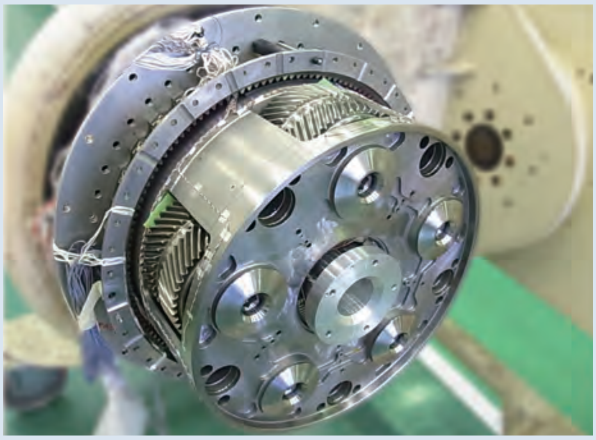
Advancement of Aircraft Gear Box Design Technology



It is necessary to reduce the weight and enhance the reliability and efficiency of aircraft gear boxes to satisfy recent severe demands for improving the aircraft's fuel efficiency and reliability. We have developed and manufactured a variety of aircraft gear box products and developed world-leading design technologies through analysis and simulation leveraging CAE technology.

Introduction

Amid the issues of global warming and fuel price hikes, the aircraft industry is facing more and more intense demands for increase in fuel efficiency, reduction in greenhouse gas emissions, and enhanced reliability. In addition, the number of flights is increasing in line with passenger growth, as is maritime transportation by helicopters mainly to oil rigs in the ocean, which is raising demand for safety improvements.

1 Background

The market for aircraft is anticipated to steadily grow also in the future. Not only will aircraft gear box products for them need to be more lightweight, reliable, and efficient, but competitively priced new models will have to be put to market as quickly as possible. This situation requires short-term and low-cost product development.

2 Design problems with aircraft gear boxes

We are the world's leading aircraft gear box manufacturer that conducts development, manufacture, repair, and overhaul of various products as shown in **Fig. 1**: the transmission for helicopters such as BK117, the accessory gear box for aircraft engines, and the constant-frequency power generator for aircraft (T-IDG), which is based on the mechanism of traction drive CVT (continuously variable transmission). Recently, there has been progress in the development of aircraft geared engines[1], such as geared turbofans, that operate fans via gears. We are also developing gear boxes for these engines.

Our aircraft gear boxes have been designed based on past achievements and experience. We based designs on repeated prototype test results, design changes, and retests until a final design emerged. This trial-and-error method took a long time and was expensive. However, gear box products for the next-generation aircraft need to be developed faster and at lower cost than ever before. They must also be lighter, more reliable, and more efficient, as well as being safer. In this light, we have needed to develop an efficient design method that meets customers' requirements in as little time as possible.

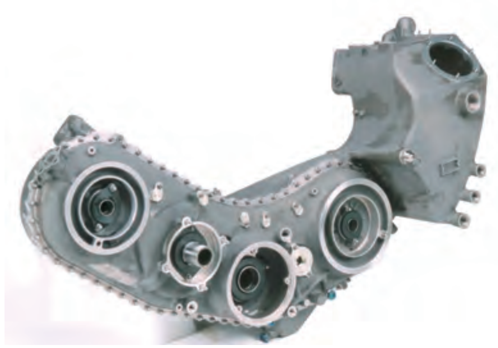
3 Efficient design method using CAE technology

To solve these problems, we developed a new design method that combines knowledge from past achievements and experience and simulation analysis that uses the latest CAE technology, and verified this method with tests. This method estimates the deformation and temperature of each component when creating designs to improve reliability, as well as predict the amount of loss to increase efficiency.

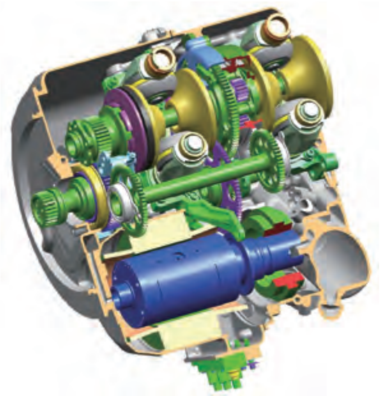
(1) Reducing misalignment by analyzing gear box deformation

Misalignment occurs due to deformation of components to

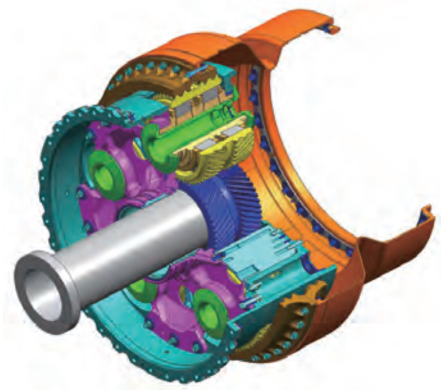
(a) Transmission for BK117



(b) Accessory gear box for aircraft engines



(c) T-IDG



(d) Gear box for geared engines

Fig. 1 Representative KHI aircraft gear box

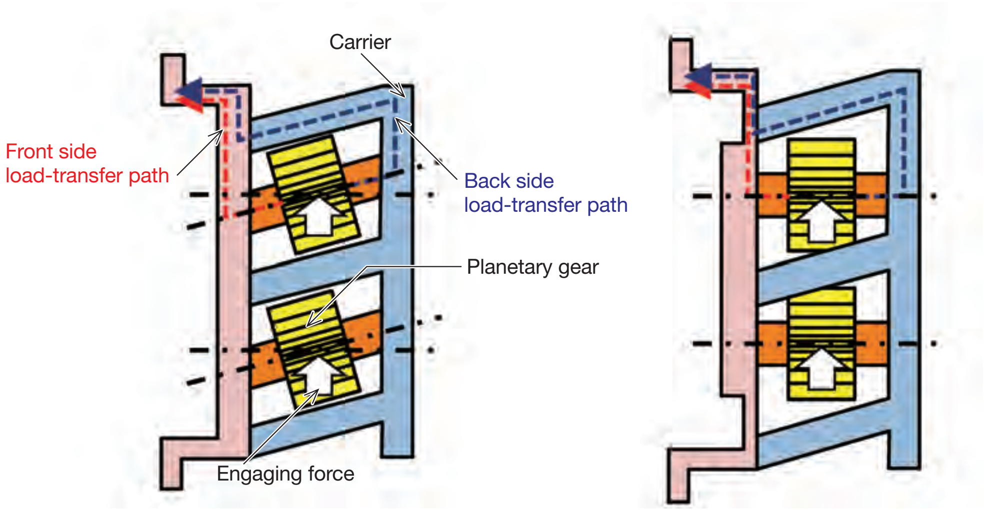
which a load is applied, resulting in non-uniform contact on gear teeth and bearing contact surfaces, reducing gear box reliability. Improving gear box reliability required reducing the misalignment. Although increasing the stiffness of a component by increasing its thickness can suppress deformation, it also increases weight. To solve this problem, we have developed a design method[2] that reduces the misalignment and reduces the weight at the same time by calculating the deformation of each component using a finite-element FEM analysis and adjusting the stiffness of each component.

As **Fig. 2(a)** shows, under the conventional design of a planetary gear system, there are differences in stiffness between the front and back sides of the load-transfer path by torque. This causes the carrier to experience torsional deformation that results planetary gear axis to tilt. In contrast, as shown in **Fig. 2(b)**, the newly developed stiffness optimization design optimizes the stiffness of the load-transfer path to suppress the tilt of the planetary gear axis.

Figure 3 shows the results of the deformation analysis on the misalignment-reducing design. The initial configuration had a front plate with high stiffness, and applying a load caused a large tilt of the planetary gear axis. The optimal configuration, however, has a uniform stiffness both at the front and back sides of the load-transfer path, which achieves reduction in the tilt of the planetary gear axis and a lightweight gear system. We built a practical-sized test unit using this design method to carry out an endurance test simulating practical operational conditions. The results of the teardown inspection after the endurance test revealed that the main structural components, gear teeth surfaces, and bearings were all in a sound condition, which demonstrated the effectiveness of this design method[3].

(2) Optimization of tooth contact taking into account deformation of components

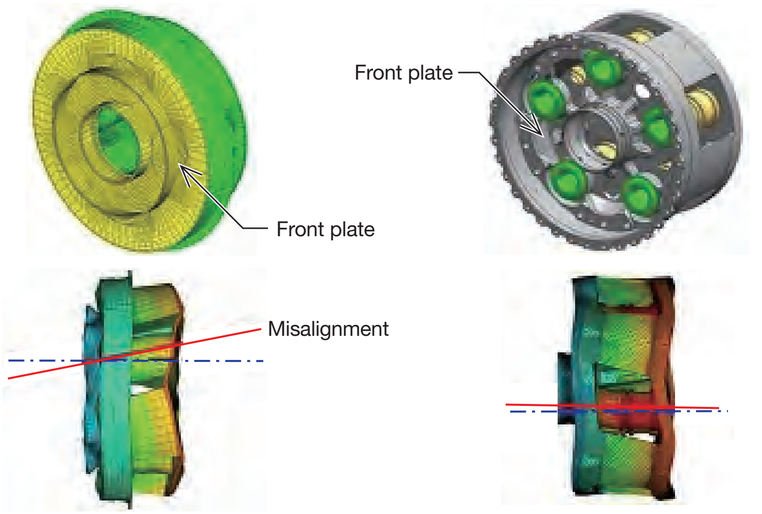
To make the high-reliability bevel gears used in aircraft gear boxes, the contact of the tooth surface (tooth contact



(a) Conventional design

(b) Optimally designed stiffness

Fig. 2 Design of planetary gear system



(a) Initial shape

(b) Optimally designed shape

Fig. 3 Misalignment reduction through deformation analysis

pattern and contact stress distribution) that transfers power under various load conditions during operation needs to be optimal. Tooth contact is greatly affected by the deformation of gears and supporting components caused by loads. To reduce deformation, it would be necessary to increase the stiffness of each component; however, that would mean increasing the weight of each component. Therefore, it took a long time to design the best tooth contact that allows lightweight and reliable gears. To carry out quick and low-cost designs for lightweight gears with reduced deformation, we developed a gear tooth surface design method that estimates load-caused deformation of each component and predicts the tooth contact condition by simulation.

Figure 4 outlines the developed design method that optimizes tooth contact conditions. In this method, first,

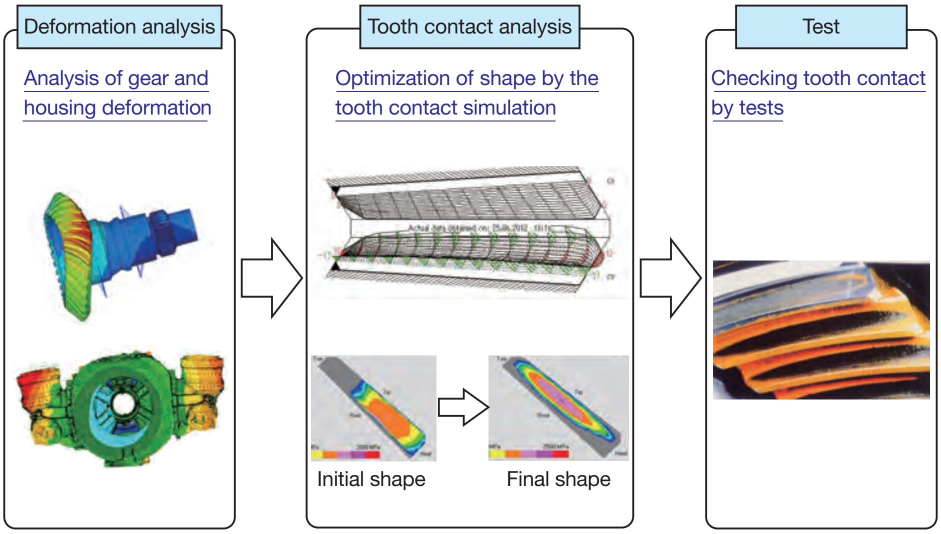
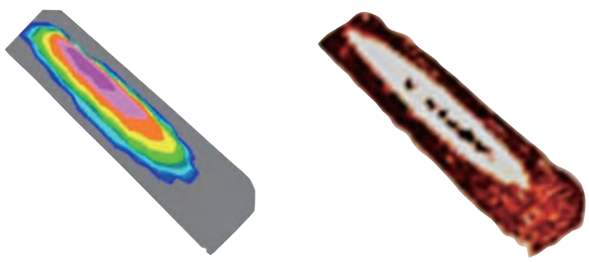


Fig. 4 Gear tooth contact pattern optimization design method

the tooth contact shape and tooth contact position following deformation is predicted after the deformation of gears and components of the gear housing is analyzed by using FEM analysis. Next, the tooth contact condition is analyzed and the tooth contact pattern is optimized by using tooth contact simulation software. After that, we manufacture a test gear and check whether the tooth contact pattern is appropriate by testing.

Figure 5 shows a prediction of tooth contact obtained by this method and a tooth contact obtained by a practical loading test. The gray area in the analysis results in **Fig. 5 (a)** and the brown area in the test results in **Fig. 5 (b)** are one tooth surface, and the central oval area is the tooth contact pattern. These analysis and test results agree well with each other, which demonstrates this design method is effective.



(a) Analysis results (b) Test results

Fig. 5 Analysis and test results of gear tooth contact pattern

(3) Loss reduction by CFD on oil flow

Loss of efficiency in a gear box product is caused by rotational components inside the gear box. The main factors causing energy loss are churning and windage losses in churning lubrication oil and cooling oil, as well as friction loss caused by contact between components.

The oil churning loss is mainly caused by the pumping action of a gear that has a structure like compressor blades and churns the surrounding fluid hard. Aircraft gear boxes use high-speed rotational gears and the oil churning loss often accounts for over 50% of the gear box's total loss. To reduce this loss, the momentum transferred to oil has to be minimized, or appropriate amounts of oil shall be supplied at suitable points, and it shall be immediately discharged.

To create a design with reduced loss, we have developed a completely new CFD simulation technique[4] by appropriately modeling the fast two-phase flow of oil and air as well as the area where gears engage. To reduce bevel gear loss, we applied this technique to a structure that covers gears with shrouds and has an oil discharge outlet, and verified this technique by conducting an estimation/simulation of the oil churning loss and windage loss and carrying out tests.

Figure 6 shows the situation without shrouds, and **Fig. 7** shows the one with shrouds. Without shrouds, oil splashes around inside the gear box and the gears churn it to increase loss. On the other hand, with shrouds, only appropriate amounts of oil flow on to the gear surfaces; moreover, adjusting the oil outlet position can smooth the oil flow inside the shroud to decrease loss. Regarding the

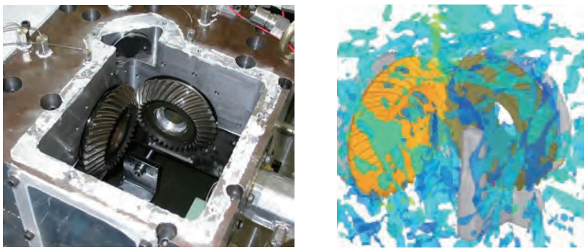


Fig. 6 Test gear box and simulation result (without shroud)

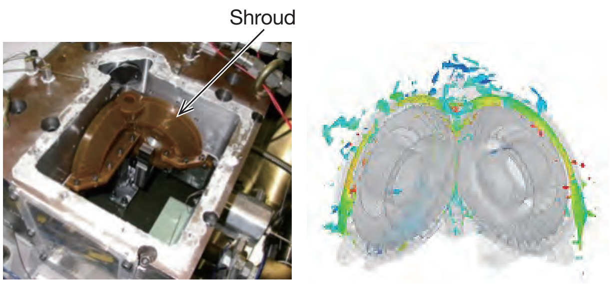


Fig. 7 Test gear box and simulation result (with shroud)

loss reduction ratio when shrouding is in place, the simulation and test results well agree closely with each other, which demonstrates that this technique is useful for optimizing the design to achieve high efficiency. In addition, this test demonstrated that adjusting the shroud shape and the oil outlet position can decrease loss by about 30% compared with the case without shrouds.

This design method was applied to the design of specimens for the planetary gear system verification test. The results revealed that for all the gear box models, the method helped to achieve a transfer efficiency of 99.5% or higher[5)], the target efficiency.

(4) Improving the loss-of-lubrication performance by CFD and heat-transfer analysis

One of the safety requirements of helicopters is transmission performance in a loss-of-lubrication state. A loss-of-lubrication means running out of lubrication and cooling oil for gears and bearings. In a loss-of-lubrication state, gears and bearings overheat and seize up, rendering them useless. This may cause an emergency landing or a crash. The loss-of-lubrication performance means the ability to continue flight in a loss-of-lubrication state. A loss-of-lubrication performance of 30 minutes or longer is required today. However, as transportation by helicopters to and from offshore oil rigs is growing, instances of long-distance transportation are increasing, and the next-generation helicopters will need to have loss-of-lubrication performance higher than ever.

Conventionally, in a design for improving loss-of-lubrication performance, sizes of gears and bearings are selected by a rule of thumb, which is based on test data, to delay seizure. It is difficult for a design depending on a rule of thumb alone to obtain higher loss-of-lubrication performance. A new design method is needed.

Figure 8 shows a history of change in bearing temperature after the oil is lost in a loss-of-lubrication test of an actual helicopter gear box. If the lubrication and cooling oil for gears and bearings is lost, the temperature of each part gradually increases to eventually damage the gears and bearings. The temperature rise from the start of the loss-of-lubrication to the finish is roughly categorized into the following three stages: ① the balance between heat generation and heat dissipation is lost due to the oil loss; ② rise in gear temperature caused by seizure; and ③ rise in bearing temperature caused by seizure. In each of these stages, the temperature probably approaches a certain time constant toward the temperature where heat generation and heat dissipation converge.

To evaluate the loss-of-lubrication performance quantitatively at the design stage without depending on past experience or practical machine tests, we are now developing a method for evaluating loss-of-lubrication performance that combines CFD and the heat-transfer analysis based on the estimation described earlier.

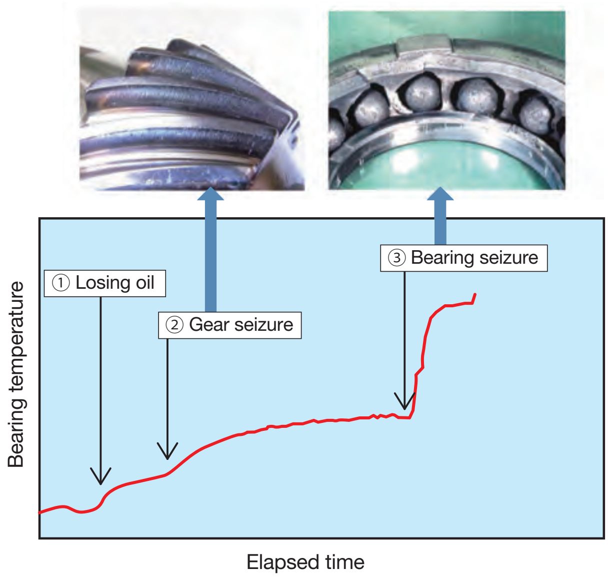


Fig. 8 Loss-of-lubrication test result

Conclusion

Thanks to the recent advances in CAE technology, the front-loading type development based on the optimum design method became available. Meanwhile, aircraft gear boxes are required to be more lightweight, reliable, and efficient than products of other fields. In addition, the recent aircraft market demands short-term and low-cost development of gear boxes.

We will further improve these world-leading design analysis and simulation technologies, and apply them to the designs of practical machines as well as developing new design technologies. Based on these technologies, we plan to promote differentiated products and increase market share, and thus aim to become a world-leading manufacturer of aircraft gear products.

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