Chiming in on Gear Noise:

THREE EXPERTS HAVE THEIR SAY

Jack Mc Guinn, Senior Editor

It is said that "The squeaky wheel gets the grease."

Ok, but what about gear noise?

We talked to three experts with considerable knowledge and experience in this area: Dr. Donald R. Houser—founder and professor emeritus of the Gear Dynamics and Gear Noise Research Laboratory at Ohio State University; University of Cincinnati Professor Teik C. Lim—elected Fellows of ASME and SAE, recipient of the Chang Jiang Chair Professorship awarded by China's Ministry of Education and a major contributor to studies addressing the dynamic analysis and development of precision machine elements including gears, bearings and drivetrains, with applications to automotive, aerospace and manufacturing systems; and Bill Mark, Ph.D., senior scientist–Drivetrain Technology Center–Applied Research Laboratory and Professor Emeritus of Acoustics at Pennsylvania State University.

Dr. Donald R. Houser, founder and professor emeritus, Gear Dynamics and Gear Noise Research Laboratory at Ohio State University (courtesy OSU).

For starters, what is gear noise? It is much more than an "I know it when I hear it" response.

"Gear noise depends a lot on the users and their applications," says Houser. "However, I like to break gear noises into three categories: gear whine—a tonal noise that usually comes from excitations at the gear mesh; gear rattle—a clattering sound that is usually excited by the driving source (such as the internal combustion engine) or loading device; and gimmick sounds—in which I lump things like the effects of nicks, plastic gear screeching, etc."

"Gear noise—often called gear whine—is the unwanted sound produced by the gear meshing teeth action," Lim states. "It is typically harmonic or tonal in nature and occurs at the mesh frequencies that are defined as the integer multiples of the gear rotational speed times the number of teeth. Gear noise is often a result of dynamic mesh force induced by transmission error and other meshing related excitations. Gear noise is often radiated off a structural surface that is excited by gear vibratory energy transmitted structurally from the gear pair to the exterior housing or connected structures. Gear noise is not desirable because it is annoying and conveys poor design and manufacturing qualities."

"This sound can be 'displayed' in the time domain or in the frequency domain. If the meshing gear pair is operating at constant speed and transmitting constant loading or torque, this sound can be displayed in the frequency domain as the super-position of two sets of harmonics—one set of harmonics from each of the meshing gears

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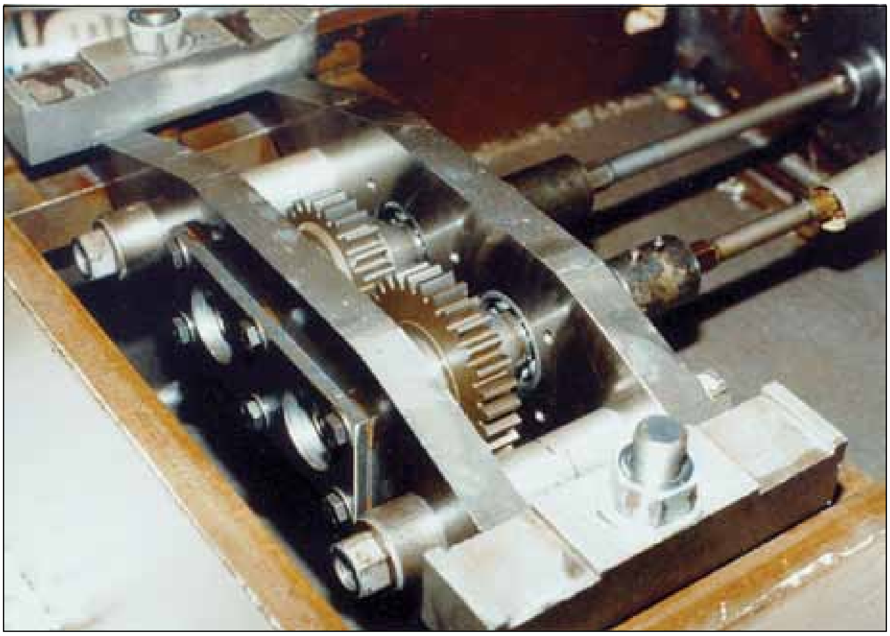
of the pair, says Mark. "Each gear of the meshing pair has its own period of rotation and, therefore, its own fundamental frequency, which is the reciprocal of its period of rotation. The frequency harmonics from each of the two gears are integer multiples of the fundamental frequency of that gear of the pair. These harmonics are the rotational harmonics of that gear. If a gear has N teeth, then the Nth rotational harmonic is the tooth-meshing fundamental harmonic. Because of the way two gears mesh with one another, the tooth-meshing harmonics of both gears of a meshing pair coincide."

Gear measurement is an important step in trouble-shooting the origins of gear noise (courtesy Penn State U).

An obvious question that comes to mind asks what types of gears are more susceptible to gear noise. Does it matter? Not really.

"All types of gears are susceptible to gear noise," says Houser, adding, "though gears with very small numbers of teeth, such as single-start worms, have their mesh frequency near the bottom of the audible frequency range and so are less likely to be heard."



Test rig with loaded gear set (courtesy Penn State U).

Taking a somewhat different view, Lim states, "Lower-quality gears (i.e., those with inaccurate tooth surface profiles) are most susceptible to gear noise. Also, a worn out gear tooth tends to make more noise. Since gear noise is really a system problem, the dynamic interactions between the gear pair and its supporting structures also play a significant role in causing gear noise. Generally speaking, geared rotor systems with stiffer torsional support and those with structural resonances at the mesh frequencies make more noise."

"Spur and straight bevel gears with operating contact ratios under 2.0 generally create more noise than gears with larger contact ratios," Mark says. "Because helical and spiral bevel gears generally have 'total' contact ratios well above 2.0, they generally produce less noise. The noise produced by gears generally decreases as contact ratios (total contact ratio) are increased. The total contact ratio is the sum of the transverse (profile) contact ratio and the axial (face) contact ratio.

As gear testing in general can be very complex and challenging, creating simulation protocols and models for noise testing is even more so. But without them, researchers would be similar to an explorer without a map or compass.

"Simulation models help us understand the fundamental gear mesh and dynamic behaviors," Lim states. "With that understanding, we can select designs that are less susceptible to gear noise generation and transmission. Also, the simulation models help us to perform many parametric studies that would otherwise not be possible to determine the best possible design solution. The reason is computer simulation is efficient and cheap to do, while experimental study is time-consuming and much more costly.

"There are two types of simulation models used to analyze gear noise. One is a quasi-static tooth contact analysis to simulate the gear tooth engagement problem. This model enables us to study the various tooth design, assembly and mounting conditions that can lead to lower gear mesh excitation. The second is a dynamic analysis of the geared rotor assembly, which can be applied to understand how system dynamics influence gear noise generation and transmission. The model can be applied to both design support structure and gearbox."

"Since I have been involved with developing such simulation models for over 30 years, this is a topic that I could address at great length," Houser says. "Thinking about the simple source-path-receiver network that can be used to describe the process of gear noise generation, we can model each of the stages to help predict gear noise. Our main focus has been on the modeling of gear whine sources—namely, transmission error, gear force shuttling and friction. Here, we need to predict the gear load distribution, which requires the input of the gear micro-geometry (profiles, leads and topographies).

"The abovementioned excitations are a byproduct of the load distribution calculation. Insofar as we understand the manufactured micro-geometry, there is a good correlation between predictions and noise. In one example where manufactured tooth shapes varied from tooth to tooth, we needed to model the tooth topography of each tooth of each gear in order to get a good correlation between prediction and noise. The major finding was that noise tends to decrease with increasing contact ratio, but having the proper micro-geometry of any gear type can minimize noise generation. My colleague, Dr. Raj Singh, has developed similar models for simulating gear rattle."

Is there a permanent fix for gear noise? Not likely, is the consensus.

"Based on today's technological capability and the trajectory of the advancement in gear design, it is not conceivable that gear noise will be completely eliminated," Lim states. "The reason is because we will never be able to cut perfect gears and even if we can, we will never be able to eliminate the effect of system dynamics. We can minimize and control gear noise to the extent that it will not be considered a problem (annoyance).

"Technically, it is always there, but often we can have gear noises that are beneath the background noise levels, hence, not being audible," says Houser. "Using automobiles as an example, if the engine is a noisy diesel engine, background noise is high so gear noise might not be heard, while if I use the same gears in an electrically driven vehicle, noise might be considered excessive."

"Probably no," is Mark's response, adding, "If the modification of the working surfaces is 'perfect' and if the variation in transmitted loading is minimal, there remains the role of friction, which is very hard to entirely eliminate."

So how do researchers and other experts begin to troubleshoot a gear noise issue? Is there an existing set of protocols that provide some degree of direction in order to determine the source? One apparent source, according to our experts, can be found on the manufacturing floor. After all, no one ever said precision gear manufacturing was a walk in the park.

While Mark points out that a source of the above mentioned tooth-meshing harmonics is deviations of the elastically deformed working surfaces from equispaced, perfect involute surfaces of each of the two meshing gears, he goes on to state that "On the other hand, the source of the remaining rotational harmonics, one set from each of the two meshing gears, is tooth-to-tooth geometric variations of the individual working surfaces from each of the two meshing gears, which almost certainly is caused by manufacturing errors. Improvements in manufacturing precision generally will reduce non-tooth-meshing rotational-harmonic amplitudes."

Taking a somewhat less complex approach, Houser believes that "just listening to the nature of the sound may help. If it is a gear whine tone, then one needs to perform a spectrum analysis

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to determine the main frequency of the tonal sounds. Usually they will be at mesh frequency and its harmonics, but occasionally there may be a 'ghost noise' that is the result of manufacturing undulations created in the manufacturing process."

"The approach I like to use is to first measure the gear noise 'signature,' " Lim states. "Using that data, I can listen to the sound and perform digital signal processing to better isolate the frequency and sometimes time characteristics. Once that is known, I like to examine the gearbox design to determine the source of excitation. If necessary, I will also want to perform a series of dynamic testing including modal analysis and operating measurements to understand the transmission paths for the gear vibratory energy. Understanding the source of excitation and also the primary transmission paths will go a long way to help mitigate the gear noise problem."

Given the responses from our three experts, one would think it quite possible to begin reducing gear noise at square-one—i.e., the design and manufacture phases. But no, that's not the case. There are a number of reasons for that, and when taken together, the result is that the gear noise issue is kicked to the curb. For manufacturers who ignore gear noise, it adds up to a pay me now or pay me later deal with the devil. But why is that?

"This is often a side or afterthought issue, since they are in a hurry to complete the design and get the product to market," Houser says. "They do not realize that designing a gearbox without consideration given to noise can lead to a substantially more expensive solution.

"It is my belief that most gear manufacturers and users do not understand the nature of gear noise generation and transmission, and also do not have the tools and capabilities to tackle gear noise up front during the design process," Lim says.

And Houser adds to that with "We have been preaching for years that noise should be considered at the design stage, and I think many do use rules of thumb such as increasing contact ratio in their designs. (But) many designers simply use gear rating-type formulas for creating their designs and these calculations give little insight into whether gears will be noisy or not, leaving designers in a situation where they will learn later whether noise is an issue."

University of Cincinnati Professor Teik C. Lim, ASME Fellow, Chang Jiang Chair Professorship award recipient and expert in dynamic analysis and development of precision gears, bearings and drivetrains (courtesy U of Cinn.).

Thus far, we've learned from Messrs. Houser, Mark and Lim that gear noise is a systemic, whole-component design issue, not confined to strictly gear design. Put another way, "System dynamics play a significant role in the dynamic mesh force generation," Lim states. "Also, the system dynamics control the transmissions of gear noise from the gear pair to the exterior surface; one can have a high-quality gear and still have gear noise if the contribution from system dynamics is substantial."

Which brings us back to the need for dependable modeling when striving to eliminate as much potential gear noise as possible from the outset.

"Things like gear system torsional resonances and housing dynamics may also have an effect on gear noise levels," Lim says. "In order to address these concerns it is necessary to perform much more in-depth dynamic modeling. I should also point out that gear rattle analysis requires a detailed model that must include both backlash non-linearities and the dynamics of the driver and driven inertias, thus requiring system knowledge that might not be available to the typical gear designer."

Breaking it down a bit further into Xs and Os, Mark points out that "In a general dynamic system there is coupling or interaction between all parts of the system. Two gears on the same shaft will illustrate this fact. If the shaft is soft (very elastic), the vibration excitation by one gear on the shaft is likely to have only a small effect on the vibration of the other gear on the shaft. However, if the shaft is rigid, the vibration excitation by one gear on the shaft will have a very strong effect on the vibration of the other gear on the shaft. To understand such coupled effects, one needs to treat (by mathematical modeling, simulation or testing) the entire system as one coupled system. Resonance effects can be important."

So if, let's say, "bad design" is the "hammer" and a "gear set" is the "head" that "design" keeps whacking, why not stop doing that? Why the apparently pervasive occurrence of such off-kilter design? The answer, is more complex than the question.

"First of all, gear designs are often done for a specific operating condition and load," Lim explains. "However, they are used under many varieties of operating and loading conditions; an acceptable design for one condition does not automatically mean it is good

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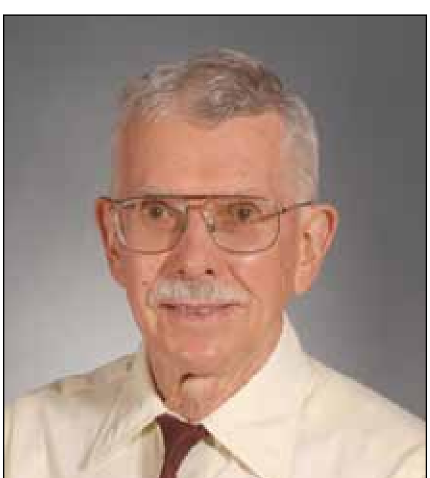

Dr. Bill Mark, senior scientist at the Drivetrain Technology Center/Applied Research Laboratory and professor emeritus of acoustics at Pennsylvania State University (courtesy Penn State U).

for other conditions. Second, gear designs are often done without regard to system dynamics. Since high-quality gears can produce noise when applied inappropriately, it is easy to see why we can encounter gear noise in operation."

Somewhat in the same vein, Mark states, "I suspect the very large benefits of increasing contact ratios are not fully understood by many gear designers. Moreover, gear noise is very sensitive to working-surface modifications. The form and ideal modification are very sensitive to the mean design loading and the range of loadings over which the gears are anticipated to operate. Exceedingly small changes—e.g., in working-surface modifications—can have a large effect on gear noise generation."

And from Houser's perspective, "Every gear application has its own peculiarities, so this is a tough question to answer in a simple manner. From a gear whine perspective, most designers apply micro-geometry corrections that might help at the design load, but hinder the design at lighter loads where noise may be of concern. Without a simulation tool that predicts load distribution, it is extremely difficult to come up with the proper micro-geometry on the gear tooth. The other aspect of this is that once the proper micro-geometry is placed on the gear print, it must be accurately manufactured and this is not always the situation."

And what about material? Do some metals process better than others when assessing gear noise? Not significantly, apparently.

"I do not think material is a big issue," Houser states. "There has long been the adage that plastic gears are quieter than steel, yet, in my dealings with plastic gear users it would seem that a major difficulty with plastic gears is making them quiet. Every now and then we hear that cast iron is quieter than steel, yet they have similar moduli and tooth deflections so their transmission errors would be very similar, hence having the same noise excitation. The only spot where I think material damping has an effect is when there are impacts such as rattle that excite gear blank vibrations that are reduced with damping. But this is likely to be a secondary effect."

Adds Lim, "The materials affect damping and structural dynamics, and that is how it can have an impact on gear noise. Lower damping and sensitive structural dynamics (i.e., the effect of mass and stiffness parameters) can lead to higher gear noise."

Space allows for one last topic on gear noise—the shuttling force that occurs in helical gears. It's important.

"Shuttling force is the side-to-side

Manual transmission set-up at Ohio State University's gear research facility (courtesy OSU).

oscillation of the tooth mesh force along the profile as the tooth pair undergoes the engagement process," Lim explains. "This oscillating force can cause dynamic excitation to the gearbox system. Since it occurs also at the mesh frequency, it contributes to the gear noise response."

Adds Mark, "Because of the helix angle of helical gear teeth, there is an axial component of the force transmitted by the teeth. In the case of a single-helical gear, there will be a time variation to this axial force caused by different numbers of teeth coming into and out of contact. This time varying axial force causes a time-varying force on the thrust bearings, which is a source of vibration excitation. Increasing axial and transverse contact ratios will reduce this time-varying axial force. In the case of double helical gears, if the teeth are not staggered and are perfect (impossible), this axial force would be eliminated."

And from Houser, "As the diagonal lines of contact of helical gears sweep across the tooth, the centroid of the tooth force distribution shifts slightly with the sweep of the lines. When one applies simple statics to this situation, one finds that this simple shifting of the load by only a few microns can result in significant changes in the force at each bearing. These changes will be at mesh frequency, thus giving them the potential of generating mesh frequency noise. The forces due to shuttling are of the same order of magnitude of transmission error forces and are common in helical gears, but also exist in other gear types such as spiral bevel, hypoid and worm gears."

Got all that? Class dismissed.

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