EDITORIAL

The Seven Immutable Laws of CAE/Test Correlation

Greg Goetchius, Contributing Editor

General Motors vice chairman Bob Lutz wrote a book in 1998 called *Guts* (John Wiley and Sons) about his time at Detroit automaker Chrysler Corporation. In the book, he developed seven "immutable laws of business" that were quite controversial – if not outright heresy – when compared with most traditional business standards. In reading these "laws," it occurred to me how similar his ideas are to what we noise and vibration engineers face with the ever-growing use of computer-aided engineering (CAE) models in our work.

I agree with Lutz's unconventional approach in that even if his laws could ultimately be brought down by the weight of evidence against them, the "disruptive nature" of his statements really got people thinking and inevitably sparked a debate in the business world, It continues to this day. Sometimes a little bit of debate can be a good thing. Having thought about this for some time, I have attempted in this editorial to transform Lutz's "business laws" into "CAE laws" with special attention paid to the subject of correlating CAE models to test. For the sake of illustration, I will repeat Lutz's seven laws:

1. The customer is not always right.
2. The primary purpose of business is not "to make money."
3. When everyone else is doing it, don't!
4. Too much quality can ruin you.
5. Financial controls are bad.
6. Disruptive people are an asset.
7. Teamwork isn't always good.

It is fair to say that if you have never read these before, you are probably somewhat alarmed; you may have immediately thought of many examples where these laws are wrong – and you're probably right. However, Lutz makes the point that each one of these laws requires a bit of explanation (most of the book is spent explaining his laws), and once you understand his rationale behind each statement, you can see what he is driving at. Similarly, I will attempt to make some brief points about each of the "CAE laws" I propose here.

Please be warned that if you have read some of my previous editorials, you will note how some of these CAE laws are in direct opposition to what I have previously written in these pages. I will explain. So without further adieu, here are the "Seven Immutable Laws of CAE Correlation."

1. **The test is not always right.**
2. **The primary purpose of a CAE model is not to correlate to test.**
3. **When everyone else is correlating, don't!**
4. **Too much correlation can ruin you.**
5. **Correlation metrics are bad.**
6. **Disruptive engineers are an asset.**
7. **Cooperation between test and CAE isn't always good.**

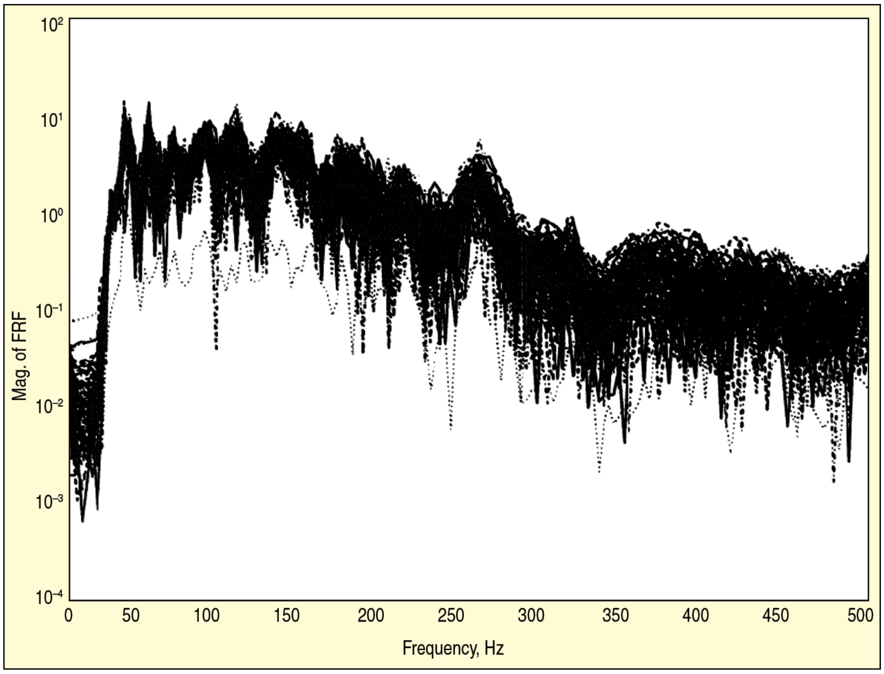

Figure 1. Structure-borne noise transfer functions for 99 'identical' production vehicles.

1. The test is not always right. One of the biggest traps that noise and vibration engineers can fall into is that CAE models must replicate the test results exactly before confidence can be put in the CAE model to make engineering decisions. While it may sound reasonable to expect that models correlate, it is based on the assumption that the test is right.

As all of you who have performed any type of measurement know, there are many places where the tests can go wrong (and often do). However, let me not even highlight the areas where test engineers and test equipment can cause problems. Let's only talk about Mother Nature here, specifically the randomness that is inherent in the universe. Though our world seems to be mostly ordered, we can never forget the law of entropy (the universe is continually moving toward greater disorder). This manifests itself in the often-unpredictable behavior of many of the systems we measure. Most of us know at some level that there is a statistical uncertainty in our measurements, but many of us are not sure the degree to which it extends.

To demonstrate this, Kompella and Bernhard performed a study in 1993 on 99 identically built vehicles directly off of an assembly line (SAE 931272). Their work was published in the 1993 SAE Noise and Vibration Conference proceedings, and I will show one of their key results here.

Figure 1 shows the structure-borne noise transfer function from the wheel spindle to the driver's ear for each of the 99 vehicles. Note that there is a huge spread of these data, as much as 20 dB above 250 Hz. Before you complain, please know that Kompella and Bernhard went to great pains to control their experiment, so this result is highly reliable. I would encourage you to read their paper to see the details.

This result has tremendous implications for the CAE world. Ignoring for a moment any human or equipment error, one can see immediately that there is no such thing as the 'correct' test result.

2. The primary purpose of a CAE model is not to correlate to test. I have known many CAE engineers whose main motivation for coming to work each day is to work on their model to get it 'right.' While this is a noble cause and certainly an important aspect of their job, the act of correlating a model is merely the means to an end. The real reason for building models is to solve engineering problems.

Well-intentioned engineers often spend far too much time attempting to correlate their CAE models. They spend countless hours running tests, running and rerunning models, post processing data, plotting results, re-plotting results, and so on, until they achieve 'correlation' or until they give up. Often, they simply run out of time and just say "good enough." If only they had known that the test wasn't right.

3. When everyone else is correlating, DON'T! It's easy to fall into the "correlate-or-perish" trap and waste precious time trying to force a square peg in a round hole. I do not mean that CAE model correlation is not important. However, I do mean that given the uncertainty in the test data and the complexity of today's CAE models, engineers should be careful to spend only enough time on model correlation to answer the basic question: "Does the model predict physical behavior well enough for engineering decision making?"

The next – and more *important* – question is: "What is "well enough?" I wish I had a definitive answer that there were some correlation metric (see Law 5) that if satisfied would guarantee that our CAE model is correlated. Unfortunately, none of these things exist in whole. However, there are some considerations we should think about when asking this question.

Is absolute value prediction performance required? In other words, must the model be used to certify the actual performance level of some future design against a known requirement (e.g. environmental noise)? In many cases, physical hardware is not available until the system under investigation is "in production," in which case the models must be used to predict the absolute performance level before the design can be accepted. In this case, a very thorough and meticulous process of correlation must be used to ensure that the model behaves properly. I propose such a process later in this editorial.

Will the model be used only to "sort alternatives" where it is more important to predict design change trends rather than absolute values? This is a much more common situation, and in this case, engineers can be more 'creative' in how they judge the correlation performance of the model.

4. Too much correlation can ruin you. I could repeat what I wrote in Law 3, but I'll simply ask you to refer to it now.

5. Correlation metrics are bad. There are many CAE test correlation metrics in use today. The most popular by far is MAC (modal assurance criteria). This metric tells engineers how close the mode shape of their model is to the mode shape measured in test. As metrics go, it works pretty well, but since it only looks at mode shape, it is an incomplete picture. Other metrics exist, like frequency response assurance criteria (FRAC) as well as a metric proposed by Moeller, *et al.* (SAE 1999-01-1791) based on statistical analysis of frequency response functions (FRFs) from a CAE model and a sample of test vehicles.

Moeller's metric is quite powerful, but like many metrics, falls short of ensuring good correlation. Why? Because metrics are inherently 'robotic' and void of any human judgment. My experience has been that correlating a CAE model is about 50% metric based and 50% engineering judgment. No metric can synthesize a 'goodness' ranking from the examination of a combination of mode shapes, frequency alignments, the shape and nature of FRFs, and so on. These data are telling the engineer something about the physical behavior of the tested system and the behavior of the model. It is up to the engineers to look at these metrics and examine the details of the data and decide for themselves if the model is correlated. This last statement is a hint at what I value most in CAE: *knowledge and application of the physics of sound and vibration.*

Without knowledge, there can be no judgment. Without judgment, there can be no correlation.

6. Disruptive engineers are an asset. Call it "stoking the fire" or thinking "outside the box" or just being somewhat unconventional, but it's true that progress is almost always achieved by someone who disrupts the status quo (just so the disruptive person is not a negative influence). There are certainly those engineers out there who are part of this CAE test correlation process and who have strong opinions about this discussion. I would encourage them to voice their opinions and perhaps shake things up a bit. Naturally, please do so in an honoring, respectful and professional way, but by all means do so!

In fact, this editorial is designed to be just a little 'disruptive.' It's my hope that it sparks thoughts and reactions that get people thinking and talking about this important issue.

7. Cooperation between test and CAE personnel isn't always good. In my last editorial on the gap between test and CAE, I made the argument that there should be much more collaboration between the two groups, and I believe that is still true. You might be wondering, how I can reconcile that position with the statement in Law 7. Here's the point (and it's the same as Lutz's): teamwork *can* be good, but only if the team eschews "the safe, the familiar, the middle of the road, the well researched" to use Lutz's words directly. If the team is locked in consensus decision-making or is stuck bickering about whose data are correct and whose are not, then that team is not working effectively.

Teams need good leadership both internally and externally and need to be held accountable to achievable goals. Ultimately, teams must deliver solutions to noise and vibration problems using a combination of engineering know-how, empirical data and CAE predictions. They must make decisions and then act on those decisions, rather than just having weekly meetings to review and discuss status.

CAE Model Creation

Until now, I have not had the chance to share one more important aspect of this situation: CAE model creation. Much of the discussion and effort that goes into CAE model correlation could be eliminated if the creators of these models had the knowledge and experience to build the models with a high degree of respect for physics to begin with. So much of model building these days has become a "push-button" activity in that much of the human element is missing. When models are built this way, they can often be notoriously difficult to correlate, since there can be systemic problems deeply imbedded in the model that are extremely difficult to find. This is often the result of assumptions that were never deeply thought through, investigated, or properly implemented by an experienced engineer.

I like to think of CAE model creation much like the creation of sculpture. Yes, it is true that one could cut a highly accurate and good-looking statue using state-of-the-art technology like a 5-axis milling machine. However, in the hands of a skilled and creative sculptor, a block of granite would give way to a piece of art whose subtleties and "perfect imperfections" and presence could never be replicated by a machine, making the artist's work infinitely more beautiful (and better) than a machine's.

In the same way, when CAE models are built by experienced engineers who are not afraid to pit their knowledge against that of a machine, challenge assumptions, and thoroughly investigate the physics of the situation before simply adding the next card to their data deck, the models are so far along the road to "good correlation" that much of the correlation effort is not needed.

Model Correlation Methodology

In light of the previous discussion here and given that model correlation is, in fact, an important step, how should we proceed with this important task? I would like to now share what I think is a "best-practice" methodology for building and correlating CAE models. This is based on my own experience as well as many others, including Moeller. *et al.*, whose *pro form*a (outlined in their SAE paper) forms the basis for this section.

CAE models are often a complex assembly of many components. It is too easy to rush and model all components, assemble them into one huge model, and immediately run it to "see what it can do." This is a disaster waiting to happen. That would be like taking a rocket-propelled race car to the salt flats and going flat-out to gain a land-speed record the first time out. At the very least, you probably won't set any records, and at the very worst . . . who knows?

Therefore, I recommend an approach that starts at the component level and slowly increases in complexity and assembly of the model, checking to make sure all systems are OK before proceeding to the next assembly step. This will take much more time at the outset than may be available, but in the end, it will ensure a much shorter correlation time and a much higher quality model.

- Model each component carefully.
- Collaborate with your test counterpart – or better yet – do the testing yourself, but perform carefully designed tests on several identical components (remember entropy) against which you can compare your component model behavior. Use

MAC, FRAC, or whatever metric you have, but also use your eyes and use your mind. Let your knowledge of physics guide your decisions along with these metrics.

- Assemble some of the components into key assemblies or subsystems.
- Challenge assumptions about how parts come together. *It is the interface between parts of a model where most errors are made and where much correlation effort is ultimately focused.* Are the parts welded? Are they bolted? Is it a single-point connection? Line connection? Challenge these assumptions by performing simple tests and convince yourself that it's OK, for example, to model a spot weld as a single rigid-point connection. It's not!
- When necessary, use empirical data in the model (rubber isolator rates, moments of inertia, damping , etc.), but understand the nature and origin of this data. Under what conditions were the data measured? Are those conditions consistent with the conditions being modeled?
- Repeat the previous steps on all components and subsystems until all subsystems are complete, and then assemble the final model.
- Get up from your computer and walk down to where the system will be running (or one like it). Watch it operate. Listen to it. Feel it. Talk about what's going on inside the machine with other engineers or the machine operator. Start to form a picture in your mind of what kind of boundary conditions and loads you will need to design, and what kinds of responses make sense to calculate. Even if the 'model' itself is perfectly correlated, if the boundary conditions, loads and responses are ill devised, the results will be worthless (except as additional input to the correlation process).
- Compel your test counterparts (or do it yourself) to measure a statistically significant ensemble of physical systems. You ***cannot*** correlate a CAE model to a test sample size of one. Let me state that again, but slightly differently: *You* **will not** *successfully correlate a CAE model to a test sample size of one!*
- Compare the full system CAE results to the statistical test results from the system. Use MAC, FRAC, Moeller's statistical metric or whatever metric you have, but also use your eyes and mind. Let your knowledge of physics guide your decisions along with these metrics. (This should sound familiar.)
- Update/improve the model and revalidate. Double-check boundary conditions, loads and response calculations, since these are often assumed to be correct and are frequently the source of many correlation problems.
- If time allows, make a physical change to the test systems, and mimic the change in the CAE model. Re-examine the correlation using the same metrics and engineering judgment as above.

Congratulations, if all went well, you should have a correlated CAE model!

Notice I never said what it means to correlate. That is up to you and is based on answering the two questions I posed in Law 3 (absolute value or trend prediction) as well as a deep understanding of what the model is being used for, and probably most importantly, an equally deep understanding of the statistical variation in the physical systems you will be modeling.

Closing Thoughts

My hope in writing this editorial is to spark some controversy and otherwise 'disrupt' the status quo of current noise and vibration CAE modeling processes. By doing so, I hope to create increased dialogue and discussion among all those who read these pages and those who are involved or affected by the use of CAE models in solving noise and vibration problems. I do not expect you to agree with anything I have written, but I do hope you form an opinion, one that I would be glad to hear and discuss with you at great length. Ultimately, I hope that this discussion leads to the better use of CAE, so that we can truly achieve innovative, efficient and value-added solutions to the myriad noise and vibration problems that we face every day. Ready, set, correlate! SV

The author can be reached at: greg.goetchius@matsci.com.