Figure 1a

Figure 1b

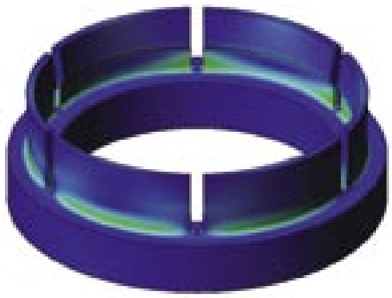


Figure 1c

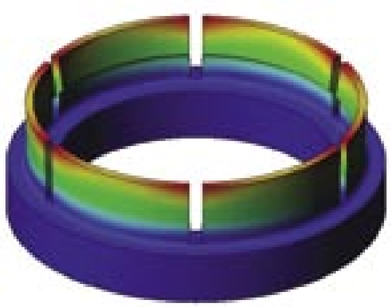


Figure 1

FEA mesh with local concentrations (1a), stress caused by radial displacement (1b) and actual displacement pattern (1c).

Paul W. Suwijn, Gear Resource Technologies Inc.

FINITE ELEMENTS

Workholding is a key link in the gear manufacturing process. Having the wrong tooling setup for the job can lead to premature cutting tool failure or poor part quality. But computer modeling and analysis help workholding designers create the right tooling for each job.

The performance quality of workholding for gear applications can be greatly improved by the use of fairly simple finite element analysis (FEA) methods. Those of us who have labored at engineering for a long time can recall the days when FEA tools were unfriendly, cumbersome, and terribly time-consuming to use. We are all grateful that those days have passed.

Four key changes have made FEA more accessible to current workholding designers. The foremost is the radical improvement in affordable computers. Lots of RAM is the key to time efficiency with FEA problems (at least one gigabyte of the quickest type you can lay hands on), and this is affordable. A quick chipset, fast bus, large cache, and generous hard-drive buffer are all good, too. But today, these are more or less standard equipment on workstation-grade computers.

Second, FEA program writers have defied the old saying that engineering software doesn't need to be friendly, since the users are capable of figuring it out. Current products are marvelously simple to operate, with good help resources built in. As quality has improved, price has come down significantly for the most common FEA program modules, in another expression of the modern economic paradox.

The third key improvement has been in FEA meshing and solving algorithms. If you ever solved an FEA problem in the old days, you can truly appreciate having a reliable solution to a 250,000-degrees-of-freedom problem in three minutes. Time efficiency per single run is the key to optimization. The designer can quickly sample the effect of specific design changes upon maximum stress or spring rate, for instance. This can all be done before committing to the final design. If the problem is set up correctly, the FEA data will normally be reliable within +/– 10% (or better than that, in many cases we have tested).

A fourth real improvement in FEA software, over the last several years, has been its integration with solid modeling software. An integrated FEA program can be turned on or off during normal solid modeling activity. When active, it will operate directly upon the

METHODS

in Workholding Design

Figure 2

FEA study of a barrel collet design showing stress (2a) and displacement (2b) plots using Von Mises stress values in psi.

Figure 2a

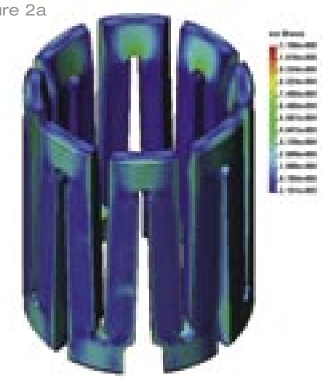


Figure 2b

Figure 3a

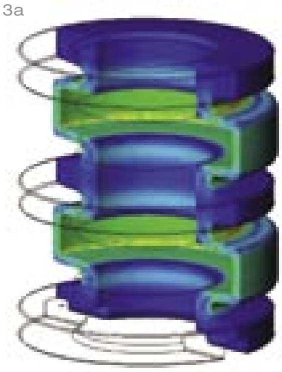


Figure 3b

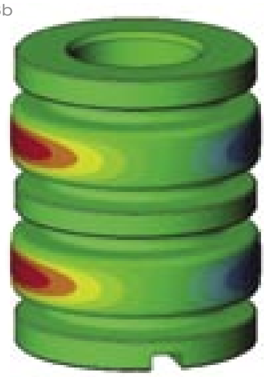


Figure 3

Compression bushing FEA study showing internal and external stresses (3a), as well as expansion, shown in a single-axis plot (3b).

solid model without any translation or hand-off step required. This overcomes the old process of exporting the design file in a neutral format, like IGES or STEP, then accessing that neutral file with a free-standing FEA program.

If we stay within the basic solid modeling program, the business of making small design variations, then re-meshing and re-running to compare results is a simple matter. By contrast, with the time delays and manipulations of exporting, there was a temptation to accept the first reasonable result rather than to optimize the product for the new application.

As workholding designers, we live in the land of the perishable, with little control over unplanned "machine events," out-of-tolerance workpieces, imperfect setups, or improper cycling. But we can use good tools, like FEA, to provide the best possible products for conscientious use.

The goal in our own business, Gear Resource Technologies (GRT), is to optimize every spring element

continued

Figure 4a

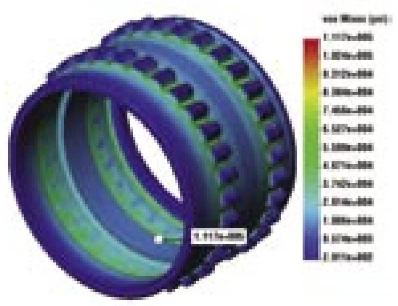


Figure 4b

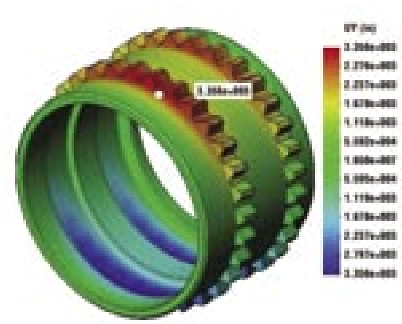


Figure 4

FEA study of a toothed hydraulic sleeve, showing internal and external stress (4a), as well as expansion, shown in one axis (4b).

Figure 5a

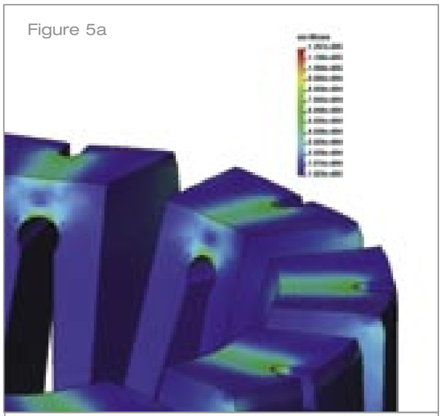


Figure 5b

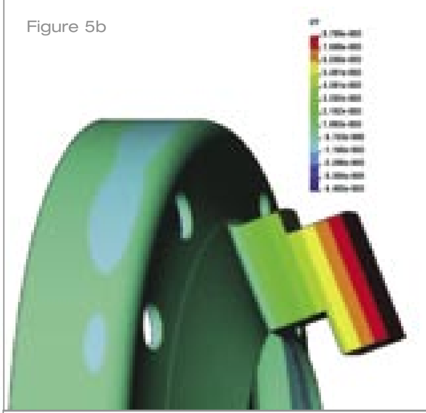


Figure 5

FEA studies of specific spring behaviors, including stress concentration in collet slotting (5a) and clamping motion of a diaphragm chuck (5b).

we design, finding the most sensible balance between maximum stress, spring rate, and element toughness. Then we can move on to other aspects of good design practice, like achieving least possible runout, simplifying setup, and enhancing simple wear resistance.

Spring Elements in Workholding

For the rest of this discussion, let's think of collets, hydraulic glands, compression bushings, diaphragms, expansion disks, etc., as special types of springs. They expand, contract, or flex in proportion to applied force. If kept within safe stress limits, they enjoy good design life. Beyond safe stress limits, we can expect permanent stretching or breakage. Since these springs are typically the most vulnerable part of the workholding assembly, they deserve special attention from the designer.

By making systematic FEA trials on a similar group of parts (variations of a particular style of collet, for instance), valid design rules can be reasonably determined as a guide to future designs of that type. An engineer with established skills might commit a week or two of good work for a systematic investigation of a new class of spring. This would involve looking at the influence of a progression of size and feature changes upon stress and spring rate. Against that time investment, very good general design rules can be identified, with a lot of downstream value. New similar designs will start out very close to correct, from the rule basis, with further FEA work confined to the optimization of each new similar part. Every new case should still be optimized and tested if the goal is to produce the best-functioning product.

Workholding Assembly Behavior

Bending or torsional stiffness of workholding assemblies, in part or as a whole, is also easy to determine by FEA methods. Again, this approach is much more efficient and timely than the traditional method of deducing approximate rules of thumb from physical tests and performance history after build. Those forms of feedback still have their place, of course.

In the case of small-bore workholding, for example, it's possible to predict how much torsional windup or bending will occur in key portions of the workholding assembly from the tool forces. Those FEA-derived values can be compared with gear tolerance limits before going further.

GRT recently executed a workholding program for General Motors Powertrain in which several small bore clamping designs for a very aggressive gear hobbing application were compared for stiffness values. Results were carefully reviewed with the customer to help determine the best design approach. FEA outcomes turned out to be quite predictive of hobbing quality outcomes, though it wasn't necessarily obvious to the eye which of the competing designs would be best.

Traditional calculations can be applied

to assembly windup and bending problems, within limits. The standard formulas are based on very simple geometric forms, though, so they're often hard to apply with equally good accuracy to the unusual shapes that we often develop in workholding assemblies.

In another FEA assembly example, we were happy to decline an invitation to design a very small diameter hydraulic arbor, which had internal fluid pressure at or above the shear limit of the best seal materials. The hydraulic gland was capable of operating within acceptable stress limits, but the actuation would have required a steel diaphragm as an actuator rather than a conventional piston-seal combination to work without leakage over time. These critical factors are difficult to calculate by hand.

The power of current-art computers allows us to analyze large complicated elements or assemblies, either in part or as a whole, without too much simplification. Some simplification of small, irrelevant details is almost always done, however, to speed FEA run time. This can be accomplished by temporarily suppressing solid model features like chamfers, non-critical radii, or small holes distant from stress concentration points before proceeding. Determining how far to go with simplification is a matter of experience. When evaluating gear machine loop stiffness, simplification can go quite far actually, as long as the spring rates and manner of attachment of the weakest links in the system are properly defined.

Interpreting FEA Results

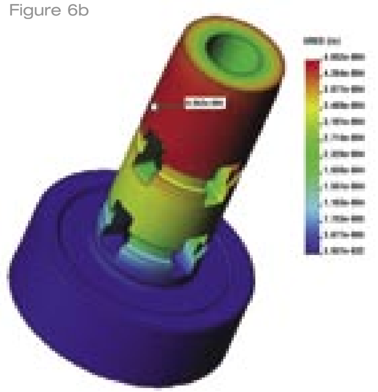
FEA software contains no instructions in metallurgy. The interpretation of good FEA outcomes requires a solid understanding of conventional metallurgy. In the ferrous world, this has to do with balancing toughness and hardness for a given material and heat treatment process. Apart from the key matter of alloy selection, one has to understand that phase composition, grain size, and residual stress of ferrous materials will vary substantially by heat treatment, with big corresponding influences upon toughness at given Rc (hardness) values.

Figure 6

Study of torsional stress and windup in a sliding-shoe arbor nose resulting from gear hobbing forces.

Figure 6a

Figure 6b



Tensile stress concentrations are the usual killer of springs. For instance, if you read the fine print in standard Belleville spring tables, you will see that only tensile stress limits are given, while higher compressive stresses are ignored. At GRT, we distinguish between tensile and compressive stresses when we review FEA outcomes, taking both into account against certain acceptance standards. Designers new to the trade may take false comfort from the way in which tensile values soar as hardness increases until they come to appreciate the less quantifiable role of toughness in the failure equation.

The metallurgical goal of workholding design is simple. We strive to make the active contact surfaces as hard and wear-resistant as practical, while maintaining adequate toughness at the extreme state of use. The key to success lies in establishing definite controls on the extreme state of use—by always incorporating appropriate physical travel limits. A few FEA runs will reveal the travel limit that ought to be applied for any given spring design.

At GRT, we always concentrate on evaluating the limit case first—the case of actuation with no workpiece in place. Stress concentrations that will cause permanent stretching or breakage are seen here, and they are generally easy to pinpoint by FEA. No other method we know of comes close.

After evaluating the limit case, we return to a study of average clamping motion. From these secondary FEA results, we identify the motive force that will provide secure workholding without stretching, compressing, or distorting the workpiece unacceptably. Since energy conservation is always at work, the part of the motive force that flexes the clamping element can't be re-used. So workholding is accomplished by the remaining force, with other factors like mechanical advantage, coefficient of friction, radius, and some de-rating for imperfect contact pattern coming into play. We also make sure that the reaction force (desire of the spring to return to its original form) is high enough to complete the return motion, after the workpiece is released. The softest spring designs are not the best, in this last regard.

In our business, we are routinely invited to review existing workholding designs

continued

Figure 7

Study of spring-stress in an index timing bracket (7a) and the bracket's function in the workholding assembly (7b).

Figure 7a

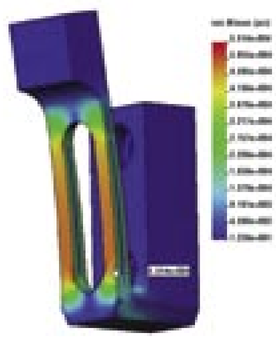
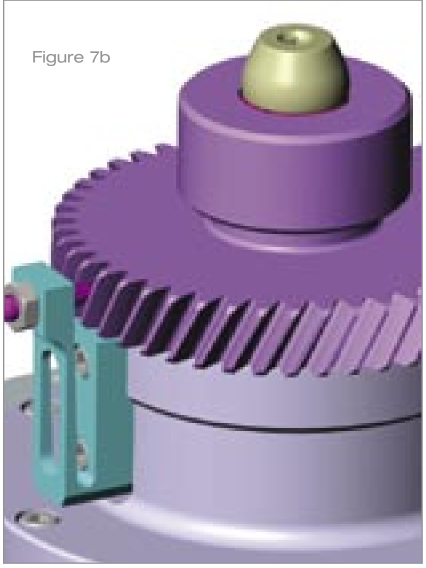


Figure 7b



that have suffered from inappropriate spring-element travel limits—created from loose rules of thumb and applied with bad consequences. It's usually not hard to find the fix for these cases, though that sometimes involves remanufacturing the arbor base or nose, in addition to optimizing the collet, hydraulic sleeve, or compression bushing design.

In general, FEA outcomes strongly agree with well-informed common sense. The great trouble with rules of thumb, used everywhere by sensible people to build our world, is determining how close to the line one is treading. FEA methods allow us to better direct our already good mechanical intuition.

Very simple design changes are often all that is needed to convert problematic designs into ones that can be comfortably recommended. In other instances, a couple of early FEA runs may help us decide that it's necessary to modify the design at a deeper level. There are a great many workholding design cases where the traditional recourse to overbuilding is not an option because of space confinement. Workholding springs have to be designed so they are neither too soft nor too stiff, within an acceptable stress limit.

To get good FEA results, we need to apply restraints and forces that truly characterize the problem. This is sometimes easier said than done. For instance, the wrong characterization of conical contact patterns between expanders and collets can cause misleading results. While it's easy to select the entire collet cone as a contact zone, more often the actual contact will be confined to quite local areas, at one end or the other of the conical surface. We won't obtain true results unless we confine the contact to those small, localized areas. The old programmer's expression, "garbage in, garbage out," does apply.

As mechanical engineers, we recall learning how to construct free body diagrams back in our undergraduate days. Later on, we came to appreciate the pivotal importance of those simple lessons to our work. FEA outcomes in workholding design are only as good as the designer's skill at identifying key vectors and contact patterns for these normally simple mechanisms. Because the use of the software is now so easy, we can concentrate on problem setup, the most critical part of the process.

FEA Software for Workholding Design

For most workholding engineering, basic statics FEA software is the real workhorse. We advise against using "lite" versions of any FEA software. There is real danger in using software that doesn't tell the whole story. The combined cost of purchase, training, and annual licensing of full-capability statics FEA programs has become quite reasonable.

But statics FEA software has two main limitations. First, the accumulative effects of impulse from quick expansion or contraction, or any other type of sharp intermittent loading, are not taken into account. If the acceptance standard for FEA results is conservative (e.g. safety factor > 2), we can generally ignore impulse for most workholding cases, since clamping motions ordinarily require at least a few milliseconds to complete.

The other limitation of statics FEA software is that accuracy is best when deflections are very small. In most workholding designs, spring travel is deliberately confined by hard physical limits, so this is not a big issue. However, as the amount of spring motion increases, stress values from statics FEA are progressively exaggerated, to the point where they are really not predictive for large flexures. For typical small spring motions, we can think of this slight exaggeration as an added safety factor.

More accurate stress data can be