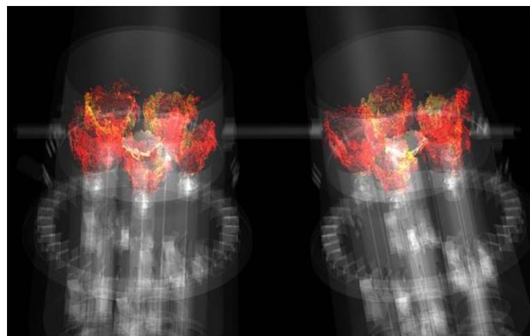
Profiles in Leadership

Understanding Behaviors in the Extreme Environment of Natural Gas Turbine Generators

Earl Joseph, Steve Conway, Bob Sorensen, and Alex Larzelere
June 2018

HYPERION RESEARCH OPINION


Source: Oak Ridge National Laboratory

Understanding physical behaviors in harsh environments is extremely hard, and at times, critically important. That is the situation General Electric (GE) engineers faced when designing their new heavy-duty gas turbine generator. Gaining even 1% greater efficiency could save their electric utility customers millions of dollars and improve GE's world-wide competitiveness. The key issues involved a better understanding of the fluid dynamics and reactive flow behaviors in the turbine's 1,500 degree Celsius combustion chambers and the interactions between the 2 to 16 individual flames in the chambers. GE Power engineers had reached the limits of theory and experiments, motivating them to apply advanced modeling and simulation.

When the engineers at the GE Power division realized that their traditional approaches to designing heavy-duty gas turbine generators were insufficient, they turned to the GE Global Research computational combustion lab. In turn, the combustion lab approached Oak Ridge National Laboratory (ORNL) and Cascade Technologies. By using the Titan supercomputer at the ORNL Computational Leadership Facility (OLCF), researchers adapted and applied the CHARLES code to understanding the complex physics found inside a gas turbine. This involved creating a nearly billion cell mesh to run simulations on 8,000 to 16,000 Titan processor cores.

With these advanced modeling and simulation capabilities, GE was able to replicate previously observed combustion instabilities. Following that validation, GE Power engineers then used the tools to design improvements in the latest generation of heavy-duty gas turbine generators to be delivered to utilities in 2017. These turbine generators, when combined with a steam cycle, provided the ability to convert an amazing 64% of the energy value of the fuel into electricity, far superior to the traditional 33% to 44%.

GE's example provides great lessons about what it takes to develop HPC-enabled modeling and simulation capabilities to create improved science-based understanding of physical behaviors in inaccessible environments. It also demonstrates the importance of “use inspired” research to accelerate the development and deployment of improvements in modeling and simulation capabilities.

Note: This page is intentionally blank.

TABLE OF CONTENTS

IN THIS PROFILES IN LEADERSHIP REPORT

What's that noise? For the engineers at General Electric Power, finding answers to that question is vitally important. In a natural gas turbine generator, noise can be an indication of instabilities that can cause significant damage to the turbine. Also, noise may indicate inefficiencies in the combustion of the fuel which can lead to increasing emissions from the turbine. The challenge of understanding the source of noise in a gas turbine is that the combustors, the possible source of noise, operate in an extremely harsh environment; the temperatures in the combustion chamber in a gas turbine can exceed 1,500 degrees Celsius. This, and other experimental restrictions, limit the ability of engineers to see directly into operating gas turbines.

This use case is a story about how GE Power engineers were challenged with finding new ways to obtain science-based insight into complex physical behaviors in an environment that was beyond the scope of theory and experiments. GE turned to Cascade Technologies of Palo Alto, CA and Oak Ridge National Laboratory (ORNL) and the capabilities of their Titan Cray XK7 supercomputer. This is also a story about how investments made by the DOE years ago in the Stanford University's turbulent mixing simulation center resulted in a commercial applications code offered by Cascade Technologies that provided the critical capability that made obtaining that insight possible.

SITUATION OVERVIEW AND THE ESSENTIAL ROLE OF HPC

Natural gas turbine generators offer a number of considerable advantages. These include relatively low installation costs and the ability to be commissioned and placed into operation quickly. Heavy duty gas turbine generators are also extremely efficient and convert up 64% of their fuel's energy value into electricity. This equates to lower fuel costs and maximizing the availability of marketable electricity.

- In addition, natural gas turbines are flexible and have the ability to quickly startup and stop (in about 30 minutes) as needed. This can be particularly important when a utility also uses intermittent renewable generation sources such as wind turbines or solar energy.
- "Advanced gas turbine technology gives customers one of the lowest installed costs per kilowatt," said Joe Citeno, combustion engineering manager for GE Power. "We see it as a staple for increased power generation around the world."

However, realizing the benefits of heavy duty gas turbines is not easy. It involves finding the right balance of numerous factors that include the right materials, the aerodynamics of the turbine blades, heat transfer considerations, the geometry of the combustors, and the proper mixture of fuel and air. "When the fuel and air are nearly perfectly mixed, you have the lowest emissions," said Jin Yan, manager of the computational combustion lab at GE's Global Research Center. "Imagine 20 tractor-trailers full of combustible fuel–air mixture. One combustor burns that amount every minute. In the process, it produces less than a tea cup (several ounces) of NOx emissions."

For years, GE Power has used theory and experiments to understand what happens in the turbine combustion chamber. The problem is that as the gas turbines get larger and more efficient, the usefulness of theory and experiments becomes limited. For that reason, GE Power and the GE Global Research computational combustion lab have started to turn to HPC-enabled modeling and simulation to understand what is happening inside a gas turbine, including, "what is making that noise?"

Why HPC is Important to GE

To overcome the challenges of understanding what is happening in the extreme environment of a gas turbine, GE turned to HPC-enabled modeling and simulation. The limitations with theory and experimental capabilities would not allow GE engineers to understand the complex physical behaviors found inside an operating gas turbine.

- GE is a long-time user of modeling and simulation to understand the performance of wind turbines and aircraft jet engines, and to develop advanced materials.
- Therefore, the researchers at the GE research computational combustion lab were confident that it could be used to accurately simulate the conditions, as well as the complex interactions, inside a gas turbine.

HPC plays a critical role because its computational horsepower can solve the equations used to represent key physical behaviors. Also, the large memory capacity of an HPC system is needed to store the models of the geometries and boundary conditions of the physical systems. It is also essential to create the visualization of the simulation results used by GE engineers to better understand what is happening inside the gas turbine generators.

Area of Research at GE and Their Research Partners

This use case includes a number of research areas. One of those is the area of fluid dynamics, turbulent mixing and reactive flows. The primary participant in this area is Cascade Technologies of Palo Alto, CA. Cascade Technologies is the owner of the CHARLES code, which was originally designed for high-fidelity jet engine simulations and supersonic jet noise predictions. In this case, the code was adapted to the combustions dynamics in the GE power generation turbines.

- This included scaling the code to operate on up to tens of thousands of cores on the OLCF Titan computer. This research resulted in the speed up of the code to 30 times its original performance.
- Another computer science aspect of the research in this use case involved creating a very fine mesh of nearly a billion cells. These cells were used to track the turbulent combustion on a micro-second basis. The cells tracked air-fuel mixture, heat transfer, chemistry, and particle diffusion.

An important area of research for this use case was visualization. There was a considerable challenge to track the massive amount of data generated by the CHARLES code. OLCF researchers, led by Mike Matheson, worked with the GE team to create visualizations of the instabilities caused by multi-combustor dynamics. These visualizations provided GE with new ways of understanding combustor behaviors and how the flames interact with each other.

Project Description and Results

Engineers at GE Power heard a noise during a full-scale test of a heavy-duty gas turbine. The questions were, what is causing it and would it cause a problem? This event occurred as GE's was developing their newest gas turbine known as the 7H.02. GE engineers suspected that the noise was caused by the interaction of adjacent flames in the combustion chamber. <u>Unfortunately, an experiment to confirm that suspicion was beyond the capabilities of their physical testing equipment.</u>

- Understanding and mitigating the pulsation was critical to improving the efficiency of the new gas turbine design. "To help meet our deadlines, we wanted to see if we could reproduce the instability numerically," said Joe Citeno, GE Power combustion engineering manager. "But we didn't have a predictive model or the internal computational horsepower needed to run it."

The engineers at GE Power turned to the computational combustion lab at GE Global Research. GE Power challenged Jin Yan and his team to recreate the pulsations observed in the computer. GE Power also wanted computational tools that could be used to design new gas turbines with greater efficiency and lower emissions.

- To make things even more difficult, Yan and his team needed to deliver results to impact the new gas turbine design. "We didn't know if we could do it," Yan said. "First, we needed to replicate the instability that appeared in the test. This required modeling multiple combustors, something we had never done. Then we needed to predict through simulation whether that instability would appear in the new turbine design and at what level."

GE Global Research turned to the Oak Ridge Leadership Computing Facility (OLCF) for help. Through the Accelerating Competitiveness through Computational Excellence (ACCEL) industrial partnerships program, GE received a Director's Discretionary allocation of 11.2 million node hours on the Titan supercomputer.

- This 27 Pflops Cray XK7 computer would be needed to provide the computational horse power and memory size needed to capture the complexity of simulating behaviors in the gas turbine combustion chamber. This includes tracking particle diffusion, chemical reactions, heat transfer, and energy exchange on a micro-second basis.

GE also engaged Cascade Technologies to provide a high-fidelity solver for large eddy turbulent flow simulations. Cascade Technologies' code, CHARLES, was initially developed at Stanford University as part of the National Nuclear Security Administrations (NNSA) Advanced Simulation and Computing (ASC) program.

- The Stanford work was one of the ASC Academic Alliances and they developed CHARLES to provide high-fidelity jet engine simulations and predict the noise from supersonic aircraft. CHARLES solves Naiver-Stokes equations to capture high-speed mixing and complex geometries of air and fuel during combustion.
- The challenge for the Cascade Technologies and GE Global Research teams was adapting the CHARLES code to the complex configuration of the GE gas turbines.

The computational capabilities of Titan allowed GE, Cascade Technologies, and OLCF researchers to create a very fine-mesh grid for the simulation. Using the CHARLES massively parallel mesh generation capabilities, they were able to create of grid of almost 1 billion cells. OLCF researcher, Mike Matheson, worked with the GE and Cascade Technologies' teams to develop a workflow for the analysis of the resulting simulation data. This included the use of visualization tools that allowed end users to view the flame structure in the combustion chamber in high definition.

- GE Power engineers saw, for the first time, the dynamic flame instabilities in one of their gas turbine combustion chamber designs.
- "It was a breakthrough for us," Yan said. "We successfully developed a model that was able to repeat what we observed in the physical test."

Value of this Project/Research

This project provides value in many ways. One was the delivery of a design tool that will be used to improve the performance and efficiency of future GE gas turbines. GE estimates that a single percent increase in gas turbine efficiency equates to millions of dollars in saved fuel costs for GE's customers and tons of carbon dioxide spared from the atmosphere. This is driving the market for GE gas turbines.

- Their newest design is the 7H.02 gas turbine that converts an amazing 64% of the energy value of its fuel to electricity (when used with a steam combined cycle).
- This efficiency is a major leap from the traditional 33% to 44% efficiency seen in other gas turbines. Joe Citeno of GE Poser said, “For our customers, that means lower fuel consumption and reduced cost per megawatt.”

An additional benefit of this project was to provide GE with new ways to understand inner working of gas turbines. Previously, GE relied primarily on theory and experiments for the design of their gas turbines. However, they had found that the complexity of large scale, multi-flame combustion chambers exceeded the capability of theory. Also, limitations on experimental devices and diagnostics prevented them from using experiments. Nevertheless, when these were combined with advanced modeling and simulation, GE was given a new way to “see” into extremely harsh environments.

Cascade Technologies and their CHARLES code also saw value from this research. This project allowed them to adapt their code for a new application. The code and its parallel mesh generation capabilities were adapted to the complex environment of heavy duty gas generators. In the course of the research the code also saw a 30X improvement in run time. Also, OLCF researchers developed new workflows that enabled the use of advanced visualization technologies.

Finally, the DOE and ORNL saw value from this project by assisting with the deployment of the GE 7HA.02 gas turbine that uses DOE-developed axial fuel staging technologies. This technology adds a second fuel injection stage into the combustion chamber. The technology helps to improve efficiency and lower emissions, but caused concerns about introducing instabilities. The work done by ORNL, GE and Cascade Technologies alleviated that concern, which was later confirmed experimentally. This project supports the DOE missions of improving energy security by improving the efficiency of power sources, reducing emissions, and increasing the competitiveness of U.S. energy companies.

An Overview of Their HPC Environment

The GE Global Research Center’s computational combustion lab was able to gain access to the Titan supercomputer through the ORNL Accelerating Competitiveness through the Computational Excellence (ACCEL) industrial partnerships program. The GE team was given 11.2 million node hours from the OLCF Directors Discretionary allocation. With this time, the CHARLES code was used by the GE and Cascade Technologies team run simulations using between 8,000 and 16,000 processor cores.

- With the improvements made to the CHARLES code, GE researchers will move their work back to their proprietary environment where they will use the HPC enabled modeling and simulation and experimental capabilities to validate the tools.
- Then those tools will be used by designers to make improvements to the next generation of their power generating gas turbines.

FUTURE OUTLOOK

The future of this work looks bright. This project started as a “proof of concept” to see if it was possible to use simulation to recreate the instabilities seen in gas turbine testing. The project was also about creating a design tool to understand and predict behaviors inside the extremely harsh environments found inside of a gas turbine. Happily, the answer to both questions was an emphatic “yes”. This

ORNL-GE use case demonstrated how a public-private partnership can be used to demonstrate the value of advanced modeling and simulation to promote business and government objectives.

GE will build on the work done in this project and plans to continue to work with Cascade Technologies. GE will continue to use the CHARLES code on its own high-performance computing resources to design its next generation of heavy duty gas turbine generators. “Access to OLCF systems allowed us to see what’s possible and de-risk our internal computing investment decisions,” Citeno said. “We can show concrete examples to our leadership of how advanced modeling and simulation is driving new product development instead of hypothetical charts.”

GE and Cascade Technologies have also applied to the DOE Advanced Scientific Computing Research (ASCR) Leadership Computing Challenge (ALCC) program for an additional allocation of time on Titan. This will be used to understand how the Titan Graphic Processing Units (GPUs) can be used to accelerate simulations using the CHARLES code. This has the potential to allow scientist and engineers to obtain an even better understanding of what is going on in the extremely harsh environment of a gas turbine combustion chamber.

Best Practices and Advice to Other HPC Sites

This use case demonstrates the power of HPC enabled modeling and simulation to access extremely harsh environments to aid in the understanding of physical behaviors. Often, in these environments, conditions are too hostile in terms of temperatures and pressures to allow direct observation. That is the situation GE found in trying to understand the interaction of flames.

- GE realized that the only way it would be able to create the understanding needed to improve gas turbine efficiency was through the use of modeling and simulation.
- These lessons can be applied to most situations where the conditions are too extreme for direct observation of too complex for the use of theory.

Another important lesson is how “use inspired” research helps to create a sense of urgency to deliver results. GE Power provided the clear objective of computationally recreating an instability seen in one of their existing gas turbines. This provides a set of geometries, materials and boundary conditions for the simulation. Also, GE Power challenged the research teams to complete their work in a timeframe that would allow the capabilities to impact a new gas turbine product. This urgency caused the research teams to look for an existing code. GE was able to leverage the investments made by the DOE in the Stanford University Center for Turbulence Research and the CHARLES turbulent mixing code.

- That code is now owned by Cascade Technologies who worked with GE to adapt it to the geometries and conditions found in a heavy-duty gas turbine.
- The ability to use an existing code allowed the project to be completed quickly and provided confidence that the simulation results could be trusted.

Finally, this use case provides valuable lessons about the challenges and opportunities of using HPC enabled modeling and simulation for design. Joe Citeno said, “A year ago these were gleam-in-the-eye calculations. We wouldn’t do them because we couldn’t do them in a reasonable time frame to affect product design. Titan collapsed that, compressing our learning cycle by a factor of 10-plus and giving us answers in a month that would have taken a year with our own resources.” The ORNL-GE use case provides a great example of using the virtual to understand the physical and then deploying those modeling and simulation virtual tools to design the next generation of the physical.

About Hyperion Research, LLC

Hyperion Research, consisting of the former IDC high performance computing (HPC) analyst team, provides HPC information, analysis, and recommendations based on technology and market trends. Research includes market sizing and forecasting, share tracking, segmentation, technology and related trend analysis, and both user & vendor analysis for multi-user technical server technology used for HPC and HPDA (high performance data analysis). We provide thought leadership and practical guidance for users, vendors and other members of the HPC community by focusing on key market and technology trends across government, industry, commerce, and academia.

Headquarters

365 Summit Avenue
St. Paul, MN 55102
USA
612.812.5798
www.HyperionResearch.com and www.hpcuserforum.com
