The Alignment of High Speed Gears

Kevan Whittle

Synopsis

This paper reviews the necessity for detailed specification, design and manufacture to achieve required performance in service. The precise definition of duty rating and a thorough understanding of the environmental conditions, whether it is in a marine or industrial application, is required to predict reliable performance of a gearbox through its service life. A case study relating to complex marine gears and other general practice is presented to review the techniques used by Allen Gears to design and develop a gearbox that integrates with the requirements of the whole machinery installation. Allen Gears has considerable experience in the design of a variety of industrial and marine gears (Ref. 1, 2). The requirements of different types of installations are reviewed to study the implications on gear alignment. Particular types of gearboxes have been developed in recent years to achieve more accurate alignment while also reducing the size and cost of a drive system.

Photo 1—Fast patrol boat for Royal Navy of Norway.

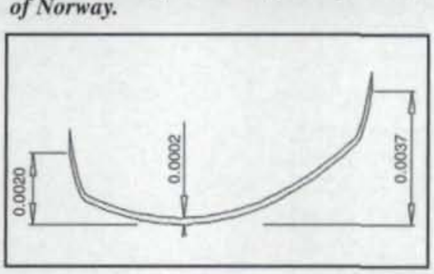

Figure 1—An overlay chart and the level of accuracy required from the form gear grinder.

Introduction

The design of gearboxes for marine and industrial applications requires exhaustive techniques to assure the mechanical integrity of rotating shafts and bearings for transmitting the duty power. The same magnitude of resources is now applied to understanding structural displacements and the consequent effect on gear mesh misalignment and stress overload factors.

Project design activity has increased to allow more detailed understanding of how the gearbox performance is affected by the supporting and connecting equipment and the applied external loading. Modern analysis techniques allow for very detailed modeling of the gearbox and propulsion system by including all relevant equipment from the gas turbine to the water jet using finite element analysis. FEA models give displacements of all gearbox flanges and bearing support blocks, as well as stress distribution and system natural frequencies. This information is an advantage to the gear designer because of the increased understanding of various factors internal and external to the gearbox that can influence gear alignment. Confidence that the gear will operate satisfactorily at the rated power for the required life reduces risk for the gear manufacturer and the end user.

Gearboxes for High Speed Craft

The experience of marine gearing within the author's company in recent years has been related to high-speed, light craft for a variety of applications, including naval patrol boats and high-speed, luxury yachts. Gearboxes for high-speed patrol boats in monohull, surface effect ship and hovercraft have been designed by Allen Gears for combinations of gas turbines (Rolls-Royce Allison, Pratt & Whitney and General Electric Co.), diesel engines and hydraulic motors driving water jets or propellers for main propulsion. Installations have used gas turbines with rated powers up to 10,000 kW and input speeds up to 16,000 rpm, with vessel speeds up to 60–70 knots.

The general configurations of gearbox design have included CODOG (COmbined Diesel Or Gas turbine) and single-input, single-output in "c" or "z" layouts. Recent gearbox designs have been carried out to satisfy the requirements of Det Norske Veritas (DNV) rules for high speed, light craft. DNV is an organization that produces rules for design of equipment, including ship propulsion systems.

The gear teeth are rated in accordance with DNV Calculation Note 41.2 (generally based on the requirements of ISO 6336). The design rules extend to the mechanical strength at full-load torque, shock loading, fatigue loading due to water jet aeration and the assessment of gear alignment in the extremes of operation. The classification rules give nominal magnitudes of shock for a specific duration for passenger, cargo or patrol-and-rescue craft, the highest being 69 m.s-2, or an acceleration of 60 m/s/s, for a duration of 0.050 seconds. This shock level is attributed to vertical slamming relative to the type of vessel in sea conditions.

Loading on the propulsion system can also include vertical, transverse and longitudinal accelerations for a particular number of cycles as deemed appropriate to the design of a vessel.

Gear Design and Alignment

Naval marine gearboxes are generally designed to be lightweight while having onerous requirements for optimizing tooth loading and gear alignment. It is not proposed to give extensive details of the design of such a gearbox, but to give an overview and discuss areas that influence gear tooth alignment.

A general configuration uses an aluminium-fabricated gearcase with horizontal and vertical joints to allow for ease of separation and support lines of gas turbine input, intermediate shafts, diesel input and water jet output shafts. The gearshafts can be supported by a combination of rolling element and hydrodynamic bearings, both of which can be designed to provide a means of adjusting gear alignment. The CODOG gearboxes have automatic changeover from gas turbine to diesel drive, which is achieved by self-synchronizing clutches and a multiplate clutch with two-stage pressure engagement (Ref. 3). The gearboxes designed for these applications generally have integral lubricating oil systems and become complex with the extent of pipework, pumping, cooling and control hardware to satisfy space restrictions.

Gear elements are designed and manufactured in either case-carburized or gas-nitrided steels for the primary and secondary reduction-gear meshes. A review of a particular gearbox is provided later where the gears have been designed to DNV rules, and a number of specific observations will be presented relating to this process. Rating of the gear teeth to DNV complies with limits that Allen Gears have historically specified in terms of surface load and specific bending, but with some exceptions. The main differences observed using DNV is in the scuffing capacity and the requirement for a greater effective case depth (at 400 HV) than would be required when rating a nitrided gear to other rules.

As is common with all manufacturers of high-speed and loaded gears, the pre-

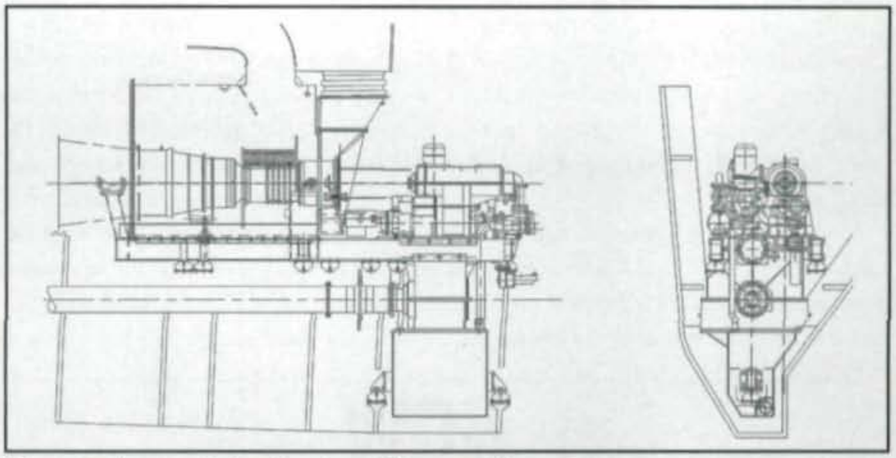

Figure 2—A general elevation view of the propulsion system.

dictions of structural displacements are used in the design of gear tooth grinding reliefs. As stated, the magnitude of distortions can be predicted by finite element modeling of the gearcase assembly, with loads applied to represent the full range of operating conditions. The predicted movements of gear-shaft bearing housings can be directly related to gear alignment, and helix-angle corrections can be calculated.

The finite element analysis of the gearbox and support system is carried out for a number of combinations of the loading conditions. At one end of the range would be self-weight plus transmitted torque, while at the other end would be these two cases plus all the maximum sea conditions, including slamming. This ensures the gearcase and support system are subjected to the range of loading likely to be experienced under service conditions.

From each of the loading cases, the gearcase deflections at all of the bearing positions are extracted from the finite element results. From these deflections, the slope of each shaft line along the line of action of each gear mesh is established. These slope values indicate the misalignment due to loading of each mesh within the gearbox. Without helix modification to the gear teeth, these misalignments will cause high overloads at the ends of the teeth and hence premature failure in these areas.

In order to reduce these high overloads, two forms of longitudinal correction are applied to the teeth at each mesh in the gearbox. One is a fixed change of helix angle, "torsional correction," to take account of the fixed amount of misalignment occurring in the same direction for all loading cases. The second correction is crowning, which will take account of those misalignments that can cause tooth overloads at either end of the face width.

Once these longitudinal corrections have been established, they are combined with any end relief and used to calculate a set of coordinate values that are suitable for input to the computer-controlled form gear grinder. This ensures minimal deviation from the design intent to that manufactured and removes an element of possible influence on gear alignment. An example of the overlay chart and the accuracy required is shown in

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is chief engineer at Allen Gears, within the industrial business section of Rolls-Royce, managing the product design and development of low and high speed gearboxes for industrial and marine applications. Whittle is a chartered mechanical engineer trained with Eaton Ltd.'s transmission division. He later worked for Vickers Shipbuilding and Engineering as a design engineer on submarine main propulsion gearing, performing design studies and supporting gearboxes on test and in service with the Royal Navy.

Figure 1. The capability of the form grinding machine tool gives the greatest possible control to minimize manufacturing errors, with a process capable of machine-grinding to master gear quality and helix alignment of around 0.005 mm.

General industrial gears are manufactured to ISO 1328 Grade 4 with machine adjustments being made to keep profile and helix errors within specified tolerances. Allen gears are manufactured to ISO 1328 Grade 4 (AGMA Grade 12).

The alignment of the teeth is set by initially meshing the gear elements in the gear case while supported by accurately machined low-clearance bearings and then grinding the gear teeth to have conforming helix angles. This sets the static gear alignment and corrects for any errors resulting from the manufacture of the gears, case and bearings.

Static alignment is verified by rotating the gears slowly and visually observing the contact pattern between the meshing teeth. Proof of the mesh is obtained by witnessing the contact markings resulting from blue lacquer transferred from pinion to wheel, the thickness of lacquer being around 0.003 mm.

The gear tooth reliefs are subsequently applied and include end relief, helix-angle correction, and crowning. A static misalignment is consequently introduced in the gear mesh but ensures that, when operating at full power, the teeth will be aligned and within design limits.

Mounting System and FEA Model

The drive configuration and model is of a gearbox, gas turbine, gas turbine enclosure, support frame and resilient shock mounts. The model of the propulsion package included the connections between the support frame and the hull mounting points, which spanned some four separate lateral bulkhead structures manufactured from a sandwich composite material. A sandwich composite consists of two glass-reinforced plastic (GRP) plates with a compound "sandwiched" in between. Detailed finite element modeling of the system would prove the integrity of the propulsion system under severe load conditions expected at sea. A general elevation view of the machinery is shown in Figure 2.

A model can be created using, for example, version 5.3 of the ANSYS suite of software. Elastic straight pipe elements and 3-D beam elements are combined to create the gearcase, or the structure that holds the gears and bearings in place, as well as to develop shafts and system connections. To correctly model the total mass at a particular center of gravity, structural mass elements are used. The gearbox and gas turbine are bolted to the mounting frame while a flexible coupling connects the two assemblies. In the model, the gearbox and gas turbine are rigidly connected to a support frame by a system of constraint equations, the frame being a combination of four- and eight-node shell elements. It is considered that, to get the best indication of final gear alignment, the total system must be modeled and therefore includes the ship's hull, which was represented by beam elements with three translational and three rotational degrees of freedom, values of which were supplied by the naval architects. An isometric view of the model is shown in Figure 3.

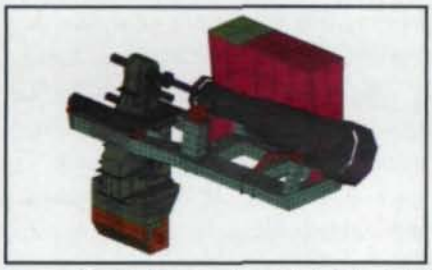

Figure 3—An isometric model of the total propulsion system using version 5.3 of the ANSYS software suite.

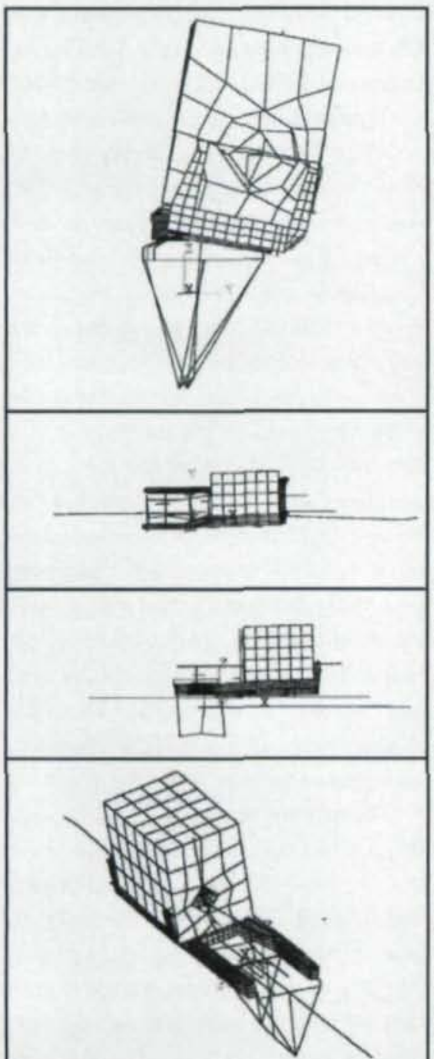

Figure 4—Model analysis of integrated gas turbine propulsion system.

Modeling work was conducted in parallel with the gearbox detail design activity and provided detailed requirements for methods of supporting the gearcase to achieve the necessary alignment of the gear to the gas turbine. The support of the propulsion unit was through 16 rubber mounts, which were modeled as unidirectional nonlinear spring elements to reproduce the force deflection curves specified. The resilient mount elements had a range of stiffness and dynamic magnifiers to allow the support frame to deflect in a controlled manner.

Analysis of the propulsion system model gave the following outputs:

a) dynamic behavior of the assembly to allow correct positioning of support structures, shown in Figure 4;

b) stresses and deflections of the gearcase at the gear-element bearing supports;

c) angular misalignment of shaft couplings;

d) natural frequencies of the propulsion package; and

e) maximum displacements of the assembly under shock loading.

This extensive analysis work allows the gear designer to gain detailed specifications on conditions of operation and provides data on the worst possible operating mode for the gear tooth alignment. This provides the means to optimize the gearcase design and stiffness and to minimize weight.

DNV Rating

Allen Gears has a long history of designing and rating gear teeth to a range of international standards, including AGMA 2001, American Petroleum Industries (API) 613, Lloyd's Rules, which involves the design of gearboxes for industrial machinery, and more recently DNV Classification Note 41.2 (Ref. 4). Most of the above calculations are performed using in-house computerized Fortran routines and are interactive programs that allow the user to evaluate various design options rather than simply rate a gear pair. The programs allow designers to have a baseline gear pair automatically selected based on a particular input power, speed, ratio, etc. Also, the programs give options to change any feature and have remaining features recalculated instantly. The programs calculate the gear service factors and data to define the salient points of the gearbox design that are suitable for supplying to a customer and to create manufacturing drawings.

DNV rating of gear teeth allows for finite and infinite life assessments of a gear pair for one or more load cases and gives service factors for contact, bending and scuffing resistance. As previously discussed, there are a number of points that are worthy of further discussion, including calculation of case depth "size factor" for nitrided gears. Scuffing assessments for flash and bulk temperatures' tooth overload factors, which relates to the prediction of scuffing between two meshing gears also should be looked into further.

The size factor Zx is particularly onerous for the rating of nitrided gears. Nitrided gear tooth permissible stresses can be reduced by approximately 40%

when

$$Zx = \left(\frac{30t_{400}}{\rho_c} \right)^{0.4} \frac{1200}{\sigma H \lim}$$

Suitable materials exist that produce a case depth versus hardness curve that minimizes the effect of this penalty to around 30%. However, it is not Allen Gears' experience that nitrided gears have such a poor surface fatigue strength.

Comparisons of the actual case depth profile for a 3% chromium-molybdenum nitriding steel and a 1.4% chrome-molybdenum-vanadium steel is shown in Figure 5 to demonstrate the increased depth achieved at 0.7 mm at 400 HV. Under most circumstances, the designer would endeavor to choose carburizing steels where the case depths achieved easily produce a factor $Zx = 1$. This does, however, introduce limitations on the construction of large gear wheels and compromise the objective of lightweight construction.

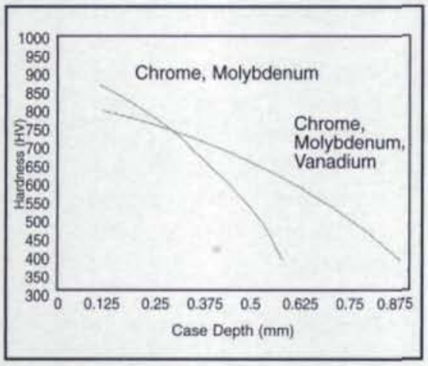

Figure 5—The difference between actual case depth profile for a 3% chromium-molybdenum nitriding steel and a 1.4% chrome-molybdenum-vanadium steel.

Scuffing assessment to DNV consists of integral and flash temperature calculations. To achieve satisfactory safety margins, the specified oil load carrying capacity must be around FZG 12. To stop asperity contact, the oils must provide a film thickness between two gear flanks.

Oils with a low load capacity are likely to suffer from pitting and scuffing. With mineral oils having a viscosity grade of ISO VG 32 or 46, it becomes difficult to procure oils with the required FZG capacity. Allen Gears have specific rules on allowable flash temperatures and have had virtually no failures through scuffing. The requirements of DNV are onerous and make Allen Gears' current limits and practice unacceptable.

Alignment of Industrial Gearboxes

Alignment of gear teeth and the resulting overloads across the gear face widths in parallel shaft gears is controlled by the structural integrity. Loading on input and output shaft bearings is influenced by the stiffness and alignment capability of the connecting shafts and couplings, and the modeling work carried out on marine gears is vital to verify the integrity of the high speed couplings and also to prevent limits being exceeded on the connecting equipment's shaft bearings. The particular case study discussed in this paper used a membrane coupling with a length of 870 mm and had finite limits on axial, lateral and angular misalignment. The FEA model confirmed that these would not be exceeded in service.

The requirement to accurately align the gearbox to connecting equipment is key to satisfying gear tooth alignment and is more critical on some epicyclic gear products depending on coupling design features. The general configuration of a single-reduction star arrangement is shown in Figure 6. The gear cluster can be configured into a range of gearcases to provide free-standing,

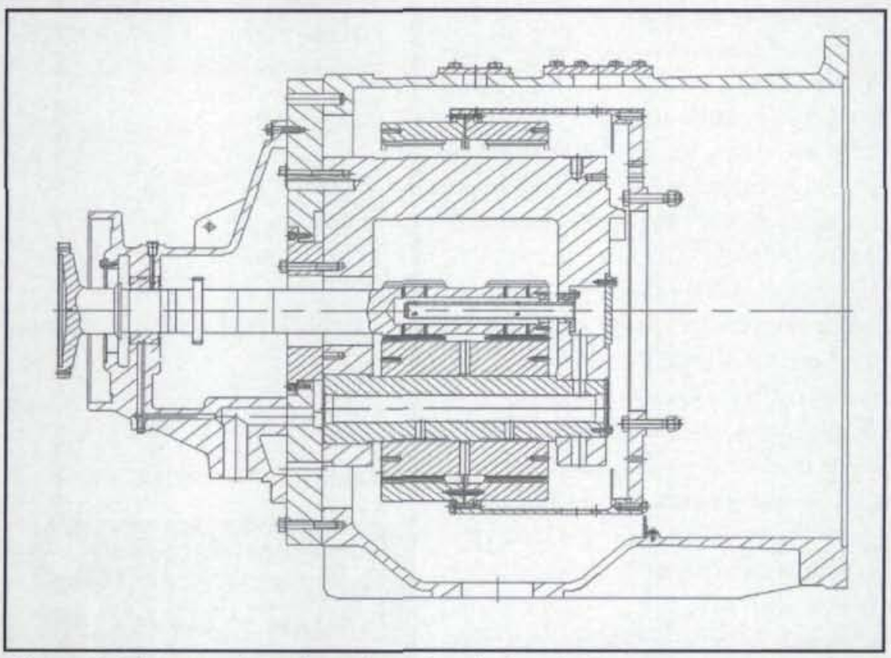

Figure 6—The general configuration of a single-reduction star arrangement in an epicyclic gear product.

engine-mounted or generator-mounted arrangements.

Figure 6 shows the generator-mounted gearbox where alignment of the gears is obtained by accurately locating the gear onto the driven (generator) shaft. This provides benefits in the package efficiency where there are no low-speed shaft bearings and benefits by reducing the gearbox length, cost and weight. Alignment of the input and output shafts is critical to control misalignment of the gear teeth and is achieved by accurate machining, assembly and measurement during the installation procedure. Any errors in alignment of the gearcase when attached to the generator will transfer through to the high-speed shaft via the gear mesh.

Accurate high-speed shaft alignment was traditionally achieved by manual methods using dial indicators, and the process could take approximately 24 hours. Indications would be that the equipment was in alignment, but the setting was carried out with a gearbox having no installed gears or bearings. The dial clock was fitted to the driven (output) equipment shaft and then checked to the gearcase driver (input) end and adjustments made. Consequently, when the gears were fitted, an alignment error was introduced due to the additional overhung mass.

Current techniques allow the equipment to be aligned in eight hours using electronic methods. Displacement probes can be fitted to the fully assembled gearbox. The gearbox is then driven, with outputs from the probes being processed by a personal computer to calculate misalignment and any necessary adjustments.

The customer support team within Allen Gears is regularly involved in the installation of gears and have a direct contribution to gearboxes in a variety of applications, from large water turbines to small high-gas turbines. In marine propulsion, the technology for aligning parallel-shaft gears and couplings has advanced in recent years with the use of laser alignment, which is accurate to 0.002 mm across distances of 5 m.

Concluding Remarks

Complex gearcases and shaft arrangements can now be designed and analyzed using FEA techniques to gain greater assurances on the safe performance of the system under load. Industrial gearboxes tend to be designed around a general type of configuration where structural integrity is known and is easily predicted. Also, the designs have evolved in recent years to allow for easier installation, and equipment/methods have also changed to improve the accuracy of the installation.

Calculations and predictions of alignment are critical to the validation of a gear design, and access to information on structural stiffness is key to determining the magnitude of the face overload factor and is easily extracted from an FEA model. Customers are demanding this level of analysis to lower the risk associated with main propulsion gearboxes.

The rating of gear teeth to DNV marine requirements can, in some circumstances, result in a larger gear pair than would be required to satisfy other standards. Current work within the British Gear Association involves researching the technology required to enhance material and lubrication technology to enable the optimum design to be obtained and to address this problem. ○

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