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UNCERTAINTY MANAGEMENT AND KNOWLEDGE GENERATION IN CAE

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Abstract. *Computer-Aided Engineering is experiencing a period of crisis. The increase of speed of computers in the past decade has indeed made it possible to run increasingly large computer models, but the amount of progress, and knowledge, that may be attributed directly to the usage of High-Performance Computing, has not grown in proportion. In fact, something quite opposite is taking place. Excess of computer power has induced, in the CAE community, the belief that, due to some divine interposition, we have now automatically entered the realm of virtual prototyping. It appears that now, we can eliminate testing and do everything "virtually". This transition has come about very quickly, almost inadvertently, and no one has really noticed thanks to which advances in finite elements, modelling and simulation techniques, can we rely entirely on the computer as source of knowledge. The scope of this paper is to first analyze the dogmatic and orthodox character of contemporary CAE, and to illustrate how, upon departure from the authoritative paradigms of CAE and HPC, computers can become an important machine of knowledge generation and computation.*

1 INTRODUCTION

There is an on-going debate on whether computers can help generate knowledge. As we know, the oldest form of generating knowledge was experimentation. Ever since man has started to experiment, initially without any rigor, almost accidentally, and later, thanks to Galileo, in a more or less systematic manner, he has realized that knowledge is equivalent to experience. Experience, on the other hand, is a set of conclusions drawn from repeated experiments. This is a very important point. Experiments, in order to lead to correct conclusions, must be repeateable, and therefore need to performed more than once. We all recall the famous cold-fusion expriment which nobody was able to repeat. This fact said more about the advocates of the experiment rather than about its underlying physics. Experimentation has been forbidden for a very long time. Since Aristoteles has established his dogmatic approach to "science", it was unnecessary to perform any experiments since any theory built on dogmas, that is upon absolute truth, doesn't require verification. It was only in the times of Galileo that people timidly realized that freedom of thought is necessary in order to acquire new knowledge. The Inquisition was very efficient in embracing the teachnings of Aristoteles and turn them into an intellectually damaging business that lasted till the mid-nineteenth century. Today, a strikingly similar situation pervades CAE and HPC, but we'll get to that later. One of the most damaging orthodoxies that came from the Aristotelian-Inquisition partnership, that many people still believe in (especially those who study horoscopes!) is the geo-centric model of the Solar System, which was officially supported by the Church till the eighteen-fifties. For almost twenty centuries nobody dared to question the Ptolemaic model. There were three very good reasons to do so. First of all, anything that is dogmatic, is based on authority rather than on truth. Authority cannot be questioned. They'll crucify you if you do. Secondly, the geo-centric system did predict the movements of the planets. Unfortunately, as philosophwrs have often demonstrated, different theories can equally well fit the same set of observations. For this reason the geo-centric model has been accepted for so long. Finally, the geo-centric system was complex. It was built on the perfect (divine) geometrical figure (the circle) and upon epicycles. The problem with complex theories is that they are difficult to dismount and discredit, especially if blessed by some recognized authority. Simple theories appeal less, are less pleasing aesthetically. The same holds for engineers. A complex model looks more credible. How can anyone question hundreds of thousands of finite elements?

Let us see briefly what are the dogmas that pervade contemporary CAE and that insulate it from physics, turning it into a new digital religion. The first one is that of determinism. Determinism is fundamental for Western Culture. Why? Because Western men want certainty, not knowledge. It is indeed incredible, we are surrounded by infinite forms of uncertainty, and yet authority has imposed the deterministic perversion at all levels of human activity. From determinism stems reductionism, the obsession with details. All those practicing deterministic CAE believe in reductionism. The more elements you throw in, the better the result, until finally, you reach the "exact solution", perfection, full control. The result of reductionism is intellectual fragmentation, the false belief that the study of miniscule details leads to the full truth about the whole. The prophets of reductionism forget that the closer you look, the less you see. One thing is clear, this approach obfusctes the whole picture and gets people away from the important things. Maybe that is the whole point. However, we must be aware of the fact that the whole can be greater than the sum of the parts. Especially in nonlinear system. Engineers prefer to speak of safety margins, rather than on probabilities of failure. Evidently, the word safety, induces confidence, and is therefore reassuring and popular. Probability of failure, on the other hand, is already admitting that failure may occure. Clearly an uncomfortable job-threatening and embarassing condition. But, as life teaches through countless and repeatable experiments, there is no such thing as a safe structure. There is no real evidence of the existence of absolutely safe systems and yet people compute and design structures from this very perspective. The parallel with the authoritative nature of religious beliefs is striking. No one questions, nobody verifies, all believe blindly.

Further consequences of determinism are other orthodoxies as accuracy, optimality and, of course, predictability. Engineers want to predict. Academics want to predict. Predict accurately, and, of course, reach the optimal solution. One fundamental point people overlook is that the essence of science is to help comprehend and explain, not to predict. Predictability in an uncertain environment is an illusion. Optimality, in an uncertain environment, is an appealing fetish. Nature very often strikes us with its solutions to the problem of adaptivity and hints unthought of approaches that inspire engineers. And yet, nature never optimizes, nature creates designs that are fit for the function. Optimality, or excessive specialization, always leads to a brittle and fragile result, which in most cases minimizes the chances of survivability. Should the same concept not apply to engineering as well. Nature opted for robustness, CAE for optimality.

The goal of science is to match theory with experiment. This requires that both theory and experiment meet on some common plane, a conceptual and technological platform where a common language and common procedures may be adopted and where comparison is possible. Today, in CAE, theory has been substituted by numerical science and experimentation has been eliminated completely. Of course, people say, CAE is done by computer, by definition. Why then introduce testing into CAE? Isn't CAE all about eliminating testing? About eradicating the experiment, the hallmark of science. Science is all about repeatable experiments. CAE wants to kill experimentation. The reason is clear. There is no common platform where to meet and there are dogmatic beliefs that could be endangered. Why risk? If determinism may be regarded as a religion, then the strive to quickly eliminate testing from engineering is nothing but a violent outburst of orthodoxy and bigotry. Thomas Kuhn has shown in his influential book, [**?**], how excessive articulation of a branch of science reflects its state of crisis. One of the most damaging concepts in CAE today is optimisation. Just think how many commercial tools are now available on the market that enable to optimise. They all employ more or less most of the known optimisation techniques, in different disguises and flavors, and all convey the same orthodox message: search of the global minimum, search of perfection. Clearly, there is no such thing, but since a fabulous cathedral has been built, based on response surfaces, partial dericvatives and gradients, how can we now tear it down? There is an overall trend towards increasing sophistication and quality but on the false assumption of full controllability and determinism. Western culture has tried to axiomatize uncertainty out of engineering, to prune it like weeds from a garden. The deterministic approach is intolerant. There is no space for contraddictions, and this fact is what makes CAE live outside of physics. CAE lives in a world of our own pleasing physics. Our lives are dominated by mechanically imposed patterns and it is thanks to these patterns that CAE has arrogantly become bureucratic, disconnected from physics, reductionist and impersonal, almost "geo-centric". Habits of the mind produce distorsions and deceptions about reality, especially if they are imposed.

2 UNCERTAINTY MANAGEMENT: THE WAY TO KNOWLEDGE

The first thing is to accept uncertainty as a fact of life. Nature has been hinting this repeatedly, showing us that uncertainty exists from quantum to cosmological scales. Take weather for example. We have the full science of weather, but our "predictability" is limited due to uncertainty. It always will, no matter how much computing horsepower is dedicated to weather modelling. The weather system is what scientists call a complex system. Complex systems, such as the ecosystem, the economy, society, climate, arise on the border of chaos and order, where Nature is most creative and prolific. Great lessons for engineers may be learnt from the study of complex systems. Engineers also build complex systems, and often they fail due to trivial causes. The thing is, that when complexity and uncertainty combine forces, something quite unavoidable, subtle changes in the system, and especially in its surrounding environment, can bring about a multitude of macroscopically different responses. These responses are never repeatable, but arrange into recognizable patterns, attractors of behaviour. Engineers should also look for these patterns, because they carry the knowledge, the understanding. When we crash many "identical" cars against the same wall, we never get identical results, but what happens under the hood may be arranged into patterns that have common features. Feature extraction, not obsession with detail, is what learning is about.

The study of complex systems, and of the implications that uncertainty has in these systems, is the key to knowledge. The fundamental mistake that is often made when studying complex nonlinear systems, is the breaking up of the system into sub-systems and then studying each separately. This reflects the illusion that the whole is equal to the sum of the parts. It is like saying that $f(x+y) = f(x) + f(y)$ when f is nonlinear!

Clearly this is nonsense. Surprisingly, this "synthetic" approach is very popular and has been beatified to such an extent that nobody notices what it implies. This dissection and fragmentation, apart from killing the nonlinearity in a system, kills also the subtlety, and with it, artificially simplifies the real problem to a mere numerical caricature. Understanding stems from the study of the whole, of the interactions between components, not in the details of the components.

The deterministic tunnel-vision is today most evident in an entity known as the response surface. The Response Surface Method, in conjunction with DOE, the Design Of Experiments, is probably the most evident manifestation of the orthodox nature of contemporary CAE. The recent introduction of stochastic simulation techniques into CAE, has exposed some of the violations of physics that DOE and RSM are based upon. If we want computer simulation to become a source of knowledge, we must abandon deterministic adventures and look reality into its eyes. But let us examine brielfy the weaknesses of the DOE-RSM-optimisation paradigm. First of all, DOE samples the design space without knowing the response. Clearly, the responses of our system that are most likely, or frequent, deserve more "sampling density" in order to describe these response in more detail. DOE does not discriminate the importance of different response mechanisms since they are a-priori unknown. And they can't be. Secondly, DOE selects combinations of design variables that are not based on the physics of the problem and, in general, the same tables of values can be applied to any problem regardless of the physics. It doesn't matter to DOE if your running a CFD or a structural mechanics problem. Now, because of the cost of DOE increases as we increase the number of levels, the response surfaces are limited, by some sort of inquisitory convention, to order two. Incredibly, without knowing a-priori the response, one decides that a second-order multi-dimensional surface will describe the physics correctly! Clearly, mathematical abstractions like the response surface cannot, for example, bifurcate, and yet they are frequently used in car crash studies. Bifurcation are, however, one of the fundamental mechanisms through which physics manifests itself. DOE and the RSM clearly emasculate reality and provide a flat slice of physics. However, those who work with response surfaces also attempt to have a go at uncertainty. What these individuals do is actually brake the $f(x + y) \neq f(x) + f(y)$ rule. They first compute the response surface, then, once the surface is available, they introduce uncertainty into the surface's variables (the design variables). But uncertainty shoud be introduced $before$ the surface is computed, not after. Mixing order is possible only in linear systems. The problem is, however, that respecting the correct order arranges the responses into clouds of points through which a response surface will rarely pass, not even a surface of the highest order.[1] Therefore, people close an eye and play with

[1] These clouds of responses, known as meta-models (or Value Landscapes) can be computed naturally with Monte Carlo techniques, which are know to preserve their information structure. Response surfaces pale in the presence of meta-models and provide a tiny fraction of the information that meta-models can convey.

overly complex procedures which introduce further error and uncertainty. This additional uncertainty, which originates from order mixing, is difficult to quantify unless one resorts to Monte Carlo Simulation (MCS). But, once an MCS is run, we don't need to go back to any other method since MCS is approximation-free and provides an undistorted picture of reality at the same cost of a large DOE-RSM experiment. MCS performs major surgery of contemporary CAE. MCS makes you realize that once you leave linearity and determinism, you're navigating on a very broad ocean. But the advantages of MCS do not end here. MCS, being a model-free approach, preserves all the complexity and subtleness of a physical system. It helps to understand uncertainty and to embrace the possibilities it offers rather than to fight it. Essentially, MCS is a non-destructive way of doing CAE (see [**?**] for details). Monte Carlo techniques are the basis of simulation as the third form of knowledge generation besides theory and experimentation. MCS lets you live off physic's income, rather than on the depletion of its capital (like we do with the ecosystem). Monte Carlo has shown that responses arrange into rugged landscapes, where most of the contemporary numerical tools fail. Science does not accept large creative steps. Would we expect large steps in CAE? By all means, no! But we must be aware, that if uncertainty is not included in our computer models, these models will become increasingly speculative and illusory. Uncertainty enables us to see the truth beyond our restrictive ideas of reality, beyond the pop-science propagated by the response surfaces. MCS pokes holes in moral absolutes. As Bertrand Russell said, "everything is vague to a degree you do not realize till you have tried to make it precise".

When a numerical model is built, it immediately limits the amount of information that may be obtained from it. Evidently, the key here is the modelling technique and the degree to which it is destructive. From this point of view, if we want to learn something about a phenomenon, we should try to delay the modelling phase as much as possible. This is exactly what Monte Carlo simulation does. Isn't the whole idea of simulation to imitate physics? So why is it then that people compute things that don't exist in nature? Smooth differentiable response surfaces don't exist. Rugged clouds of responses do. Anything we do to meta-models (like emasculate them with polynomial surfaces) invariably destroys information. Monte Carlo is a model-free technique which engulfs things like optimization, what-if and sensitivity analyses, because it *simulates*. Simulation is the last thing we can do with a computer.

3 Concluding Remarks

Uncertainty is responsible for the fact that the more a system gets complex, the less precise statements about it make sense. The incorporation of uncertainty into computer models establishes a radically new approach to CAE and, most importantly, enables, for the first time, to speak of *knowledgecomputation*. The conditions to fulfil in this sense are:

1. Adandon response surfaces and DOE in favour of response clouds (meta-models) and Monte Carlo Simulation. They are infinitely more realistic, simpler to generate, to handle, and convey fantastic amounts of information. Most importantly, they don't destroy information.

2. Avoid modelling (with polynomials, of course) as much as possible. A model, once built, can only convey the information that has been programmed into it. This is called "unwrapping". For examples, response surfaces can't reveal bifurcation-type mechanisms.

3. Abandon optimisation in favour of robustness. Excessive specialization leads to fragile results, in which changes in boundary conditions may be catastrophic.

4. Abandon the idea of eliminating testing. Testing may be reduced drastically if CAE reconciles with experimentation, when a common ground is found.

Contemporary CAE has reached a state of crisis. The almost dogmatic approaches that pervade CAE and HPC have led to excessive articulation of certain outdated and conservative concepts such as optimisation. The search for accuracy (in the presence of uncertainty) has created overly complicated procedures, which, being based on stacks of simplifications, linearizations and all types of assumptions, introduce additional uncertainty into the entire process. Since error analysis is rarely performed, the impact of these approaches is practically always unknown. And yet, people speak of "accurately approximate" solutions! Finally, these methods filter information so much, that they result highly destructive and biasing in terms of physics they can reflect. If engineers are to design successfully more complex systems in the future, they will have to adopt more tolerant, information-preserving and less speculative techniques such as Monte Carlo Simulation. The idea is to look for patterns and not for details.

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REFERENCES

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