3.11-3. Unlike gear whine, rattle issues assume intermittent contacts and tooth separations, resulting in the generation of periodic impulses entering under some external vibration source. Rattle problems are more system-oriented than whine. Figure 3.11-4 shows the types of impacts based on mean and dynamic loads, and Figure 3.11-5 depicts the role of backlash within a system: Too little backlash could create a whine problem, while too much would induce rattle.

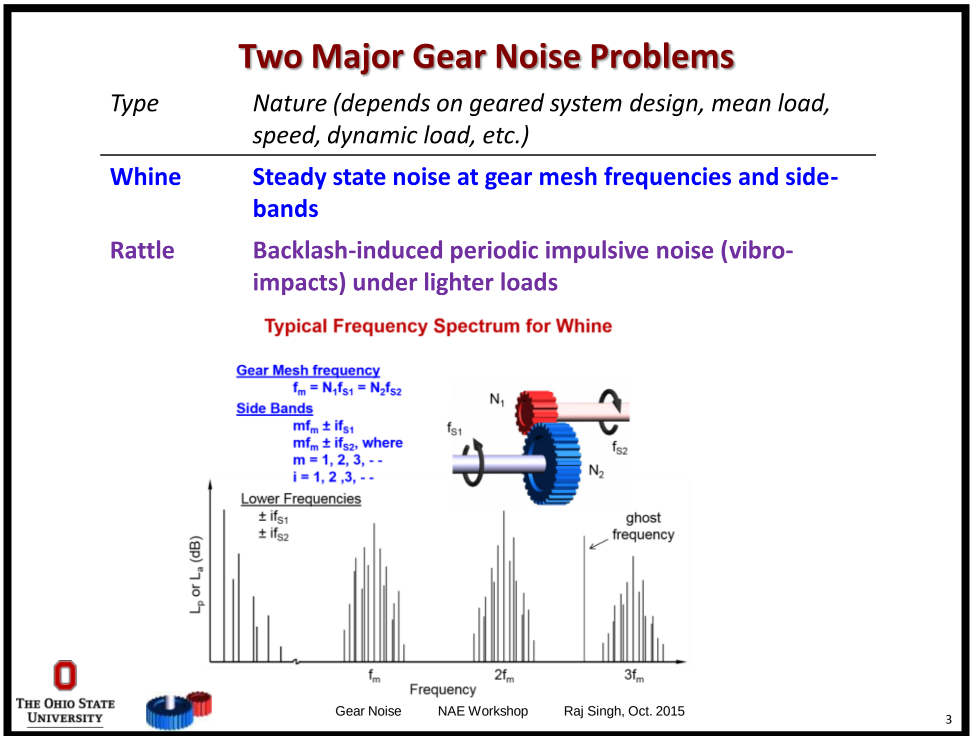
Singh moved next to trends in automotive transmission designs. Changes to fuel economy over the last 40 years, he said, are directly associated with rattle problems in the U.S. and around the world. Changes contributing to increased vehicle rattle include: decreases in cylinder number; turbocharging; the use of diesel rather than gasoline; reduced flywheel inertia; synthetic lubricants; the addition of transmission speeds; and high torsional system loads.

Turning to the subject of education, the presenter stated that gears receive only a brief mention in undergraduate machine design courses. And when they are covered, involute gear design is the focus, when in actuality it is impossible to produce a perfect involute and every gear has various errors. In graduate education, few institutions address this topic, especially in the context of noise and dynamics.

As for research, investigation in this area is rarely funded by government agencies and other large research sponsors. And only two national laboratories are conducting research in this field: NASA Glenn, which focuses on aerospace and helicopters, and the National Renewable Energy Laboratory (NREL), which concentrates on wind turbines.

Future research should investigate many fundamental issues, given the complexity of high-speed machines; the extensive nonlinearities in these types of physical systems; and time and spatial variations of contact parameters involved. To achieve quieter products, manufacturing improvements are also critical.

Increasing power density and a rising variety of products, along with problems in manufacturing, require attention. Limited calculation capabilities and inadequate time allotted to experts to solve complex problems in this field are additional challenges. While additional knowledge must be generated, design guidelines (especially in the context of noise control) must also be better disseminated, Singh emphasized. The Ohio State University is one institution that has been teaching a short course in the area. More than 1,900 engineers (from over 350 companies) have taken the class over 36 years, and it is clear that the 50 or so students (from industry) in each class are usually eager to learn about various aspects of gear noise.



Two Major Gear Noise Problems

Type	*Nature (depends on geared system design, mean load, speed, dynamic load, etc.)*
Whine	**Steady state noise at gear mesh frequencies and side-bands**
Rattle	**Backlash-induced periodic impulsive noise (vibro-impacts) under lighter loads**

Typical Frequency Spectrum for Whine

Gear Mesh frequency

$f_m = N_1 f_{S1} = N_2 f_{S2}$

Side Bands

$mf_m \pm if_{S1}$

$mf_m \pm if_{S2}$, where

$m = 1, 2, 3, --$

$i = 1, 2, 3, --$

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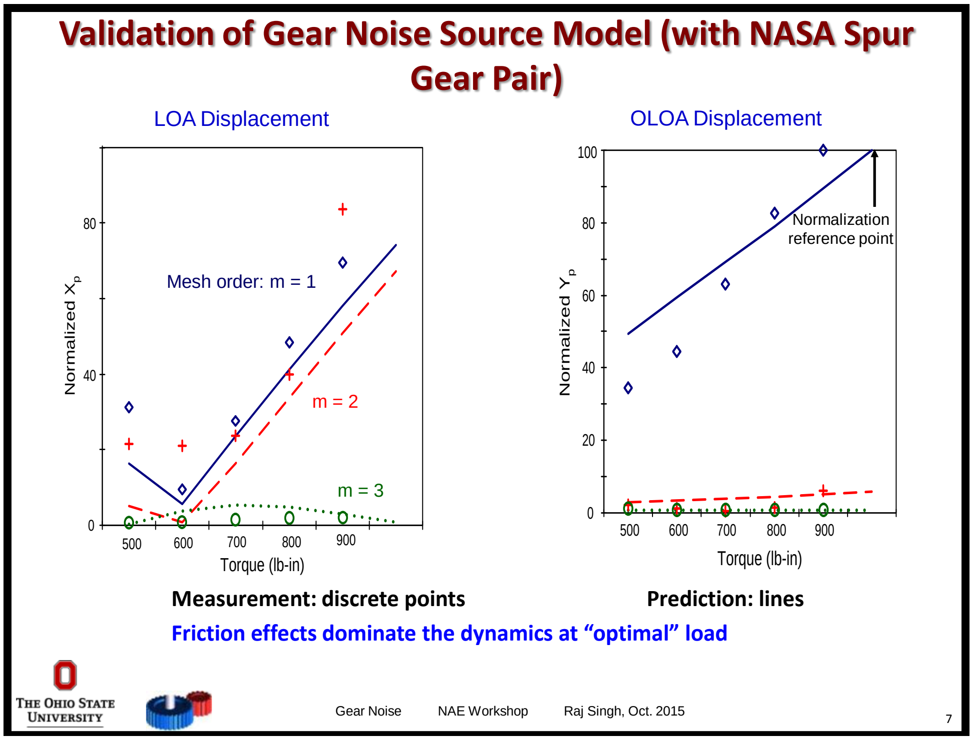
Figure 3.11-1 Gear noise: whine versus rattle.



Validation of Gear Noise Source Model (with NASA Spur Gear Pair)

Measurement: discrete points **Prediction: lines**

Friction effects dominate the dynamics at "optimal" load

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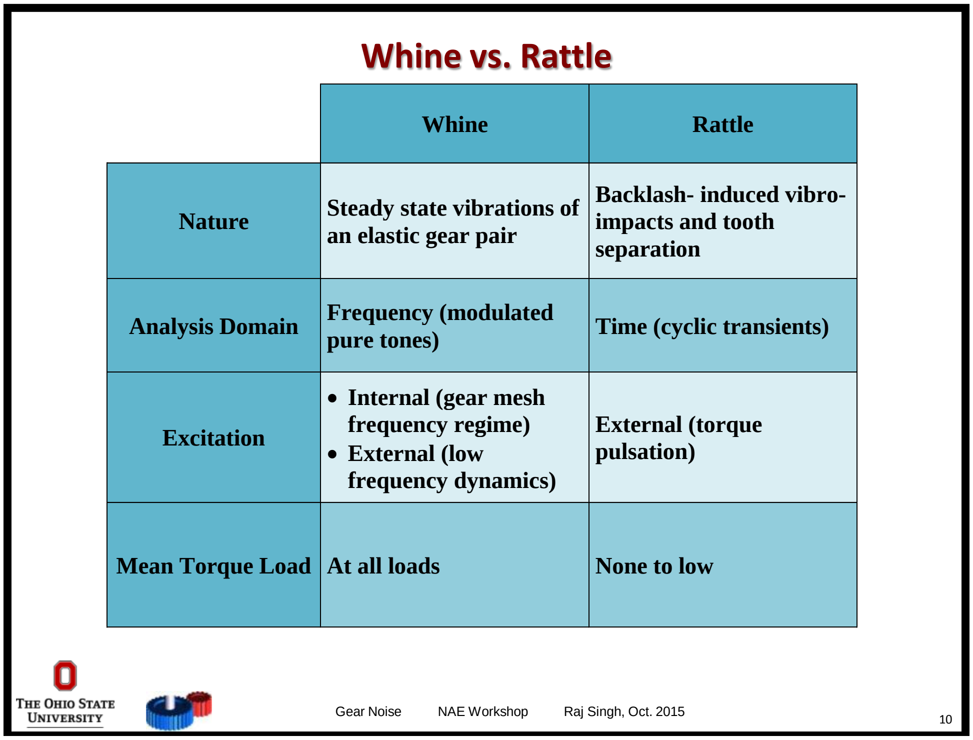
Figure 3.11-2 Gear noise validation: shaft displacements vs. torque.



Whine vs. Rattle

	Whine	**Rattle**
Nature	**Steady state vibrations of an elastic gear pair**	**Backlash- induced vibro-impacts and tooth separation**
Analysis Domain	**Frequency (modulated pure tones)**	**Time (cyclic transients)**
Excitation	**• Internal (gear mesh frequency regime)** **• External (low frequency dynamics)**	**External (torque pulsation)**
Mean Torque Load	**At all loads**	**None to low**

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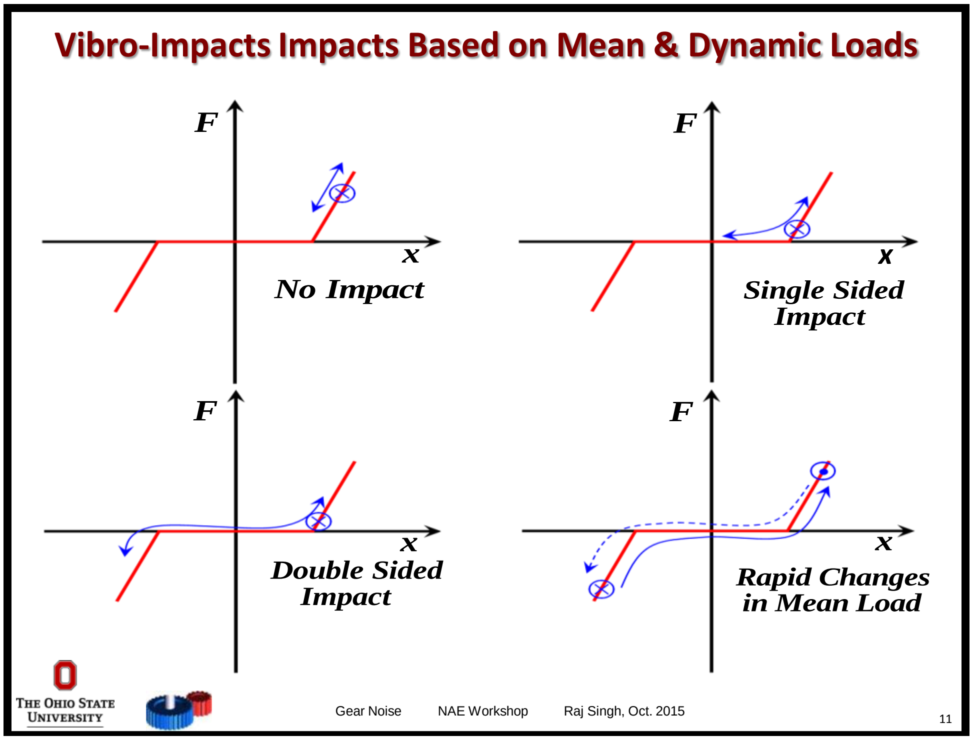
Figure 3.11-3 Comparing gear whine and rattle.



Vibro-Impacts Impacts Based on Mean & Dynamic Loads

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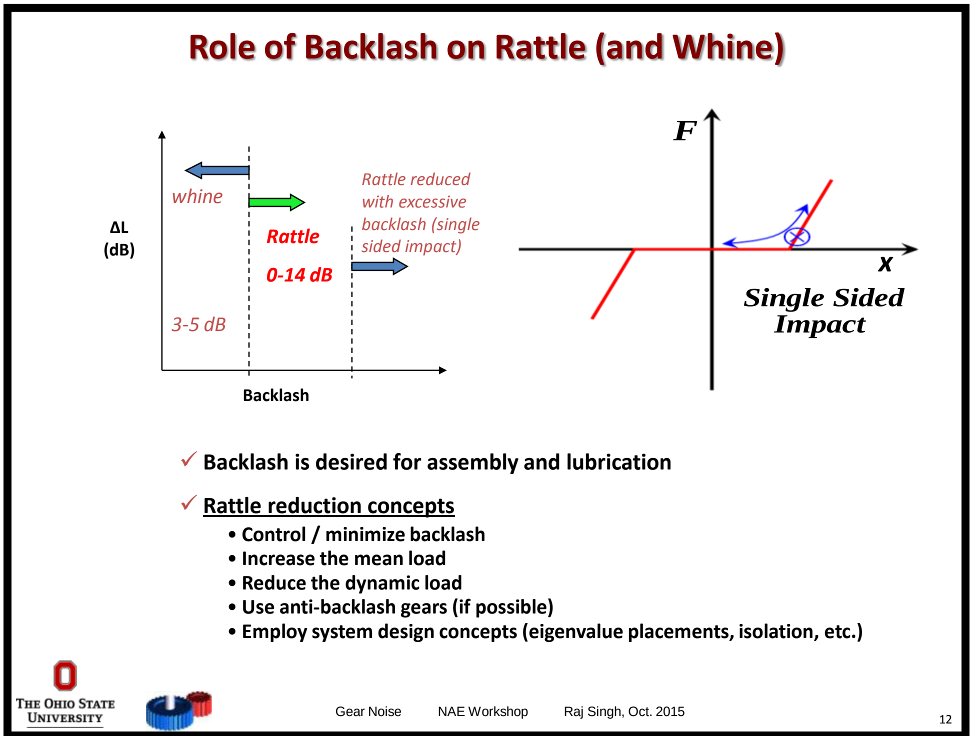
Figure 3.11-4 Vibro-impacts based on mean and dynamic loads, given backlash.



Role of Backlash on Rattle (and Whine)

- ✓ **Backlash is desired for assembly and lubrication**
- ✓ **<u>Rattle reduction concepts</u>**
  - **Control / minimize backlash**
  - **Increase the mean load**
  - **Reduce the dynamic load**
  - **Use anti-backlash gears (if possible)**
  - **Employ system design concepts (eigenvalue placements, isolation, etc.)**

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Figure 3.11-5 Effects of backlash on noise and some concepts to reduce gear rattle.