Doing It Right & Faster... The Computer's Impact on Gear Design & Manufacture

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Introduction: The availability of technical software has grown rapidly in the last few years because of the proliferation of personal computers. It is rare to find an organization doing technical work that does not have some type of computer. For gear designers and manufacturers, proper use of the computer can mean the difference between meeting the competition or falling behind in today's business world. The right answers the first time are essential if cost-effective design and fabrication are to be realized. The computer is capable of optimizing a design by methods that are too laborious to undertake using hard calculations. As speeds continue to climb and more power per pound is required from gear systems, it no longer is possible to design "on the safe side" by using larger service factors. At high rotational speeds a larger gear set may well have less capacity because of dynamic effects. The gear engineer of today must consider the entire gear box or even the entire rotating system as his or her domain.

We will take a brief look at some of the methods traditionally used by the gear industry and investigate possible improvements using state-of-the-art software technologies.

Computerize the Right Stuff

In the past, handbooks, rules of thumb, modification of previous designs, etc., were the most commonly used design techniques. Slide rules gave way to hand calculators; the hand calculators gave way to the first desk top calculators, and they gave way to personal computers. The first computer programs for gear design and manufacturing were, for the most part, cookbook computerizing of industry standards and design handbook formulae. Users were not aware that programming the usual formulae for gear design and gear tools can result in serious, unexpected problems. The formulae were used by people who, often without being aware of it, made judgments concerning the results as they went along. The computer does not have the ability to make any judgments without being programmed to do so.

The following equations (marked "linear") for the contact limit radii (Start of Active Profile) for a pair of gears was taken from a text on gear design and entered without change into a computer. The numerical data is for a 20 D.P., 13/30 spur tooth gear set.

cd = operating center distance = 1.075

Gear 1:

Ro1 = outside radius = 0.375

Rb1 = base radius = 0.30540

Gear 2:

Ro2 = outside radius = 0.800

Rb2 = base radius = 0.70477

$$tpà = \arccos \frac{Rb1 + Rb2}{cd} = \text{operating PA} = 20°$$

Linear Equations (from text book):

$$R1c = \sqrt{\left[cd \cdot \sin(tpà) - \sqrt{Ro2^2 - Rb^2}\right]^2 + Rb1^2}$$

= gear 1 contact limit radius (SAP) = 0.30559 (incorrect)

$$E1cL = \sqrt{\left[\frac{R1c}{Rb1}\right]^2 - 1} =$$

= roll angle at SAP 1 = 2.04085°
(incorrect)

$$R2c = \sqrt{\left[cd \cdot \sin(tpa`) - \sqrt{Ro1^2 - Rb1^2}\right]^2 + Rb2^2} =$$

gear 2 contact limit radius (SAP) = 0.72057.

$$E2cL = \sqrt{\left[\frac{R2c}{Rb2}\right]^2 - 1} =$$

roll angle at SAP 2 = 12.19928°

The SAP diameter and roll angle for gear 1 are incorrect. The value of

$$cd \cdot \sin(tpa`) - \sqrt{Ro2^2 - Rb2^2}$$

is actually negative, but the computer, in precise accordance with instructions, squared it anyway.

The following equations for the SAP of the gears are much better suited to the computer, as there is no necessity to square a number that may be negative, giving the wrong result. The roll angle at the SAP is calculated directly.

Roll Angle Equations:

$$ERo1 = \sqrt{\left[\frac{Ro1}{Rb1}\right]^2 - 1} =$$

roll angle at OD 1 = 40.82629°

$$ERo2 = \sqrt{\left[\frac{Ro2}{Rb2}\right]^2 - 1} =$$

roll angle at OD 2 = 30.77504°

E` = tan(tpa`) = roll angle at operating pitch point = 20.85396°

$$E1c = E` - \left[\frac{Rb2}{Rb1}\right] \cdot$$

(ERo2 -E`) = roll angle at SAP 1 = -2.04085°
(correct)

$$E2c = E` - \left[\frac{Rb1}{Rb2}\right] \cdot (ERo1 - E`) =$$

roll angle at SAP 2 = 12.19928°

The value of the roll angle at the SAP of gear 1 is negative. This, of course, is not possible and indicates that the tip of gear 2 is attempting contact below the base circle of gear 1.

The "linear" equations tell us that the situation is as shown in Fig. 1.

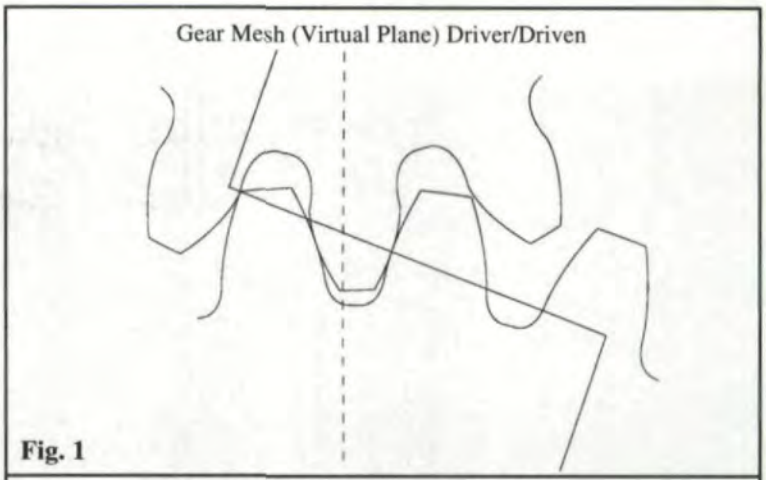

Fig. 1

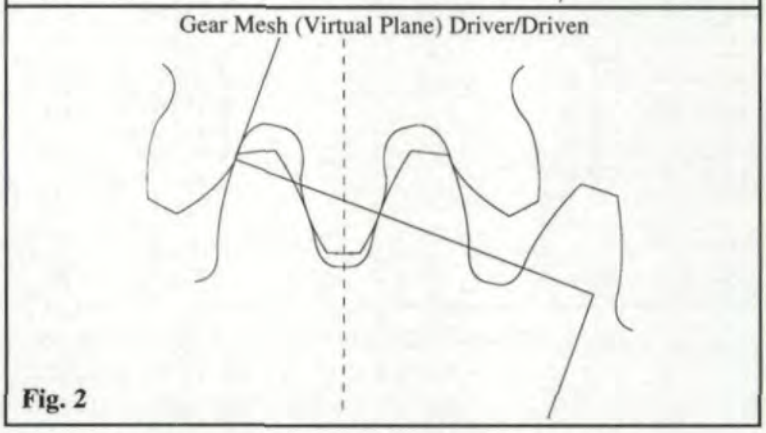

Fig. 2

The figure shows the first point of contact on the driver to be at +2.04085°. The actual situation is shown in Fig. 2.

It is obvious that if we believed what the computer told us using the "linear" equations, we would have an unusable gear set. The negative roll angle produced by the "roll angle" equations is the true situation and is easily seen by the computer or the operator.

Cases like our example are quite common in the gear literature. The geometry of a pair of involute gears leads naturally to the use of equations for linear dimensions squared. The use of angles instead of lengths does not seem to be as natural for human beings. However, the use of angular relationships instead of linear relationships wherever possible will keep errors to a minimum, and computer code for gears should be written in this manner.

Analyze the System

When a gear set is to be designed and manufactured, the usual procedure is to consider it as an independent mechanical pair. The gears must mesh together properly and carry the load imposed upon them for the required length of time. The gear unit may consist of only a single pair of gears, or there may be many stages of the same or different types of gear sets. For a given total

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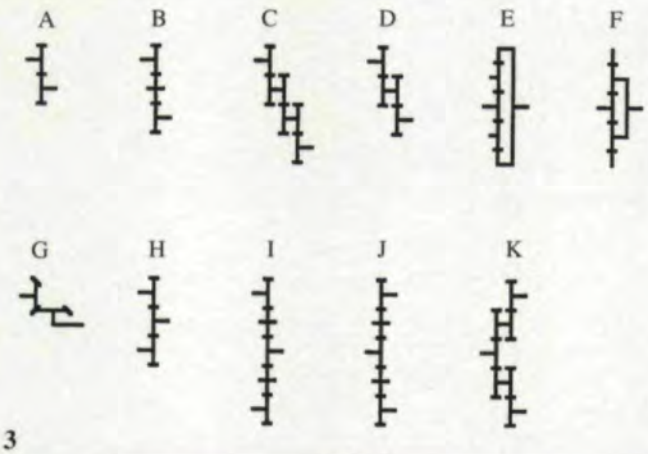

Fig. 3

Fig. 4

Fig. 5

Table 1 - Minimum Weight Transmission System

Date: 0/0/00
Job ID: Triple Reduction

Total System Ratio = 67.000
Sum (Fd2/C), min = 349.041
Ratios listed are minimum weight ratios.

TRIPLE REDUCTION GEAR SET
(Pin->Gear->C.S.Pin->Gear->C.S.Pin->Gear)
Helical Gears, Low Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.30
Branches = 1
Ratio (1) = 5.685
Ratio (2) = 3.725
Ratio (3) = 3.164

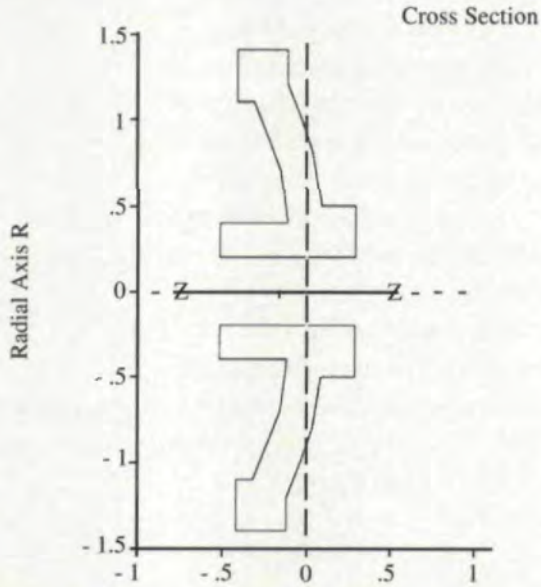

Fig. 6

ratio, there is a combination of gear sets (maybe a single set) that will produce the optimum result. The optimization criteria may be reducing failures, increasing life, reducing noise, minimizing cost, maximizing reliability, minimizing weight, etc. The optimum will usually be the gear set combination with the least total gear rotor volume; i.e., the sum of the face * diameter squared for all gears in the unit. The computer is capable of quickly giving us this information for various combinations of gear sets. In addition, for any combination of gear sets, there is only one set of ratios which will produce the required overall ratio and at the same time yield the lowest total gear rotor volume. The computer can give us the "best" ratios at the same time as the total rotor volume.

Fig. 3 is the menu sheet from a program for minimum weight (volume) for gear units.

A gear unit may be made up of single sets as shown, or various sets may be combined.

As an example, we will look at a gear unit with an overall ratio of 67 to 1, first as a triple-reduction, parallel axis unit, and then as a double-reduction connected to a final planetary set.

Fig. 4 is a schematic for the triple-reduction from the program.

Table 1 is the computer output for the triple-reduction with minimum rotor volume. Any other ratio combination that produces 67 to 1 will have a larger rotor volume factor (349.041) and hence will weigh more.

Fig. 5 is the schematic for the double-reduction driving a planetary. Table 2 is the output for the double-reduction driving a planetary with minimum rotor volume.

The triple-reduction unit, even when made with minimum weight ratios, would be more than twice the weight of the double-reduction and planetary at this overall ratio. Other combinations would be lighter still. The possible extra cost of the parts for a planetary set would have to be weighed against the benefits of the smaller volume and weight, but the computer will furnish solid data with which to make the choice.

Since a gear unit is used to transmit motion or power from one shaft to another, it is always part of a larger system. Any rotating system has natural frequencies of torsional vibration. (There are as many natural frequencies as rotating masses less one.) If there is an exciting source which produces pulsating energy input at about the

same frequency as one of the natural frequencies, the system is said to be in resonance. The amplitude of vibration will build up in such a system until the exciting energy is dissipated by damping in the system. Many systems containing gear units do not have enough damping to keep the amplitude of vibration (and the vibratory shaft torques) from becoming destructive. The computer can help us determine the natural frequencies of a rotating system, so that we can make sure that resonance will not be a problem.

In order to determine the natural frequencies of a system, we first need to build a mathematical model. Fig. 6 is from a computer program used to determine, among other things, the moment of inertia about the rotation axis for solids of revolution. The figure might represent a wheel or a gear blank with a hub.

Table 3 is the output from the program for solids of revolution.

Computers can also be used for finding the torsional spring rate of the connecting shafts between the inertias.

Once we have all the inertias of the masses and the spring rates of the connecting shafts, the computer can quickly find the natural frequencies of the complete rotating system.

For example, a simple six-mass system might consist of an electric motor driving a rotary pump through a two-gear reducer. The masses would then consist of the motor, the input coupling, the driving gear, the driven gear, the output coupling, and the pump. Fig. 7 is a schematic plot of such a system with the first natural frequency relative amplitude plotted (the mode shape) from mass to mass. Table 4 is the numerical output for the first natural frequency. All the natural frequencies that are near excitation frequencies can be quickly found, and if a resonance exists, the system can be "detuned" by changing masses or shaft stiffness.

Concurrent Engineering

There is a move in American industry to use "concurrent engineering" to develop a design that can be produced in the least time and at the least cost.

In the past, the design of a product was usually done by the design department, the drawings were produced by the drafting department, and then the drawings and specifications were sent to the manufacturing engineering department. Little consideration was given to the design and availability of required tools or the capabilities of manufacturing equipment at the design stage. These concerns

Table 2 - Minimum Weight Transmission System

Date: 0/0/00
Job ID: Double Reduction and Planetary

Total System Ratio = 67.000
Sum (Fd2/C), min = 155.108
Ratios Listed Are Minimum Weight Ratios

DOUBLE REDUCTION GEAR SET
(Pin->Gear->C.S.Pin->Gear)
Helical Gears, Low Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.30
Branches = 1
Ratio (1) = 4.395
Ratio (2) = 3.366

PLANETARY GEAR SET
(Pin->Planets->Carrier: Ring Gear Fixed)
Spur Gears, High Pressure Angle
Capacity Factor for Tooth Type & Pressure Angle = 1.04
Actual Planets = 4
Effective Planets = 3.7
Ratio (3) = 4.529

Table 3 - Output From Solids of Revloution Program

St Input	Name	Output	Unit	Comment
				SOLIDS OF REVOLUTION Axes: Z-rotation, R-radial
.284	rho		lb/in3	Density of Material
	As	18.406816	in2	Surface Area
	V	1.8232757	in3	Volume
	M1	.00134009	lb-s2/in	Mass
	M2	.51781029	lb	Mass
	Irr	.00068583	lb-in-s2	Transverse Moment About R-Axis
	Zc	-.1420155	in	R-Axis to Center of Gravity
	Izz1	.00125142	lb-in-s2	Moment of Inertia About Z-Axis
	Izz2	.48355008	lb-in2	Moment of Inertia About Z-Axis
	Zz	.96635209	in	Radius of Gyration About Z-Axis

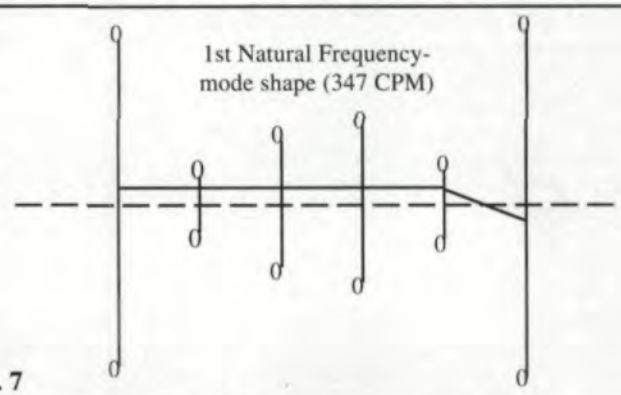

Fig. 7

Table 4 - Relative Amplitude & Torque

Mass/Spr #	Rel Vel	Rel Amp	Rel Torque	
1	1	1	5.97119E4	
2	1	.917067	6.02972E4	
3	1	.916273	6.59176E4	
4	1	.847166	6.60926E4	
5	1	.843881	6.65497E4	NODE
6	1	-.87842		
		347.467	NAT. FREQ. NO.	1

Table 5 - Optimum Gear Hob Designed by "Expert System"

Driver Non-Topping Hob	#1	#2	#3
Tool Number	DEFAULT TOOL	#1	#2
Nominal Pressure Angle	20	20	20
Flank Angle	20	20	20
Tip to Reference Line	0.125	.1157	.125
Tooth Thick at Ref Line	0.1571	.1571	.1571
Tip Radius	0.025	.0157	.03
Protuberance	0	0	0
Root Diameter	1.3043	1.3229	1.3043

DEFAULT TOOL OK

(Press F1 for Help)

Table 6 - Output Sheet for "Expert System" Program

UTS
Gear Analysis

*Denotes Input Data

*Normal Diam Pitch	=	10.0000	
*Normal Pressure Angle	=	20.0000	
*Helix Angle	=	0.0000	
Trans Diam Pitch	=	10.0000	
Trans Pressure Angle	=	20.0000	
*Face Width	=	1.0000	(Deg Roll)
*Number of Teeth	=	22	
*Outside Diameter	=	2.6000	(43.70)
*Cut Transverse Backlash	=	0.0030	
*Delta Addendum	=	0.1000	
*Total Normal Finish Stock	=	0.0000	

HOB FORM DATA		NON-TOPPING	
*Hob Pressure Angle	=	20.0000	
*Hob Tip to Ref Line	=	0.1250	
*Hob Tooth Thickness at Ref	=	0.1571	
*Hob Tip Radius	=	0.0300	
*Hob Protuberance	=	0.0000	
Hob SAP from Ref Line	=	0.0451	
Hob Space Width at Hob SAP	=	0.1243	
(<0.3/NDP) Normal TT at OD	=	0.0180	
Normal Tooth Thickness, (Hobbed)	=	0.2269	
Pitch Diameter, (Ref)	=	2.2000	(20.85)
Base Diameter	=	2.0673	
Root Diameter	=	2.1418	
Max Undercut	=	0.0000	
Dia at Involute-Fillet Tangent	=	2.1819	(19.34)
Minimum Fillet Radius	=	0.0300	
Hob Tool Number	=	UTS#2	
Steel Gear			

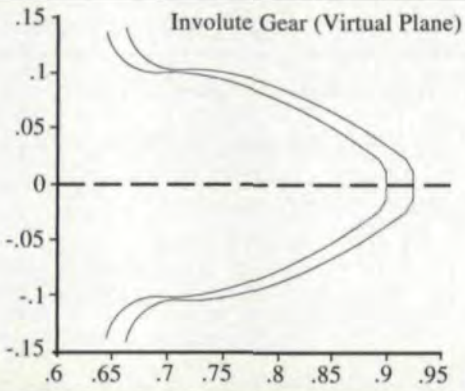

Fig. 8

were the responsibility of the manufacturing engineering department, and cooperation concerning changes between the design and manufacturing engineers was sometimes difficult after the design was frozen. Usually new tools had to be purchased because tools on hand were not considered at the design stage.

The "concurrent engineering" concept requires the design and manufacturing engineering functions to be addressed right from the first design specifications. Available tools and machines can *thus be considered as the design is developed.* This reduces initial manufacturing costs along with lead times for new tools. Any new tools can be placed on order long before the design is finalized and the drawings sent to manufacturing. The computer can support this concept by furnishing information on tools presently on hand and, if not suitable, furnishing specifications for new tools long before the production drawings are made.

• *Selection of gear tools at the design stage.* A good example of the use of the computer in concurrent engineering is the selection of tools required to make gears during the design of the gears. Table 5 is from an "expert system" gear design program at the stage where the program has designed an "optimum" gear hob. The program designed hob is listed as the "default tool," and two more hobs that are presently on hand are listed, along with their tool numbers and cutting edge geometry. The designer may then complete the design analysis using the new hob designed by the program, or he may use one of the hobs already on hand. Table 6 is the output sheet for the program. Hob 2 was selected and the analysis completed using this hob.

• *Design data for molded gears.* Gears made of plastic or powdered metal require a mold of proper size and shape. Molds for these gears must take into account the fact that the plastic materials shrink when cooling, and the powdered metals sometimes change shape when being sintered.

The steel molds have usually been made by machining an electrode and then using the electrode to produce the mold by electric discharge machining. This required long lead times to procure a special hob to cut the electrode to the oversize dimensions required for the mold, cut the electrode, and machine the mold. Many times the part did not meet the dimensional require-

ments, and the process had to be repeated.

A more direct method of making the mold can be used if coordinates of the mold are available. This method is called wire electric discharge machining. A wire is used as an electrode, and the wire is moved in accordance with a programmed path, producing the mold cavity. The coordinates must, of course, take into account the shrinkage of the material. The computer can quickly produce the required coordinates. The necessity for the gear- shaped electrode and the tooling required to make it, along with the lead time, are eliminated. If any changes to the mold are necessary, a corrected set of coordinates can be quickly produced. Fig. 8 shows the gear tooth and the required mold. (Only one tooth is shown, but, of course, coordinates for the entire mold are produced.)

Prototype Design and Testing

The traditional method of proving a design is to build a prototype and subject it to testing that simulates the service for which the equipment is to be produced. In many cases, the prototype fails the test and must be altered and tested again. The computer can help us by utilizing sophisticated software to identify possible problems before the prototype is built and tested. This can result in considerable saving of costs and time, as building and testing are very expensive.

• *A high-speed precision gear set problem.* A precision ground Class Q12, 8 DP, 34/133 tooth gear set is designed to transmit 2,000 HP at 20,000 RPM. The lubrication was to be with MIL-L-23699 synthetic turbine oil at 160°F. The set was built and tested. The surfaces of the teeth showed distress almost immediately and the test was aborted. The failure was diagnosed as hot scoring due to the lubricant being raised above its flash point in the mesh. Another set of gears was made with the proper amount of tip relief and retested with no further difficulty.

A computer analysis of the gears might have saved the time and expense of the failure of the first prototype. Fig. 9 is a computer-generated plot of the lubricant temperature rise from the start of active profile to the O.D. of the pinion for the first prototype. Table 7 is the computer output for the hot scoring probability for various oils. Note that the scoring probability for MIL-L-23699 is 64%.

Fig. 10 is a plot of the lubricant temperature rise for the second prototype with the tip relief applied. Table 8 shows the hot scoring probability

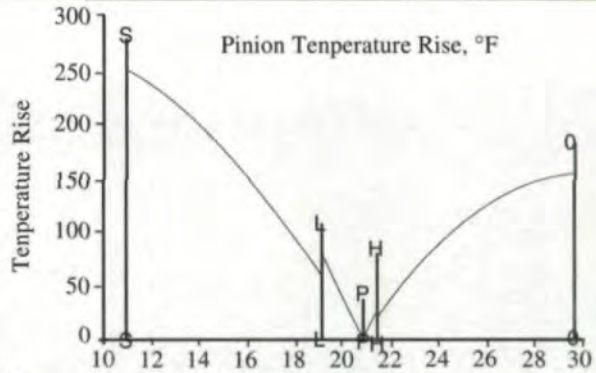

Fig. 9

Table 7 - Scoring Probability - Non-Reactive AGMA & SAE Oils

Flash	AGMA	Score Prob	SAE	Score Prob	SAE	Score Prob
413°F	Gear Oil		Crank Oil		Gear Oil	
	#1	98%	#5W	Over 99%	#75	Over 99%
		94%		Over 99%		95%
	#2	87%	#10W	Over 99%	#80	95%
		69%		Over 99%		20%
	#3	49%	#20W	Over 99%	#90	17%
		23%		57		2%
	#4	23%	#20	Over 99%	#140	2%
		7%		66%		Under 1%
	#5	17%	#30	66%		
		5%		35%	MIL-L-	
	#6	5%	#40	35%	23699	64%
		2%		11%		
	#7	2%	#50	11%		
		Under 1%		3%		
	#8	Under 1%				
		Under 1%				

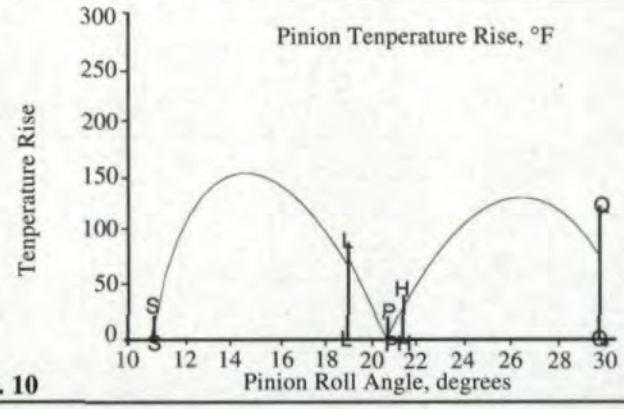

Fig. 10

Table 8 - Scoring Probability - Non-Reactive AGMA & SAE Oils

Flash	AGMA	Score Prob	SAE	Score Prob	SAE	Score Prob
317°F	Gear Oil		Crank Oil		Gear Oil	
	#1	12%	#5W	61%	#75	61%
		6%		39%		7%
	#2	3%	#10W	39%	#80	7%
		Under 1%		19%		Under 1%
	#3	Under 1%	#20W	19%	#90	Under 1%
		Under 1%		Under 1%		Under 1%
	#4	Under 1%	#20	19%	#140	Under 1%
		Under 1%		Under 1%		Under 1%
	#5	Under 1%	#30	Under 1%		
		Under 1%		Under 1%		10%
	#6	Under 1%	#40	Under 1%	MIL-L-	
		Under 1%		Under 1%	23699	
	#7	Under 1%	#50	Under 1%		
		Under 1%		Under 1%		
	#8	Under 1%				
		Under 1%				

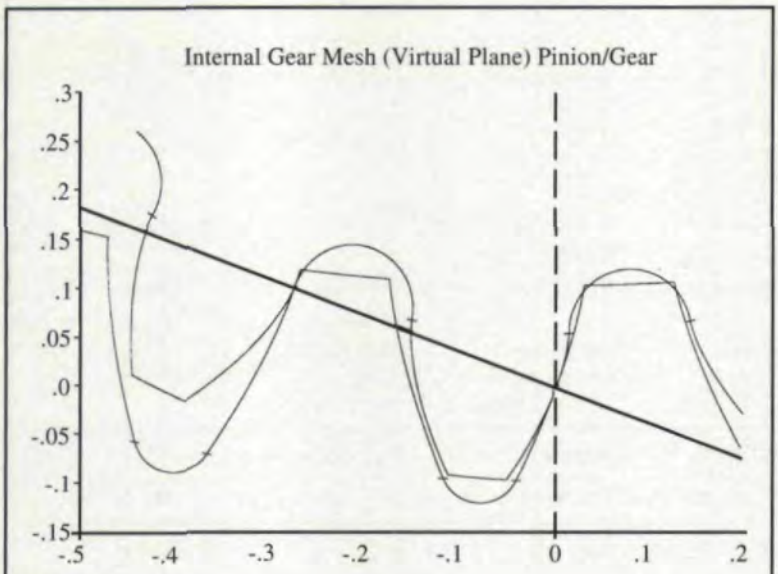

Fig. 11

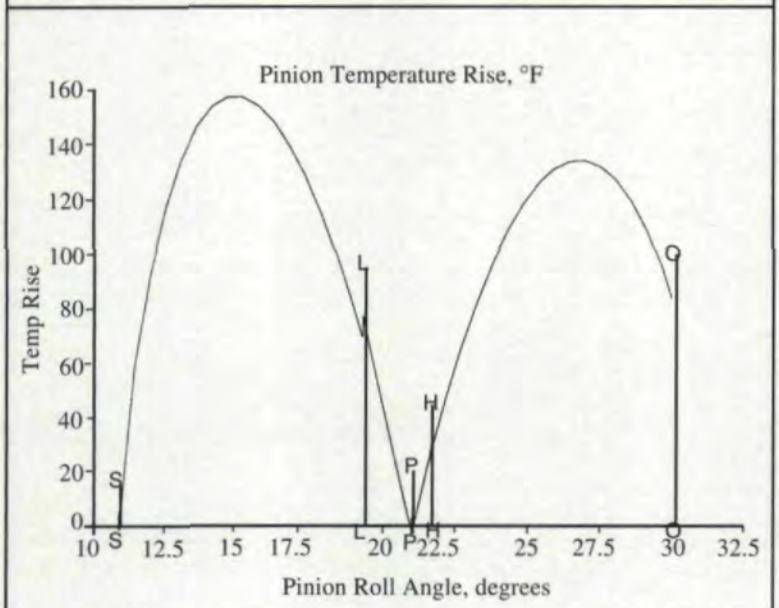

Fig. 12

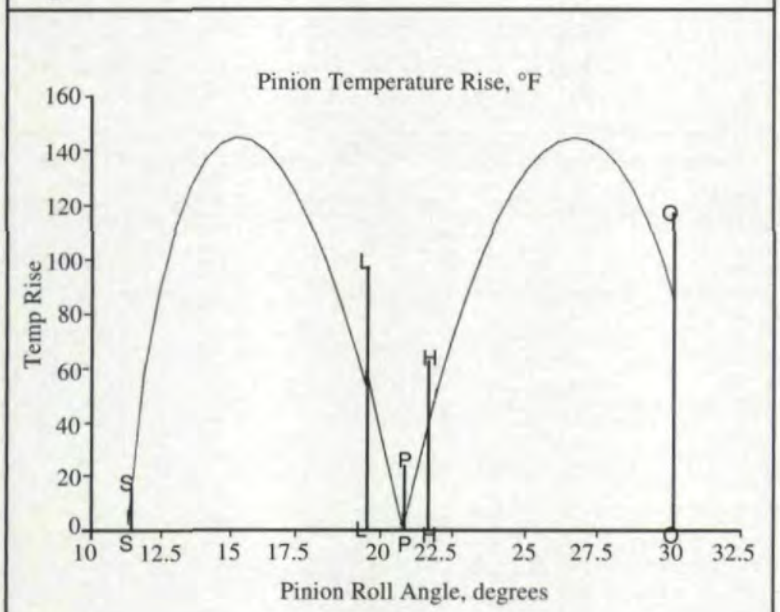

Fig. 13

for the second prototype. Note that the scoring probability for MIL-L-23699 is now only 10%. If the probability of scoring had been checked before the first prototype was built and tested, the expense of the first gear set and testing might have been avoided.

• *An internal gear set geometry problem.* Fig. 11 is a computer plot of an internal spur gear set with a 17-tooth pinion driving a 46-tooth internal gear. The gear set is designed in accordance with standard handbook dimensions. The gears are to be molded and have full circular fillets. On the pinion the fillet starts at the base circle. It is obvious that the tips of the internal gear teeth are interfering with the pinion roots. A test of a prototype would certainly have found this problem, but new molds would have to be made to correct it.

Computer software can be used to generate the plot from only the production prints. This is an advantage because these, not the engineering data, which never reaches the shop floor, are the only documents the manufacturing department sees. The production prints control what is built.

Design Optimization

Without the help of computer software written with it in mind, design optimization seldom takes place. Once a design is obtained that meets the requirements of a job, the process usually stops. It is hard to justify spending more time on improving a successful design when it is not known if there will be a payback. The optimization should be done at the same time as the initial design work.

As an example, we will look at the probability of scoring for a gear set. The temperature rise in a gear mesh is dependant upon, among many other things, the load and rate of sliding between the teeth. For most gears with some tip relief, there are two zones of high temperature rise. One zone occurs when contact is between the first point of contact and the pitch point (where sliding is zero), and the other zone is between the pitch point and the outside diameter. Fig. 12 is a computer plot of the temperature rise vs. the location on the tooth from the first point of contact to the OD. The temperature rise is maximum between the start of action and the pitch point. In this case it is about 157°F. The scoring probability is about 28% for the lubricant being used.

With a small change in the outside diameters

of the gears, it is possible to decrease the rise between the start of action and the pitch point at the expense of increasing the rise between the pitch point and the OD. When they are both the same, we have optimized the scoring probability controlled by gear geometry. Fig. 13 is the plot after optimization. The rise is now about 144°F, and the probability of scoring has been reduced from 28% to 20%.

The cost of the improvement is only the cost for getting the gear geometry right. The tooling cost remains exactly the same for either design. A small amount of time asking "what if" with computer software designed for this type of interaction can pay off quickly with a better design at no extra cost.

Communication with Management Personnel

Good computer software can make communication between technical and management personnel much easier. In many cases, management personnel may not have the time to get into the technical issues, resulting in lack of management backup. This can cause delays in adoption of the latest technologies and even result in delays in production caused by a manager's need to dig for the information he or she needs to make a proper decision. Showing a busy manager a long list of numbers and trying to explain what they mean can take a lot of time and be frustrating for both parties. Computer graphics that can be quickly generated to make a problem immediately clear are most welcome to busy people.

As an example, we will look at a system reliability report on a system containing nine bearings. The required life of the system is 9,000 hours. Each bearing has a calculated life that is different, and so the likelihood that each bearing will run 9,000 hours is different. The total reliability of the system is 43.6%. We wish to improve the overall reliability of the system. Table 9 is the computer data in table form.

The information is in the table to decide the best course to improve the system reliability. Fig. 14 is the same data in graphical form. From the graph it is immediately apparent that the reliability of bearing 3 is the main problem. It is a pretty safe bet that a busy manager would rather be presented with the graph than with the table.

Table 9 - Anti-Friction Bearing System Reliability

Brg #	B-10 Life	Required Life	Reliability
1	22150 Hr	9000 Hr	96.4%
2	18450 Hr	9000 Hr	95.6%
3	3250 Hr	9000 Hr	70.7%
4	26500 Hr	9000 Hr	97.1%
5	34600 Hr	9000 Hr	97.8%
6	52350 Hr	9000 Hr	98.7%
7	9360 Hr	9000 Hr	90.4%
8	7840 Hr	9000 Hr	88.4%
9	8633 Hr	9000 Hr	89.5%
System		9000 Hr	43.6%

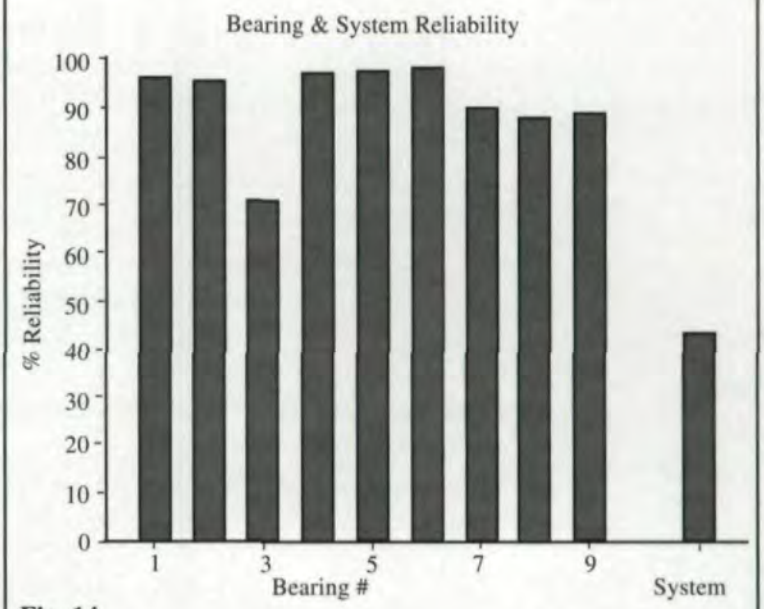

Fig. 14

Summary

Use of computers in product design and manufacturing is now fairly routine. However, to get the best results, it is important to keep the following helpful hints in mind.

- Do not simply computerize cook book formulae. Instead, first organize the underlying mathematics properly.
- Analyze and optimize the total system by first defining and then focusing on your objectives, such as reducing failures, increasing life, reducing noise, reducing cost, reducing lead times, etc.
- Use the concurrent engineering approach to develop product and tooling designs up front.
- Cut down on trial and error by designing correctly to start with.
- Use graphics to present your results to your colleagues and to management. A picture is worth a thousand words. ■

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