Topological Gearing Modifications: Optimization of Complex Systems Capable of Oscillation

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Vibration and noise from wind turbines can be significantly influenced—and therefore reduced—by selecting suitable gearing modifications. New options provided by manufacturers of machine tools and grinding machines, and especially state-of-the-art machines and controls, provide combined gearing modifications—or "topological gearing corrections"—that can now be reliably machined. Theoretical investigations of topological modifications are discussed here with the actual machining and their possible use.

Introduction

Regulations relating to noise emission of wind turbine systems are becoming increasingly stringent worldwide, especially close to residential areas. When generating electric power with offshore wind turbine systems, the excitation of vibration of towers and other wind turbine components plays a special role, and component manufacturers must also take this into account. Standard IEC 61400–11 (Ref. 1) also specifies noise levels that must be complied with.

For wind turbine systems equipped with a main gearbox used to convert torque and speed, vibration and noise are excited as a result of meshing gears under load in the gearbox. This vibration and noise can be significantly influenced—i.e. *reduced*—if suitable gearing modifications are selected.

Gearing Corrections

In practice, a significant differentiation has always been made between specific tooth width and tooth height modifications when modifying gearing (Fig. 2). Excluding the topological modifications, specific profile modifications are frequently orientated to the roll distance or the corresponding gearwheel diameters (Fig. 3), and they apply to each width coordinate of the gear wheel. Previously, many modifications involved a linear gradient; today, parabolic-shaped gradients are employed that enable a continuous-function transition. For helical gear wheels which, in principle, have slight advantages over gear wheels with straight teeth regarding noise, this type of separate modification also has disadvantages. This is because in the tooth meshing area—in particular segments—modifications are made that are actually not required. These unnecessarily increase the maximum pressure when meshing. However, this disadvantage can be resolved by applying specific topological modifications; at the tooth flank, the modified flank shapes shown in Figure 4 are derived from the standard shapes shown in Figure 3 as differences to the theoretical involutes.

The basic relationship between the profile angle modifications and the pressure gradient in the profile direction is shown

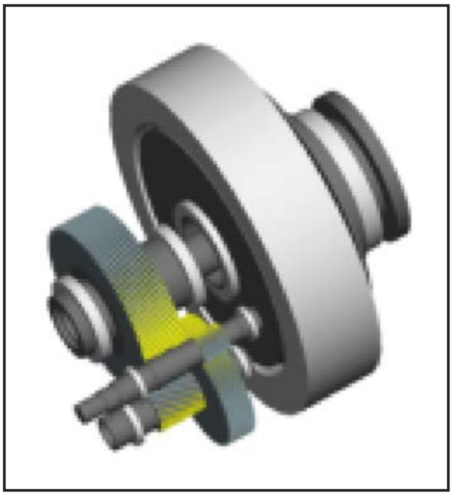

Figure 1 Principle design of a main gearbox for a 2 MW wind turbine (Ref. 2).

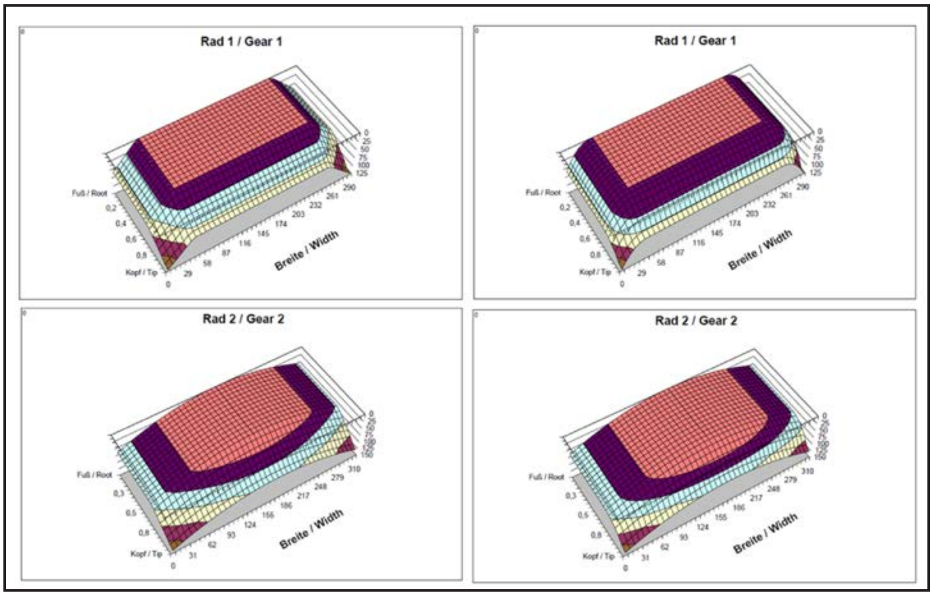

Figure 2 Gearing modifications (Ref. 9).

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(Fig. 5). If the exit impact is reduced by using the appropriate profile angle modification, the maximum pressure level is reduced. If the approach impact is reduced, noise excitation can be further reduced. However, the maximum pressure level is increased when compared to the version without profile angle modification. As a consequence, the profile angle modification must be variably defined over the tooth width.

Influence of the Modification in Tooth Meshing

As a result of new options provided by manufacturers of machine tools/grinding machines — and especially state-of-the-art machines and controls — freely defined gearing modifications can now be reliably machined. These can be applied more specifically to reduce the excitation of vibration and noise without necessarily having to have a negative impact on the load-carrying capacity.

In theory, a distinction can be made between the topological modifications possible in such a first and second generation. For the first generation the profile angle modification is specifically varied across the gearing width. For the second generation a variable modification gradient is incorporated in the tooth width and tooth height directions. For example: For the "Forschungsvereinigung Antriebstechnik (FVA)" Research Association for Drive Technology (FVA), in the form of modification versions known as "generated end/tip relief." For the first generation, in some instances, existing machines with expanded or new control systems can be used. However, this is not possible for the second generation; however 5-axis machines may be used for this purpose.

Two examples of possible variable profile angle modification gradients over the tooth width are shown (Fig. 6). For helical gearing the definitions at the left-hand and right-hand end of the tooth are decisive for influencing impact at both tooth approach and exit. Depending on the design, modified profile angle modification gradients over the tooth width can influence harmonics within specific limits. In principle, the first-generation profile angle modification according to Equation 1 comprises a constant component and a variable component over the tooth width with coordinate x_b.

The functional chain of the excitation effects in the gearbox is shown (Fig. 7), as is the associated formula (Equation 2). One can see that excitation from the meshing gear wheels can normally only be indirectly detected with measurements when the gearbox is operational.

$$C_H\alpha(x_b) = C_H\alpha_{,k} + C_H\alpha_{,v}(x_b) \tag{1}$$

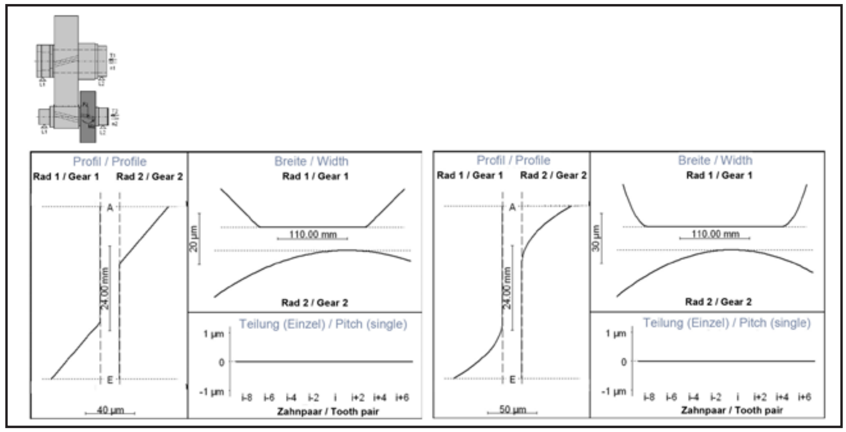

Figure 3 Gearing modifications, separately made in the tooth width and tooth height directions (Ref. 3).

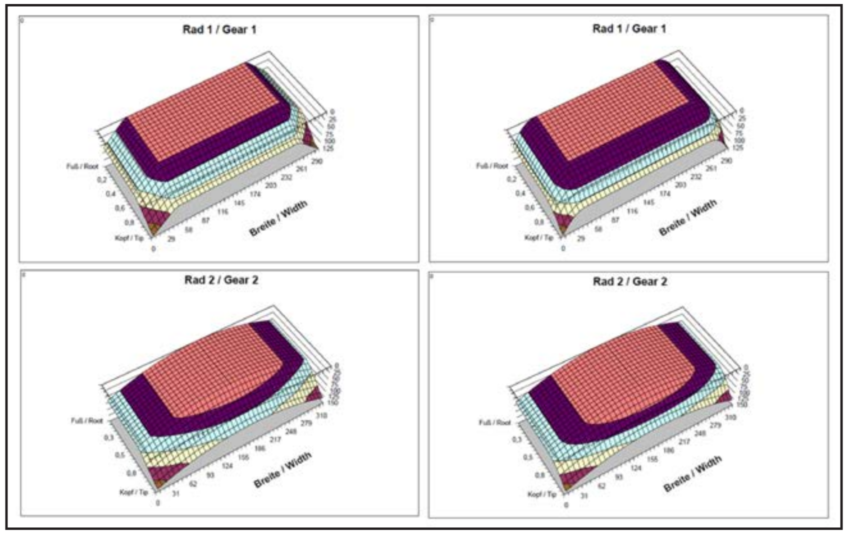

Figure 4 Gearing modifications when combining tooth width and tooth height modifications.

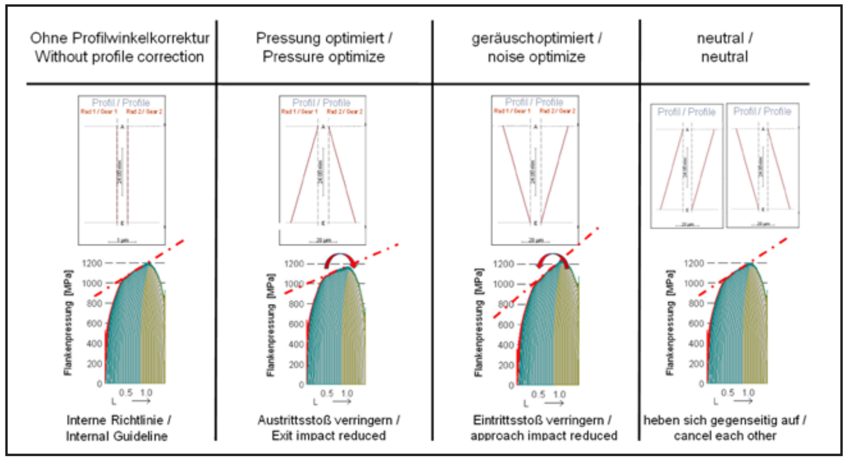

Figure 5 Principal correlation between profile angle modification and pressure gradient.

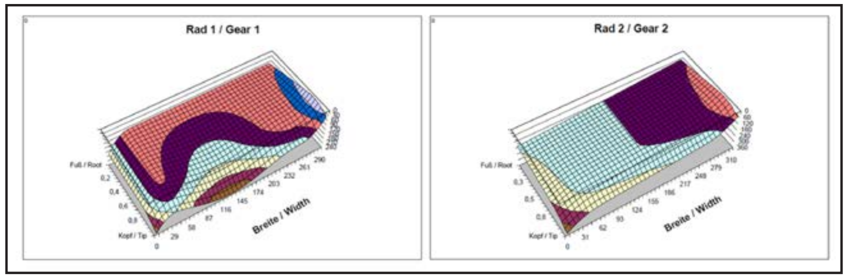

Figure 6 Examples of topological first generation gearing modifications.

$$L_W(f) = L_F(f) + L_h(f) + L_\sigma(f) \tag{2}$$

Gearbox Behavior on the Test Stand

Every wind turbine gearbox manufactured in our company is tested up to its rated load and rated speed. The gearboxes are driven along a ramp-up curve, which is then evaluated to identify possible resonance points and excessive excitation levels. The evaluation of the vibration measurement is shown (Fig. 8) and it also includes the effects of excitation generated as a result of gear wheels meshing. The measured values can be allocated to the sources of excitation based on the gear meshing frequencies.

Figure 9 documents actual examples for reduced excitation levels that have been achieved by optimizing the profile modification when excited with the gear meshing frequencies f_{zE}. From Figure 9 — in conjunction with the principle from Columns 2 and 3 from Figure 5 — it can be concluded that it makes sense to relieve the approach impact at the beginning and to relieve the exit impact at the end of a meshing operation. Following the principle from Figure 6 and Equation 1, this is illustrated by the example in Figure 10, in which the constant component is set to zero. This type of modification allows the excitation to be specifically reduced and, at the same time, uses other areas to increase the load-carrying capacity by reducing the maximum pressure in the meshing area.

When making the design, possible deviations as a result of statistically defined deviation levels for the tooth trace can be taken into consideration. In so doing, the various combinations should be checked with plus and minus ($+f_{ma,ß}$, $-f_{ma,ß}$, $+f_{ma}α$, $-f_{ma}α$). In addition to optimizing the rotation path, the speed-dependent excitation level should also be observed when designing the gearbox.

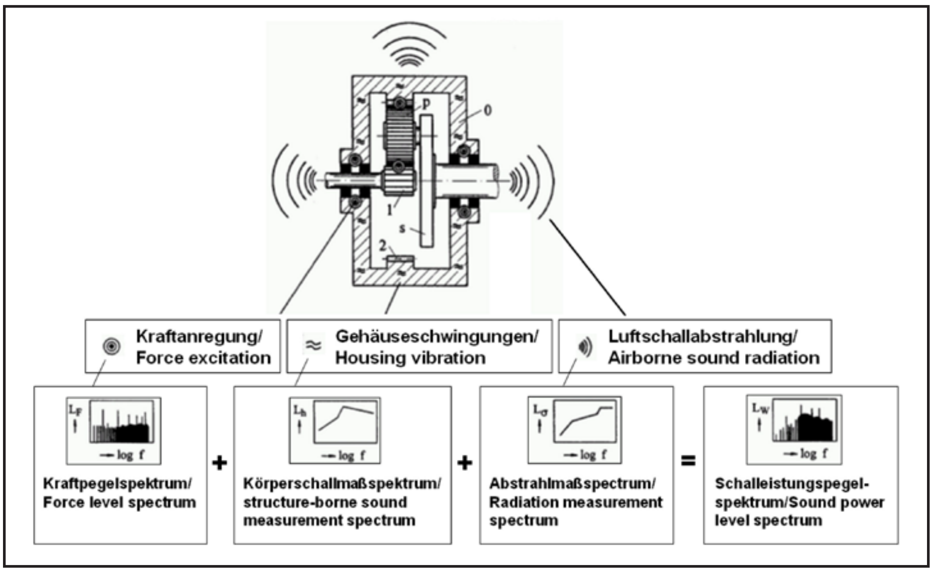

Figure 7 Functional sound transmission chain for a planetary gearbox with continuous estimated curves for L_h and L_σ (Ref. 10).

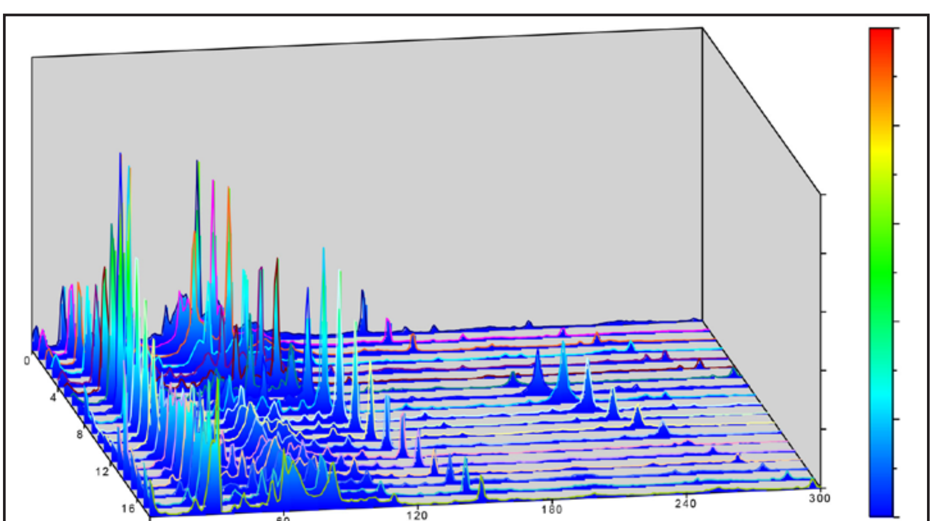

Figure 8 Vibration measurements when ramping up speed.

Manufacturing Prototype Parts

When machining the tooth flanks, deviations are obtained with respect to the theoretically required topology. The differences between the left and right tooth flank topologies of a gear wheel used as example can be identified in Figure 11. The highest deviations with respect to the theoretical topology are at the sides; the differences for the pinion can be taken from Figure 12. For the pinion it can be seen that the left-hand and right-hand flanks are almost identical.

The deviations from the theoretical specification and between the left-hand and right-hand edges are predominantly defined in production by the magnitude of the modification specified. If, for instance, only the pinion is to be modified, then for larger modification, correspondingly higher deviations are obtained. Whether these deviations can be tolerated can be determined when checking the rotation path.

Summary and Outlook

For gearing modifications, a very significant differentiation has always been made in practice between tooth width and tooth height modifications.

- As a result of new options available to manufacturers, topological gearing modifications can be established reliably during the production process — and can be specifically used to reduce vibration and noise excitation sources.
- Using first-generation, topological gearing modifications as examples, it has been shown that it is possible to reduce the approach and exit impact levels without losing load-carrying capacity.
- The deviations in production with respect to the theoretically designed modification topology depend on production technique.
- As a consequence, it also makes sense to take production technique into account when designing and checking gearing modifications.

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Daniel Lütfrenk is an authority in mechatronics, receiving in 2010 his bachelor's degree at the University of Applied Sciences, Gelsenkrichen, and his master's at Westphalian University of Applied Sciences in 2012—both degrees concentrating on mechatronics. From 2006 until 2010 he apprenticed as a draftsman in the engineering department at Winergy AG and Siemens AG, respectively, before becoming in 2010 a calculation engineer in the engineering/technology department at Winergy AG. He assumed his current position—project engineer for FLUDEX couplings, at Siemens AG—in 2012.

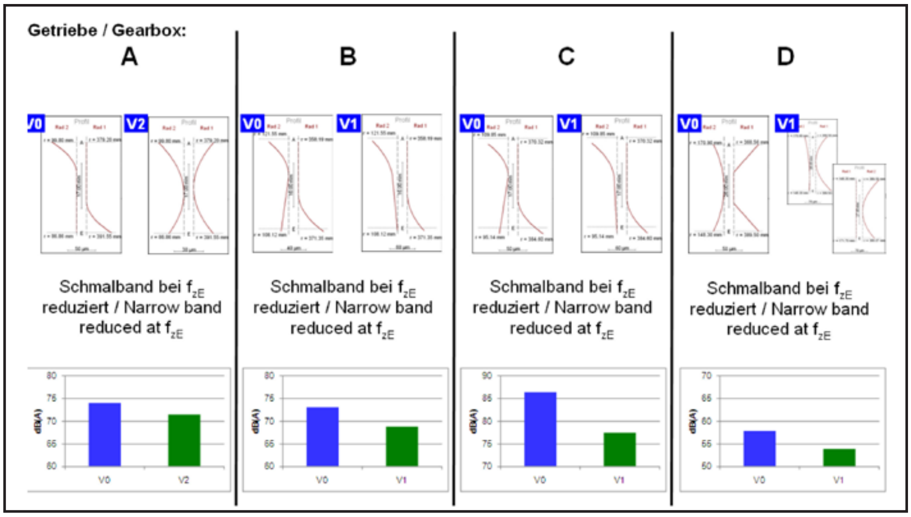

Figure 9 Real examples for specifically reducing excitation by adapting the profile modifications a) pinion; b) wheel.

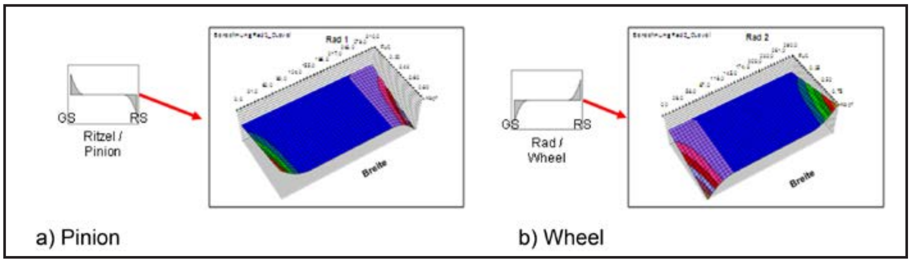

Figure 10 Gear wheel flanks with varying profile angle over the tooth width.

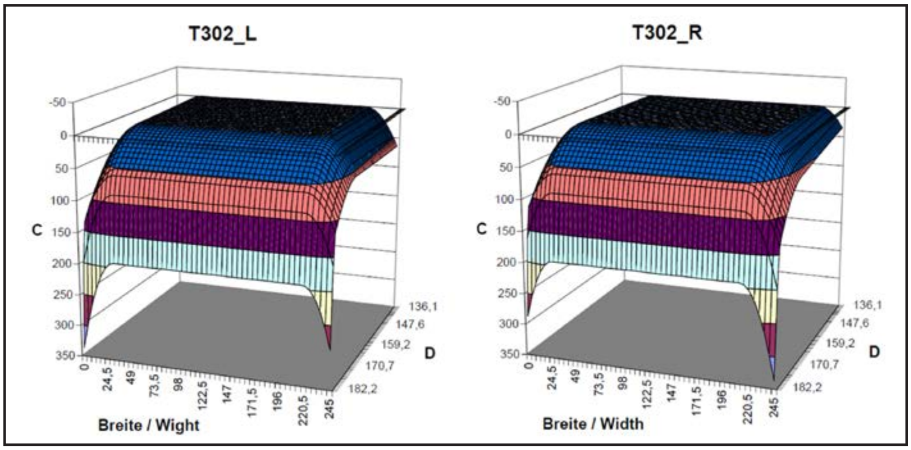

Figure 11 Topology of the production simulation of the left-hand and right-hand gear wheel flanks.

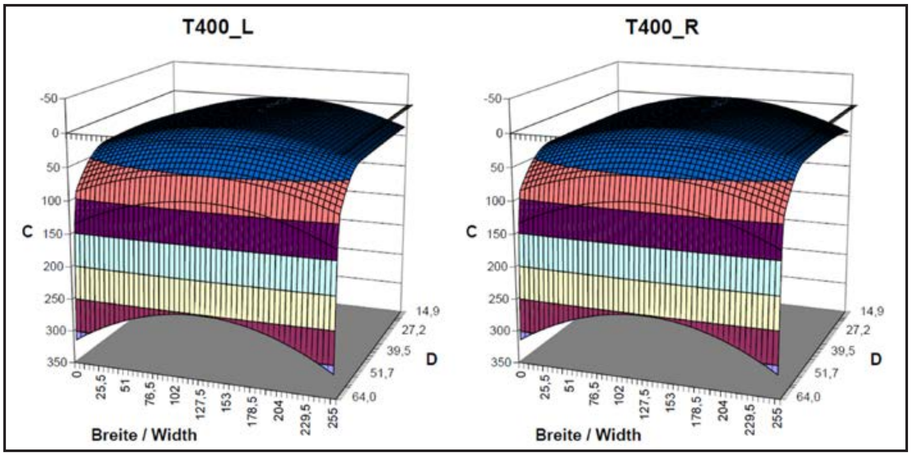

Figure 12 Topology of the production simulation of the left-hand and right-hand pinion flanks.