Spiral Bevel Gear Development: Eliminating Trial and Error with Computer Technology

Joseph L. Arvin and Thomas C. Mifflin, with contribution from James J. Cervinka

A New Era

Computer technology has touched all areas of our lives, impacting how we obtain airline tickets, purchase merchandise and receive medical advice. This transformation has had a vast influence on manufacturing as well, providing process improvements that lead to higher quality and lower costs. However, in the case of the gear industry, the critical process of tooth contact pattern development for spiral bevel gears remains relatively unchanged.

The procedures needed to develop spiral bevel gear sets for a new product can require months of trial-and-error work and thousands of dollars. In view of increasing global competition for lower-priced products, bevel gears are a prime target for the next generation of computerization. Answering this challenge, Arrow Gear Co. of Downers Grove, IL, has realized a new era through a shift in the way spiral bevel gear development is performed.

This article will provide some fundamental information pertaining to gear development and detail the procedures and techniques utilized by Arrow Gear to achieve maximum quality while substantially lowering development costs.

Understanding Contact Pattern and Gear Displacement

A critical attribute of a spiral bevel gear's design is its contact pattern. Simply stated, the contact pattern is the area in which the gear teeth come in contact as they engage and disengage during their rotation. This area of contact is checked by the following procedure.

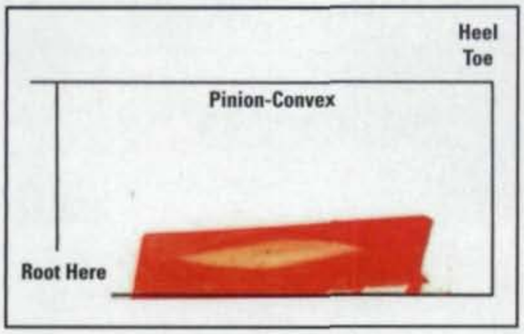


Figure 1—Typical contact pattern.

The teeth are coated with a special marking compound and then run together in a tester. The area of contact can be seen in the disruption of the marking compound, and an experienced inspector is required to interpret the visual results. To document this contact, adhesive tape is then applied to the tooth surface and transferred to a piece of paper (see Fig. 1).

When a gear is installed in a gearbox and is powering the designated application, there are varying degrees of pressure, or load, on the gear teeth. These pressures include box deflections, bearing movement and temperature changes. When the gear teeth are subjected to these variables, the contact pattern will change.

Figure 2 shows the contact pattern from a gear with a very light load and a contact pattern from the same gear with a very heavy load. There is a general rule of thumb, which states that the heavier the load, the larger the contact pattern.

Now here is where the issue of contact pattern becomes so important. For a gear to perform properly under load, the contact pattern must be a certain shape and at a certain location. Typically, an ideal tooth contact pattern under load should encompass the bulk of the tooth surface while avoiding any contact with the edges of the tooth surface (see Fig. 3).

Another critical issue to consider, when assessing how the contact pattern will perform in an operating gearbox, is gear displacement.

In the operation of many gearboxes, the gears and their shafts do not remain in a fixed orientation. Thermal forces and stress from being under load can cause significant movement of the gearbox components from their original positions.

There are typically four different types of movement that can take place. These types are described as offset, pinion in and out of mesh, gear in and out of mesh, and shaft angle (see Fig. 4). It is this movement that is referred to as gear displacement, and it can occur in any combination of the four types.

In aerospace gearboxes, where keeping weight to a minimum is a high priority, the mass of the gearing used is usually smaller, and these displacements can be significant. On the other hand, in commercial applications where the gearbox components are typically more rigid, there is not the same degree of displacement.

Conventional Methods for Contact Pattern Development

The size and position of the contact pattern has always been a primary design consideration for gears. And for many years, achieving a good contact pattern was performed through the same methods that the vast majority of gear producers still use today.

The conventional method of achieving an ideal contact pattern is performed in the following way. First, an engineer will make an educated guess at the gear tooth geometry required to provide a correct contact pattern. Next, the part is fabricated and the gear teeth are machined to an undeveloped summary.

When the gear and its mating pinion are finished, they are run together in a tester. More often than not, the contact pattern will not be correct in this first attempt. This requires going back and changing the settings on the gear tooth grinder, then producing a new pinion. The parts are checked again. This trial-and-error process can continue through many cycles until the best educated guess for contact pattern location is achieved. But how will the gear perform under load in a gearbox, and what will the contact pattern look like then? Answering this question leads to more steps in the trial-and-error process.

First, the gears are mounted in the gearbox and run under light load to determine the contact pattern movement. Then, the gears are visually inspected to check the contact pattern, which is indicated by a light wear pattern on the mating tooth surfaces. If the pattern is not correct, which is commonly the case, the gear tooth grinder has to be set up again with new machine settings, and another pinion is ground. This cycle continues until a suitable contact pattern is developed when run under full load.

For a new gear design, this process can take several months to complete. And while this is a time-consuming and costly process, it was just the way it had to be done—or it was until new computer-based technologies for gear development became available.

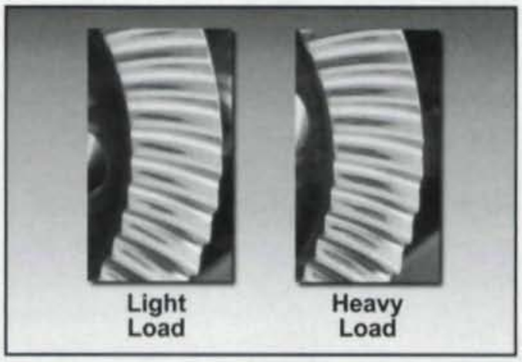


Figure 2—Same gear with light load and heavy load.

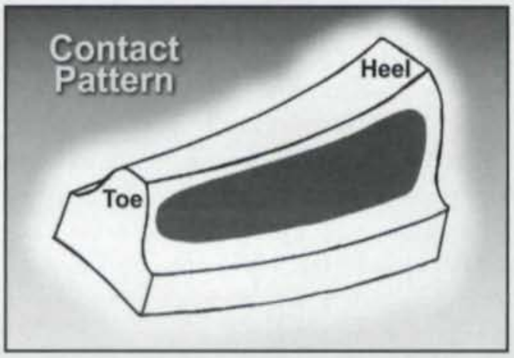


Figure 3—Ideal contact pattern under load.

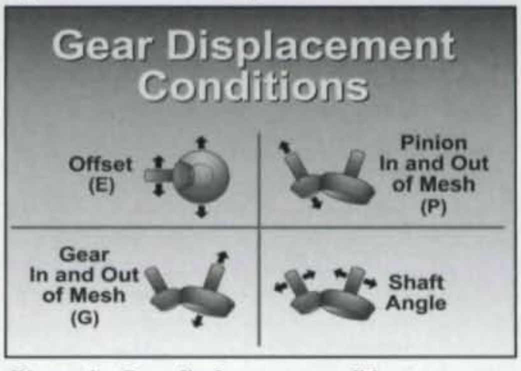


Figure 4—Gear displacement conditions.

A New Method for Contact Pattern Development

To address the traditional limitations of conventional methods, Arrow Gear implemented a highly advanced system for performing contact pattern development, a system that provides a dramatic reduction in the time and expense of the process when compared to conventional methods. This system uses a combination of state-of-the-art development software and machine tools. Among its key components are The Gleason Works' G-AGE, CAGE, MINIGAGE, loaded TCA and T-900 finite element analysis software packages. And for machine tools, the system utilizes Gleason Corp.'s Phoenix® CNC tooth cutters and Phoenix CNC tooth grinders, in conjunction with

Joseph L. Arvin
is president of Arrow Gear Co. of Downers Grove, IL. An industrial engineer, he started in the gear industry as a machinist at Indiana Gear of Plymouth, IN, in 1959. With Arrow Gear since 1972, Arvin helped introduce advanced manufacturing technologies and computer integration to the company.

Thomas C. Mifflin
is a gear engineer at Arrow Gear. Also with the company since 1972, he is responsible for gear manufacturing, perishable tool design and contact pattern design.

James J. Cervinka
is CEO and chairman of the board at Arrow Gear. He co-founded the company in 1947. Like Arvin, Cervinka helped introduce advanced manufacturing technologies and computer integration to Arrow Gear.

a Zeiss-Höfler CNC gear inspection system. More detailed information on the use of this system will follow, but here are a few highlights of its capabilities.

Using the development software, engineers can build virtual models to predict how the gear will perform in actual operation. This in turn generates the settings to be used by the machine tools. In addition, these settings for the machine adjustments are automatically downloaded to the machine tools, greatly reducing the time spent on setup. Perhaps the most dramatic aspect of this system is that ideal settings of the machine tools—which are required to produce the desired contact pattern—are typically achieved in the first or second attempt on the gear manufacturer's shop floor.

In essence, this system eliminates the trial-and-error process that was once required. And the bottom line is that development time is reduced and the gear producer is able to provide a significant cost savings to the customer.

Developing the Contact Pattern Through Computer Modeling: Overview of the Process

The process of developing a contact pattern with this system is very complex. However, to provide a clear understanding of how the system works, the conceptual highlights of a typical development will first be presented. A more detailed explanation of the steps involved will be presented later.

The process begins by receiving the customer's design requirements. This would include drawings of the part detailing the critical geometry, such as ratio, diametral pitch and so on. In addition, it is helpful if the customer can supply specifications on operating torque and the gear displacements.

Engineers begin the process of contact pattern development by establishing a working file for the part based on its geometry. Using the CAGE software, a tooth contact analysis study, or TCA study, is performed. This indicates the location of the contact pattern without load.

Finally a loaded TCA is performed, taking into account all the displacement conditions. Once the TCA study is performed for all displacement conditions, the ideal contact pattern is identified. With this information, a finite element analysis is performed that predicts real stress on the tooth surface as well as the root fillet. This study allows the engineers to determine whether there is a potential for failure resulting from excessive or nonuniform pressures anywhere along the line of engagement of the gear tooth.

A more detailed explanation of how the TCA and finite element studies are actually performed is presented in the next section.

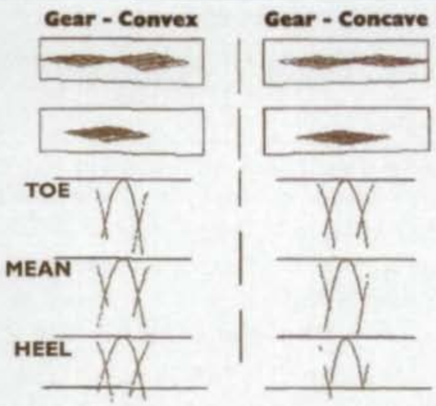
Developing the Contact Pattern Through Computer Modeling: Details of the Process

In this section, we will present the details involved in the process of designing the contact pattern through computer modeling and how the software integrates with the machine tools.

To begin, Figure 5 is a summary printout of a TCA study. This particular TCA is from an upper tower or PTO (power take-off) gear set, for use in an aircraft jet engine. For the purpose of illustration, we will be looking at the concave side of the gear and addressing the loaded TCA phase of the design work, when various displacements were taken into account. The different displacements came from thermal and external forces, in addition to the normal operating torque load.

Figure 6 shows the contact pattern design that was created to meet the load requirements and the different displacements that the gear set would encounter.

The different displacements that would result from varying thermal and external forces and from a load of 3,140 in.-lbs. of torque are shown



Arrow Gear Co.
Summary No. 3029
Ratio: 65 x 74 Date: 2/17/99

Generated Gear	Convex	Concave	
Pin Blade Angle	11.500°	16.300°	
Gear Blade Angle	16.000°	16.000°	
Point Diameter	9.812"	8.438"	
Contact Length Factor	0.310	0.310	
Delta Ax	0.600	–0.080	
Delta E	–0.100	0.040	
KP	5.000	6.000	
Delta EM	0.150	0.600	
Delta 60X	0.000	0.000	
Delta 2C	0.000	0.000	
Delta E-DR	–0.500	0.600	
Profile Separation Factor			
IN* 1,000	Mean	Toe	Heel
CX E(U)	–9	16	–28
P(H)	–3	–18	9
CU E(U)	13	–12	38
P(H)	–35	–29	–47

Figure 5—Printout of a TCA study.

in Figure 7. Some of those displacements are considerable, such as the pinion moving above the gear (E) by 0.013", the pinion going into mesh (P) by almost 0.029" and the gear going out of mesh (G) by 0.026".

The objective was to design a contact pattern that would have an acceptable shape and size, would never run off the ends, make contact in the root fillet, or run off the top lands—while taking into account the different displacements the gears would experience under normal operating conditions.

The contact pattern that was designed then met the requirements of the different displacements shown in Figure 7. Next to each requirement is the contact pattern from the loaded TCA study. If these contact patterns were overlaid or their contact areas combined, the result would—in essence—be a depiction of what the load zone will be for this gear set while it is in operation and encounters all of these different displacements at 3,140 in.-lbs. of torque.

In addition to each one of the different displacements on the contact study, the study will also look at the various pressures that are occurring along the path of engagement. In Figure 8, as the tooth comes into mesh, the path of engagement starts at point A. It then rolls through mesh and exits at point B.

Given a load of 3,140 in.-lbs. of torque, the table in Figure 9 shows what the surface pressure is at the start of engagement all the way through to the end of engagement. The pressures at the start of engagement are low, which are a result of tooth sharing—due to the high contact ratio. The pressures then start to climb and will reach a peak of 238,000 lbs./sq. in. in the center of the tooth. The pressures will then diminish, finally falling to nearly 84,000 lbs./sq. in., where this tooth has exited from mesh.

A key objective of this study in Figure 9 is to verify that there are no hard spots occurring in the pattern. Hard spots would show as spikes in these surface pressures. If a spike in these surface pressures is present, there is a strong indication that a failure mode may be present. As the teeth would come into mesh, the spike or ledge would create a nonuniform pressure, potentially causing pitting and subsequent failure. However, in this example, the pressures do not include any spikes. There is a gradual increase to the center of the tooth, followed by an equally gradual decrease. These gears will move in and out of mesh very smoothly.

This study will be performed for all of the dis-

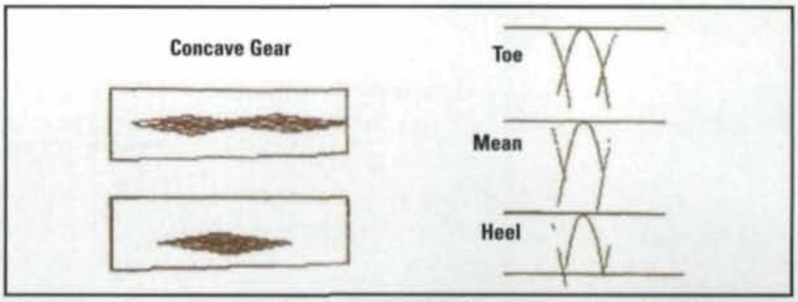


Figure 6—Contact pattern design to meet load requirements and displacements.

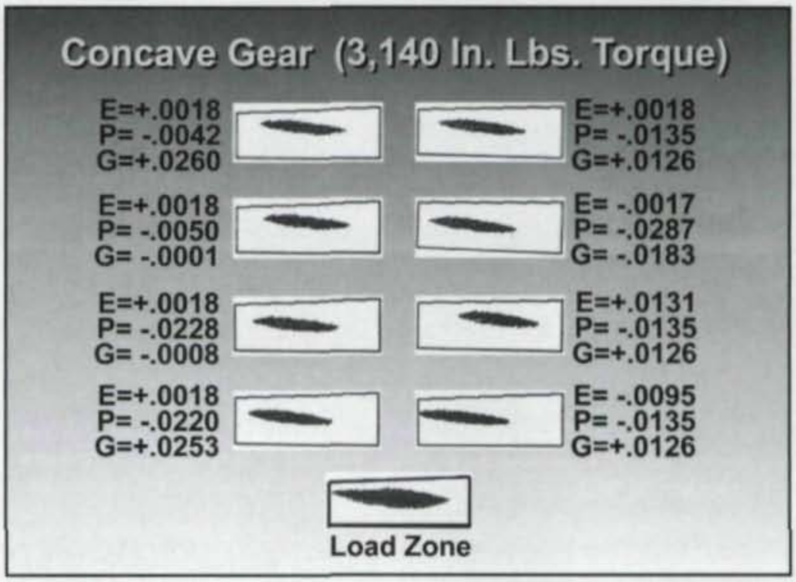


Figure 7—Displacements in aircraft jet engine project, corresponding contact pattern designs and combined load zone.

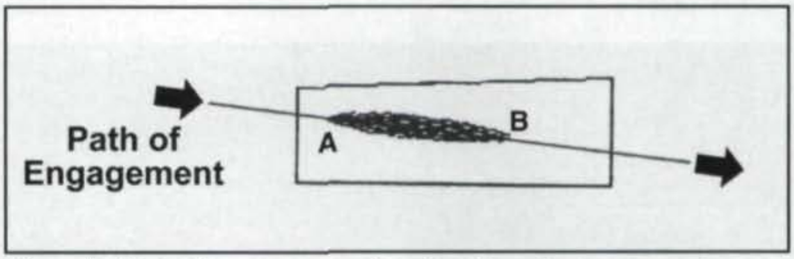


Figure 8—Study of pressures occurring along the path of engagement.

Summary No. 3029 Ratio: 65 x 74
Q 0.94983 THP 0.00000 QG 0.95819 THG 0.00000
DXGR 0.00000 U 0.00000 H 0.00000

Torque (in.-lbs.)	0	500	1,000	1,500	2,500	3,000	3,140
Max. Applied Pressure/1,000 (psi, Toe to Heel)							
	0	0	0	0	0	10	70
	0	0	0	0	114	139	145
	0	0	0	60	153	172	176
	0	0	0	116	171	189	193
	0	0	88	134	179	196	200
	0	0	123	152	190	205	209
	0	0	143	166	200	213	217
	0	0	158	177	208	220	224
	0	0	169	187	215	226	230
	0	0	179	195	221	232	235
	0	0	180	202	226	237	238
	0	0	178	205	226	233	235
	0	0	178	203	225	233	235
	0	0	177	192	215	225	227
	0	0	171	185	209	220	222
	0	0	157	174	199	210	213
	0	0	142	161	189	201	203
	0	0	124	147	178	190	194
	0	0	100	130	166	180	183
	0	0	53	109	153	168	172
	0	0	0	77	139	156	159
	0	0	0	0	112	129	133
	0	0	0	0	0	73	84

Figure 9—Table showing surface pressures.

placement conditions, and when complete, the design will be ready for finite element analysis.

The results of the loaded TCA are first downloaded to the T-900 finite element analysis software. The program then performs a real stress analysis of the tooth surface.

A report is generated (see Fig. *10*). Through the use of different colors, the report shows the load distribution along the different areas of the tooth. The areas where there is the heaviest contact on the tooth are red. As the stresses decrease, the colors change and continue out until there is a base load, which is the lowest surface pressure or stress that will be seen on the gear tooth.

A similar study is then performed on the root fillet (see Figs. 11a and 11b). Again, the varying levels of stress are indicated by different colors.

A bar graph that specifies the corresponding pressure is generated on the reports for the tooth surface (see Fig. 10) and root fillet studies (see Fig. 11a) . If the maximum value exceeds the rating of the material being used, there is a high potential that the gear will fail.

Another insight that is provided by the finite element analysis is the potential for ledges or edge contacts. As was mentioned before, a red area is an indication of the highest pressure. If the study indicates any red areas outside the center of the contact pattern, it would suggest that a failure might occur in these areas.

If the finite element study reveals any problems, the engineer can then go back to the CAGE software and modify the contact pattern as needed, then perform a second finite element analysis.

Once the TCA and finite element studies are performed, and the ideal tooth contact pattern size and location is achieved, the CAGE software creates the summary settings required by the Phoenix cutters and grinders to machine the parts. In addition, the G-AGE software is used to generate the inspection file for the Zeiss-Höfler CNC inspection system. Using the Zeiss-Höfler system, electronic digital topographical plotting of the tooth surface is performed and the G-AGE software automatically changes the machine settings to match the computerized tooth shape desired. Through a hard-wired network connection, both the summary settings and the inspection file are downloaded. After all these development procedures, the production process begins.

Customer Benefits: A Case Study of the PTO Gear Set

This advanced approach for design and contact pattern development provides numerous customer benefits. Foremost among these are dramatic savings of time and money.

An example of these two benefits to the customer was illustrated in Arrow's involvement with the previously mentioned aircraft jet engine project. The details of this project are presented in the following case study.

Arrow supplied gearing on two locations of the engine. The first bevel gear set was used in the upper tower shaft or power take-off. The second bevel gear set was used in the accessory gearbox.

As this was a new engine, Arrow was called upon to perform both the gear tooth design and the fabrication of these bevel gear sets.

As with all jet engine gears, this was a

Duplication of Operating Conditions with Universal Load Testers

As a supplement to the theoretical calculations that are performed to achieve the design of contact patterns, Arrow Gear utilizes universal load testers that are used to simulate the performance of the gears in a gearbox (see Fig. 1). These Gleason Corp. testers, which Arrow retrofitted, can test gears under loads of up to 700 in.-lbs. of torque. To accomplish this testing, an eddy brake was added to generate the load and a strain gage was integrated for monitoring the amount of torque applied. Control of revolutions per minute and load is performed by an onboard computer. The testers also allow for the adjustment of the gear and pinion position, *thus replicating the gearbox displacements.*

These testers first allow the engineers to view the contact pattern as they typically would in a gear tester during the manufacturing stage. Figure 2 shows the pattern that resulted from no more than a few inch-pounds of torque—and the contact pattern is a localized area halfway up the flank and toward the toe.

Figure 1—Universal load tester.

In Figure 3, the tester has applied 120 in.-lbs. of gear torque as well as the gear displacements. As can be seen, the contact pattern has moved from a toe location to a heel location and has grown in size and changed in shape.

The ability of these testers to monitor the movement of the contact pattern can be a valuable aid in manufacturing the gears, as well as for checking their actual performance without requiring them to be installed in a gearbox.

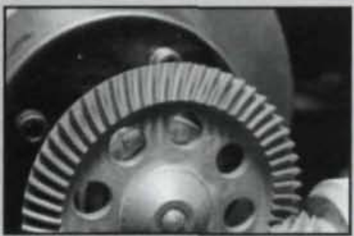


Figure 2—Contact pattern with no more than a few inch-pounds of torque.

There is another substantial benefit of these testers. Often, the customer is unable to determine what its gearbox deflections will be. If this is the case, the engineer can—in essence—back into the deflection values required for TCA and finite element analysis.

Backing into those values is done in the following way. Using the operating torque and the wear pattern from a gear set that has been run in a gearbox, the engineer can duplicate the same wear pattern by adding displacement and load. This will generate all the numerical values required for further evaluation.

Figure 3—Contact pattern with 120 in-lbs. of torque.

demanding application due to the high degree of gearbox deflections. Faced with the double-edged challenge of both a difficult job and a short lead time, Arrow began work on the project utilizing the design and manufacturing tools explained earlier.

The two different gear sets were then produced and shipped for installation in the engine. Here are the results.

First of all, a normal time frame for developing the desired contact pattern under full load can be up to six months. Arrow's initial development was performed in less than one week through computer modeling techniques—and this initial development required no further modifications when run under full load during engine tests. For the actual manufacture of a new gearing application, the typical time frame is 22 weeks. Arrow performed this work in 12 weeks.

After the gears were run in the engine for 75 hours, they were visually inspected. Shown in Figure 12 is one of the gears. Both contact patterns on the run side and start side were exactly as predicted. This approach saved a significant amount of expense and time for the company creating the engine.

Troubleshooting and Failure Analysis

This system for designing gears is used for the most part to design or improve designs on new or existing gear sets. However, there are additional capabilities of the system.

If the system is provided with the proper information, virtual models of the gear teeth can be created to predict the proper location of the contact pattern. This information compared with the actual contact pattern can provide valuable insight to the cause of a failure or other problems. In addition, this approach can improve beam strength of the tooth up to 30% and significantly increase gear life.

Conclusion

In today's competitive manufacturing environment, customer demands for fast delivery and lower costs are prevalent. In this climate, the computerized closed-loop approach to gear production is ideally suited. In addition, by reducing development time, this technique allows the product to be released to the market much sooner—substantially reducing costs to the OEM.

In view of the numerous benefits of this technology, the closed-loop methodology promises to become the standard development technique in the gear industry for years to come.

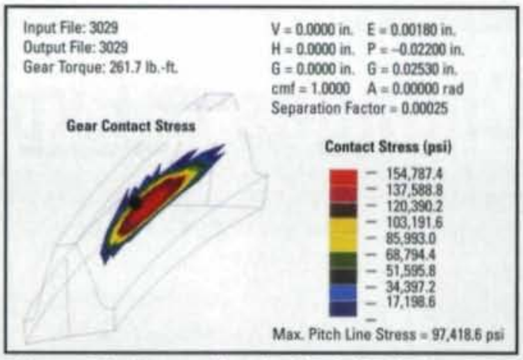


Figure 10—Report showing load distribution.

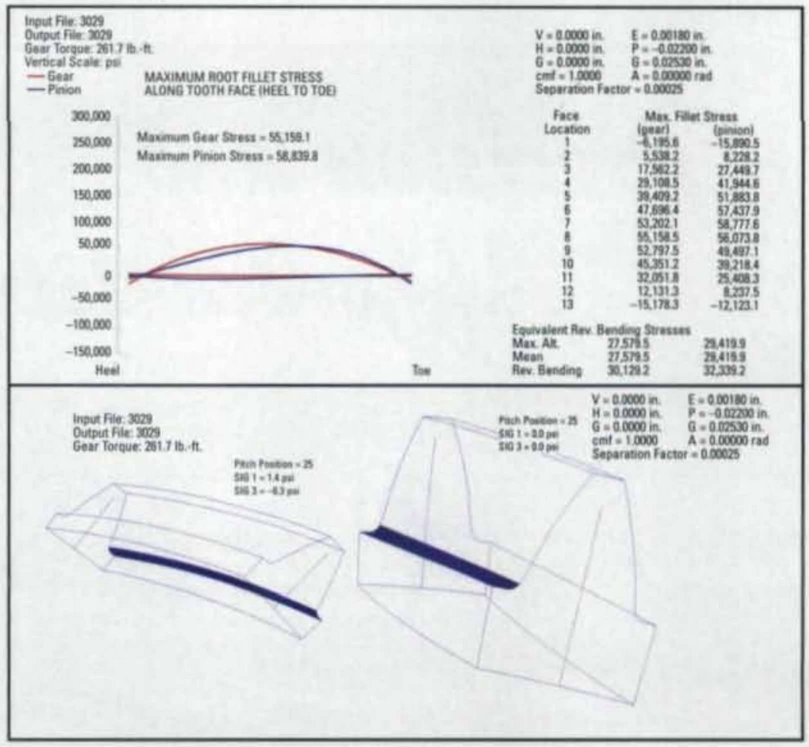


Figure 11—Load distribution study on root fillet.

Figure 12—A spiral bevel gear after running in the aircraft jet engine for 75 hours. Contact pattern is exactly as predicted.