Design for Silence: New Concepts and Techniques for Industrial Gears

Dr. Peter Flamang

Introduction

For a long time, relatively high noise levels have been generally accepted for industrial gear units in the 10–1000 kW power range. However, due to changing environmental awareness—both in and around industrial sites—customer expectations have moved drastically towards low noise as a key differentiating factor.

Gear drives, such as those used in cooling towers, water treatment plants and wind turbines, are frequently installed close to inhabited sites, and so low noise behavior has long been considered critical. More recently, however, noise is becoming a concern even in heavy industrial applications such as the large conveyor drives used in extraction and mining.

Not only are low noise expectations met in an increasing variety of applications, the accepted noise levels themselves are continuously decreasing. Severe low noise requirements in the past were met by using sound protection hoods over the installation, requiring extra expense, hampering installation and decreasing accessibility for maintenance and inspection. Customers' expectations have now often lowered acceptable noise levels down to the point where no protective hoods are needed, even for extreme applications.

The technologies available to meet these requirements have also changed, and so have the noise levels of state-of-the-art industrial gear units. Compared to the mid-eighties (VDI 2159, Ref. 5), the average noise levels of leading industrial gear products have decreased by 10 or more dBA. This is for standard drives without special-order modifications.

Design for Silence

In order to obtain these low values, a number of conditions have to be met. The literature describes the extensive research carried out in this field. In all cases, "accuracy under load" seems to be key in obtaining low noise behavior in gear units.

However easily defined, a lot of influences may counteract each other. The gear unit designer should meet the numerous requirements imposed by these influences in order to achieve the "total quality" of his design. Enabled by modern design and manufacturing technologies, a variety of measures can be taken. The challenge, therefore, has become making the right choices at the right time in the design process and carrying through with those choices in the manufacturing process.

"Design for silence" means that in order to meet today's low noise expectations, the designer has to make a series of consistent decisions, starting with the very concept, as exemplified in the following.

Accuracy Under Load

Manufacturing accuracy. Gear vibration, the root cause for generated noise, starts from the imperfect taking over of the contact between consecutive teeth. For example, this can be caused by a simple geometrical pitch error. The combination of pitch, lead and involute errors leads to transmission error, which can be measured on a single flank test machine (Refs. 1, 2, 3). Transmission error is defined as the difference between the real and the theoretical rotation of the gear when being driven by a uniform rotation of the pinion.

Aiming at lowest transmission error leads to excellent manufacturing accuracy of the gears. This is a primary condition for low noise behavior. For example, the limited curing effect of lapping on geometrical pitch errors can not sufficiently improve noise to meet today's requirements for industrial gear units (Ref. 1).

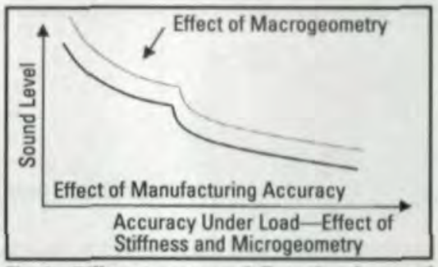

Fig. 1—Different measures influencing the sound level.

To achieve the required levels of accuracy in combination with the typical flexibility requirements in the manufacturing and logistics of industrial gear units, a first level decision is taken to grind all gears, both helical and bevel.

The manufacturing tolerances of the housings need to be in line with the high quality of the gears. In fact, a complete system of tolerances covering both the gears and the housing needs to be studied and implemented during the design phase of the new product. However, improving manufacturing quality can affect the noise level only up to a certain extent.

Dr. Peter Flamang

is the technical director of Hansen Transmissions International, a member of the Rexnord group of companies. He is responsible for gear technology in the group and has coordinated the development of a number of industrial gear products. He is a graduate of the University of Ghent, Belgium, where he obtained a Ph.D. in applied sciences. He also holds an MBA from the University of Antwerp.

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As described in the literature, Figure 1 shows that once manufacturing accuracy reaches a certain level, little or no further noise improvement can be obtained. This is due to the effect of load on the geometric accuracy of the gears. All of the components within the force flow deform under load. The gear teeth bend and the shaft deflects, as do the bearings and the gear unit's housing. It is clear that all of these act in a way similar to the geometric errors described above. In order to create the lowest possible transmission error, vibrations and noise, accuracy under load is the next consideration.

Stiffness is the key. In an ideal world, no deflection would exist. Obtaining the highest stiffness of all components in the power chain is, therefore, the closest thing a designer in the real world can aim for.

The typical construction used for standard, industrial gear units results from the need to easily machine the housing. In earlier days, this need led to the use of straight housing sides to support the shafts. As the dimensioning of the low-speed gear sets dictates the overall width of the unit, one of the disadvantages of the conventional design is that the narrower, high-speed gears are found on relatively long and flexible integral pinion shafts (A, Figure 2). Deflection under load will make optimization of these gear sets' noise behavior more difficult.

With the advantages offered by today's flexible machining centers, the housing sides can be designed and manufactured in such a way that the high-speed gears are supported by shorter bearing spans. This stepped housing is shown in Figure 3, and has additional advantages:

- Both the high-speed and intermediate-speed pinion shafts and gears can be standardized over all sizes where the same center distances are applied, irrespective of the number of stages in the respective units (Ref. 6). Note that integral pinion shafts, the key components of modern gear units, can not be truly standardized in a conventional gear unit. In Figure 2, the two intermediate pinion shafts B have different lengths in different housing sizes. In Figure 3 they are identical.

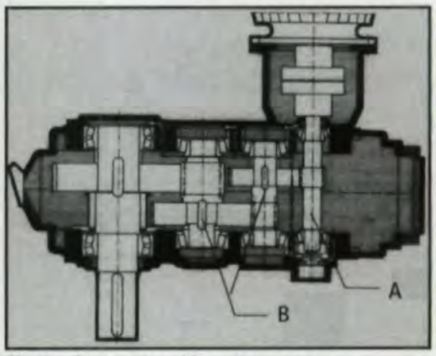

Fig. 2—Conventional housing concept.

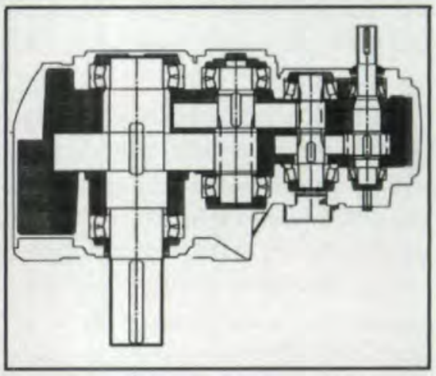

Fig. 3—Stepped housing concept.

- The standardized pinion shafts are those with the highest stiffness, as opposed to the more flexible, non-standard shafts, which need no longer be applied.
- Standardization allows cost-effective batch production of pinion shafts to the required manufacturing accuracies.
- Standardization allows the best optimization of corrections at the micro-geometry level in order to obtain the most uniform load distribution and lowest noise.
- The stepped housing design has an inherent stiffness that is beneficial to both the load contact pattern of the gears and to the sound emission behavior of the housing.
- Standardization works just as well for parallel as it does for right angle designs, which are even more critical in noise generation (Ref. 5).

Housing Design

Material. The use of cast iron for the housing offers significant advantages because the dampening qualities of cast iron are much greater than those of steel. The design flexibility of cast iron parts allows the designer to integrate the data and expertise gained from extensive studies such as those carried out by modal analysis of housing deformations and intensity analysis for minimal noise emission (Ref. 4).

Coping with external forces. External forces may deflect the housing and cause excessive noise and vibrations. The designer must consider these and minimize deflection, which distorts the contact patterns of the gears.

As an example, a finite element calculation can be used to limit deformations to the external side (mounting pad) of a gear unit, rather than distorting the internals of the housing.

Gear Geometry

Optimized macrogeometry. Referring back to Figures 2 and 3, it is clear that the presence of the shaft extension differentiates the high-speed integral pinion shafts from the intermediate-speed integral pinion shafts. Standardization between high- and intermediate-speed pinion shafts thus being impossible, the designer has a unique opportunity to optimize gear parameters such as module, face width, helix angle or contact ratio in different ways in order to meet different market needs. Indeed, the market needs for respectively high-speed and low-speed gear sets differ as follows:

- The low-speed gear set, being the largest gear set and therefore the highest cost factor in the gear unit, has to be designed for maximum torque in order to obtain the lowest cost for a given torque rating.
- The high-speed gear set, being the largest source of vibration and noise, needs to be optimized for lowest noise generation, because:
- For a given transmission error, the higher the rotational speed, the higher the generated vibrations.
- The human ear is less sensitive to very low frequencies, as reflected in the 'A' weighted spectrum. The most disturbing frequencies typically result from the mesh frequencies and harmonics of the higher speed gear sets.

The same applies *a fortiori* to bevel gear sets. These are always the high-speed gear sets in right angle gear units, and apart from the beneficial effect of being ground (Ref. 1), they also need to be optimized concerning low noise generation.

Microgeometry: the fourth level. State-of-the-art gears are corrected for deflections by profile and lead modifications. Sophisticated grinding techniques allow for the implementation of corrections, such as those calculated by Tooth Contact Analysis (TCA) software developed by Gleason or the Research Institute WZL-RWTH Aachen. However, as deflections are proportional with load, the applied modifications are optimal only for a given load situation.

Consider the straight tip relief correction as an example (Figure 4). This correction is the amount one has to take away from the mating gear tip in order to avoid interference with the driving pinion due to deformation under load.

The applied tip relief, however, is optimal for one load situation only. For other loads, the tip relief will be sub-optimal, resulting either in reduction of active profile or in tip interference.

Many gear units, however, are subject to a variety of loads. Figure 5 shows the amount of tip relief needed versus a given

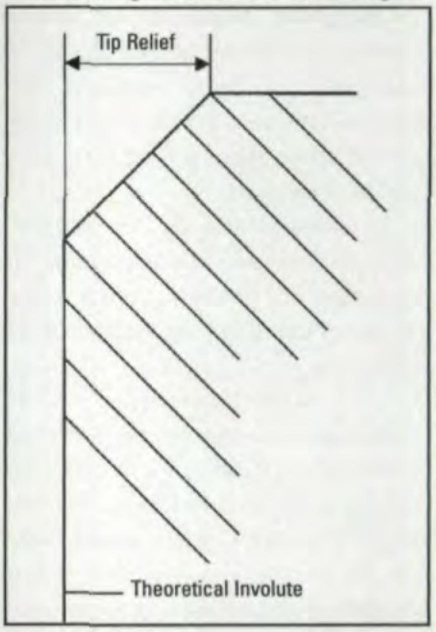

Fig. 4—Straight tip relief.

variation of load conditions for a certain high-stiffness design. This proves again how stiffness is key in the design:

- The level of corrections needed is lower. Consequently, there will be less reduction of active profile under low load conditions.
- For a given load spectrum, the mean deviation from the optimal correction is much lower.

Another approach to minimizing the effect of a load spectrum on the emitted sound is exemplified in Figure 7. By applying a modified tip relief geometry, which is enabled through the use of modern manufacturing equipment, the active profile gradually increases as the load increases. Therefore, the noise specifications can be maintained over a wider range of absorbed powers rather than only for the design power of the unit. The same principles are also applied for bevel gear sets, as exemplified in Reference 1, which discusses the measured noise behavior of a given gear unit over a variety of loads.

Results

Figure 7 shows sound power levels generated by a range of standard industrial gear units designed in line with the principles above. The sound levels, indicating

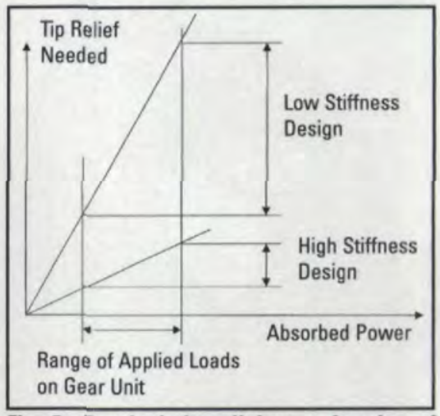

Fig. 5—Required tip relief as a function of absorbed power.

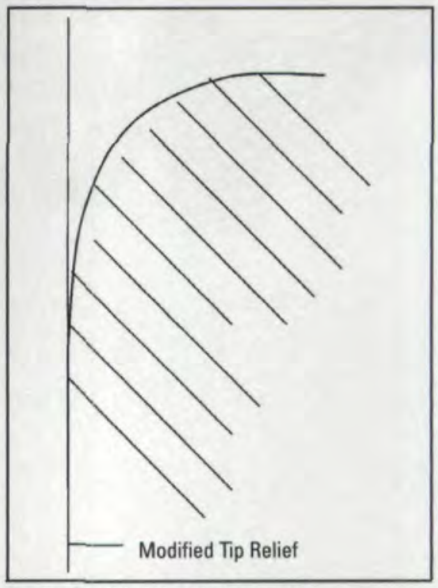

Fig. 6—Modified tip relief geometry.

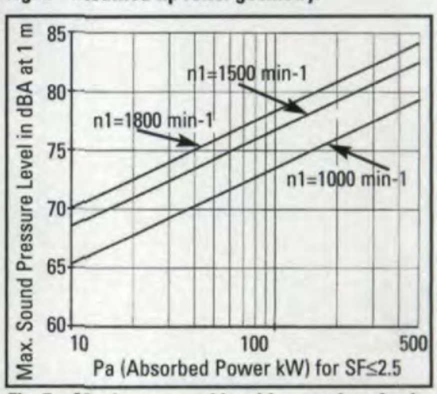

Fig. 7—Maximum sound level for a series of units designed according to the described strategy.

maximum rather than average values, are derived from a number of experiments on a variety of standard gear units, both parallel and right-angle, in a load range between 10 and 750 kW, without special modifications. The tests were carried out on in-house test benches, by means of intensity analysis. The horizontal axis on Figure 7 shows the absorbed power; the vertical axis shows the corresponding sound pressure level.

Conclusion

Low noise behavior in standard industrial gear units is becoming an important selection criterion for the customer, even in businesses that used to be considered "heavy industry." In addition, the accepted noise levels themselves are continuously decreasing. State-of-the-art machinery for manufacturing both housings and gears allows the designer to meet and even to exceed customer expectations. This presumes, however, that a number of careful and consistent design decisions are made from the very concept phase. The "Design for silence" strategy has been exemplified by describing this series of decisions as embedded in a range of standard industrial gear units. Results show the approach to be successful. ○

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