Combustion Dynamics Monitoring Special Issue: Outage Handbook

Most gas-turbine (GT) users familiar with dry low-emissions (DLE) combustion systems have heard the acronym CDMS, short for combustion dynamics monitoring system. This certainly sounds important, and it is. But the term “combustion dynamics” and what it means to GT owner/operators often is not well understood at the plant level.

Dr Timothy Lieuwen, PE, associate professor, School of Aerospace Engineering, Georgia Institute of Technology, knows this and devotes much of his time helping users understand in simple terms what combustion dynamics is, why it happens, how to recognize it, how to deal with it, etc. Lieuwen is a beacon in a graying industry, a bright engineer, not yet 40, who is as comfortable in a powerplant as he is in a classroom or laboratory. Think of Tim, the name he prefers, as the electric-power generation sector’s “Indiana Jones.”

CD is difficult to understand by just speaking to industry colleagues because you get snippets of knowledge that are hard to connect not knowing what the finished puzzle looks like. The editors have had access to, and have been helped by, several of the industry’s subject-matter experts—including EPRI’s Len Angello, PSM’s Jesse Sewell, PPL’s Mike Magnan, GTE’s Marcus Turner, and Siemens Energy’s Phil Karwowski—but the fog didn’t clear until they attended Lieuwen’s “short course.”

That Lieuwen is dedicated to making the subject matter understandable is evident in the course title, where he substituted “instabilities,” a term virtually everyone understands, for “dynamics.” He uses the terms “oscillations” and “pulsations” as well—two words more descriptive to most people than “dynamics.” Perhaps even more descriptive synonyms are “humming,” “rumble,” and “screech”—the sounds you hear when combustion approaches instability.

There was just enough combustion physics and math in the course to allow an understanding of the science and how engineers apply it to prevent the damaging effects of dynamics on hardware. Those who wanted more were referred to a reference work on the subject edited by Lieuwen and Vigor Yang (Sidebar 1).

Most disappointing about the workshop was that only two of the 22 participants represented the electric power industry; 14 were from companies in the oil, gas, and chemical sectors. Even turbine OEMs and third-party parts suppliers outnumbered the power producers two to one. Certainly an opportunity lost for electric-power generators.

Course outline. Lieuwen divided the workshop material into six segments; a break after each segment enabled group discussion and allowed time to answer specific questions. The course outline follows:

- Key factors influencing GT combustion performance.
- Combustion instabilities: What they are; historical experience.
- Conditions conducive to instabilities and the influence of fuel composition.
- Strategies for eliminating instabilities.
- How to monitor instabilities.
- Additional uses for data gathered while monitoring the combustion process.
- How to recognize instabilities.
- How to deal with instabilities.
- How to prevent the damaging effects of instabilities on hardware.

In his introductory remarks, Lieuwen emphasized that dynamics are not unique to DLE combustion systems, or even to GTs. They occur in many combustion processes—including boilers, furnaces, etc. He would later show in the historical-experience segment of the course how ramjet, afterburner, and rocket components were routinely destroyed by CD until engineers were able to run thousands of full-scale tests to understand what was happening and how to mitigate the damage.

Learned at IGTI’s Workshop
“Combustion Dynamics in Gas Turbine Powerplants”

Next meeting: Sept 14-17, 2009
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### 1. Compressor pressure ratio

Lieuwen applied technology developed in support of the space program and the lessons learned to land-based GTs. His thesis was based on an investigation of self-excited, combustion-driven oscillations in low-NOx gas turbines.

### GT backgrounder

The first half hour of the workshop was spent reviewing GT combustion fundamentals to be sure everyone was “on the same page.” A few words on the Brayton cycle’s key components—compressor, combustor, and turbine—were followed by a review of cycle efficiency and its impacts.

Lieuwen put the ideal simple-cycle efficiency equation up on the screen to show that it was impacted little by compression ratio. Fig 1 illustrates the significant thermal efficiency gain in going from the typical pressure ratio of 15 to 20 for large frames to the 32-39 for aeroderivative engines. Coupling the Brayton and Rankine cycles, so-called combined cycle, dramatically increases plant efficiency because it extracts heat from the GT exhaust prior to discharge.

**Moving to combustor performance**, Lieuwen identified the metrics of greatest importance: operability, low pollutant emissions, and good turndown. Discussion of the first metric focused on what you don’t want a combustor to do: extinguish the flame (blowout), vibrate, or initiate a flashback. These are not mutually exclusive phenomena—changing one can impact one or both of the others.

#### Matrix assists in identifying cause of combustion dynamics

<table>
<thead>
<tr>
<th>Description</th>
<th>Frequency range, Hz</th>
<th>Amplitude alarm setpoint, psig</th>
<th>Component risks</th>
<th>Potential causes</th>
<th>Mitigation strategies</th>
</tr>
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<tbody>
<tr>
<td>Low-frequency dynamics</td>
<td>0 to 25</td>
<td>0.5</td>
<td>• Swirler damage &lt;br&gt; • Basket damage &lt;br&gt; • Nozzle damage</td>
<td>• Flashback indications &lt;br&gt; • Lean blowout &lt;br&gt; • Damaged swirler(s) &lt;br&gt; • Air-flow restriction &lt;br&gt; • High injection flow rates &lt;br&gt; • Pilot-nozzle distress</td>
<td>• Increase pilot-stage fuel fraction &lt;br&gt; • Increase C-stage fuel fraction &lt;br&gt; • Repair/replace the basket &lt;br&gt; • Remove air-side obstructions &lt;br&gt; • Reduce the injection flow rate</td>
</tr>
<tr>
<td></td>
<td>25 to 100</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate-frequency dynamics</td>
<td>100 to 500</td>
<td>2.0</td>
<td>• Transition panels &lt;br&gt; • Transition seals &lt;br&gt; • fretting &lt;br&gt; • Wear</td>
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<td>• Downstream components &lt;br&gt; • fretting &lt;br&gt; • Wear</td>
<td>• Equipment distress</td>
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<tr>
<td>High-frequency dynamics</td>
<td>500 to 5000</td>
<td>0.5</td>
<td>• Baskets &lt;br&gt; • Cross-flame tubes &lt;br&gt; • Flashback thermocouples</td>
<td>• Over-firing &lt;br&gt; • IGV position error &lt;br&gt; • Fuel composition &lt;br&gt; • System damping &lt;br&gt; • Basket distress</td>
<td>• Install Helmholtz resonators &lt;br&gt; • Adjust IGV position &lt;br&gt; • Increase steam injection &lt;br&gt; • Preheat the fuel</td>
</tr>
</tbody>
</table>
Early detection CAN prevent costly machine failures.

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Run your turbine at its optimum setting.
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DLE systems have particularly sensitive combustors and decisions on tradeoffs are common. One is the optimum mixing time to limit NOx emissions versus the time it takes for autoignition to occur. The more time the better the mixing, but autoignition is the risk and the higher the carbon content, the faster it will happen. Bullet-point refresher:

- Blowout is caused by a low fuel/air ratio. One way this happens is that load is reduced too quickly: The change in fuel flow is instantaneous but the inertia of the GT rotor keeps air flowing at a high rate.
- Fuel composition influences the blowout limit; addition of hydrogen, for example, significantly extends the range of operation. Temperature and humidity also impact blowout limit, but generally to a lesser degree than a change in fuel composition.
- Flashbacks occur in premix systems when flame speed is higher than the speed at which the fuel and air mixture travels to the combustor. A hydrogen/air mixture has the highest flame speed; methane/air is much slower. This is why there are well-defined limits on the percentage of hydrogen in GT fuels for premix combustion systems. If you have a great deal of hydrogen to burn, a non-premix combustor is necessary.
- Autoignition refers to an ignition site upstream of the combustor in premix systems. Fuel injected into hot air will autoignite, but the time it takes to happen is what’s important. You want the fuel and air mixture to move into the combustor before ignition occurs.
- Methane (CH₄) has a significantly higher autoignition temperature than higher hydrocarbons—such as ethane (C₂H₆), propane (C₃H₈), butane (C₄H₁₀), etc. This is important to remember if your fuel source is changing to include LNG—and especially so if your GTs are high-pressure-ratio aeroderivative.

Flame temperature, important because it directly impacts emissions, depends primarily on fuel/air ratio and compressor discharge temperature. Fig 2 shows that peak flame temperature occurs at an equivalence ratio of 1.0 (stoichiometry) because there is no leftover fuel or air to heat up. To the right of stoichiometry, combustion is fuel rich—that is, there is extra fuel in the mixture that can’t burn because there’s not enough air to support its combustion.

Equivalence ratios of less than unity are fuel lean, meaning there’s oxygen left over after combustion. DLE systems operate in this regime to hold down flame temperature. Types of flames—diffusion and premixed—was the next topic. The defining characteristic of diffusion or non-premixed flames, is that fuel and air are introduced into the combustor separately and the mixture burns at an equivalence ratio of 1.0. As mentioned above, this produces the hottest flame possible along with high levels of NOx and some soot. Diffusion flames are robust and offer wide turnooldown; also, autoignition and flashback are of little concern.

In the premixed combustion process used for DLE-equipped turbines, air and fuel are mixed upstream of the combustion chamber, allowing tight control of mixture stoichiometry and, therefore, flame temperature. A few things to keep in mind:

- For GTs burning liquid fuels, the oil or kerosene must be vaporized before the premix step.
- Operability windows of DLE units contract because to avoid extinguishing the flame.
- Almost all air goes through the front end of the combustor in lean-fuel operation; little is available for cooling.
- Multiple fuel nozzles are required for turnooldown (one combustor design for large frames relies on five identical fuel nozzles around the combustor can, another on five identical outer burners and one smaller center nozzle).

Emissions from natural-gas-fired land-based engines of greatest importance are NOx (oxides of nitrogen) and CO (carbon monoxide). Unburned hydrocarbons may be of concern when combustion is not properly tuned and incomplete; SOx emissions occur when fuel contains sulfur; particulates may be noticeable under certain operating conditions with specific fuels.

Three mechanisms are associated with NOx formation. So-called “thermal NOx,” that related directly to flame temperature, is the dominant mechanism in most GT combustors. The other two are “prompt NOx” and the reaction that converts nitrous oxide (N₂O) to nitric oxide (NO). Thermal NOx production is controlled by limiting flame temperature by use of premix combustion or by water or steam injection directly into combustion chambers with diffusion flames.

High CO levels are a characteristic of fuel-rich flames (equivalence ratio greater than 1.0) because there is insufficient oxygen to react fuel to CO₂. CO also is found in lean flames because they are relatively cool and the conversion of CO to CO₂ depends on temperature—the higher the flame temperature, the faster the conversion. CO ultimately limits engine turnooldown; the low combustion temperatures associated with low-power operation cause a rapid increase in CO level.

In sum, operation at high power is limited by NOx production, at low power by CO production. SOx emissions, most often associated with liquid fuels—black oil in
particular—cannot be reduced during the combustion process. Fuel-bound sulfur must be removed before combustion. Particulates, or soot, are found most often in fuel-rich diffusion flames. Possible health impacts aside, the major problem with particulates is that they radiate heat to the combustor wall.

**Combustion Instabilities**

Combustion dynamics are pressure waves of defined amplitudes and frequencies that are an inherent result of the combustion process. They are caused by large-amplitude acoustic oscillations driven by heat-release oscillations as depicted above.

In the typical can-annular combustor of a large frame GT, combustion dynamics can range in frequency from less than 50 Hz to up to about 5000 Hz. In terms of their impact on turbine components, dynamics of these frequencies can range from benign to highly destructive.

Trouble occurs only when the vibrations have large amplitudes or when they occur at frequencies corresponding to natural resonances in that particular system. Such trouble can culminate with fatigue failure of combustor components, which when released into the flow stream can cause serious damage to other hot-gas-path components.

Reasons why DLE combustion systems are susceptible to severe dynamics problems include the following:

- They operate near the lean blow-out limit. Thus such systems are marginally stable to begin with and small perturbations can have very significant impacts.
- A minimal amount of combustor cooling air is used to minimize CO production. This substantially reduces the acoustic damping capability of the combustor. In effect, sound waves resonate in the combustion liner because dilution holes have been eliminated.
- A high-velocity premix section is used to protect against flashback and this maximizes pressure at the flame front.
- Compact reaction zone to limit CO production concentrates heat release where combustor pressure is at its maximum.

**Characteristics of Instabilities**

During instabilities, the combustion process generally excites one or more of the natural acoustic modes of the combustor, which is similar to an organ in that it has several natural frequencies. Recall that the natural frequency, or pitch, of each individual organ pipe depends on its length and inner diameter. Short pipes with small diameters produce high notes; larger, longer pipes produce the bass tones.

The resonant modes for a combustor are known as Helmholtz, longitudinal, and transverse. Picture an empty beer bottle. Blowing across the top produces a rumbling sound which is representative of the Helmholtz mode characterized by frequencies often in the range of 10 to 40 Hz. Experience shows that as you make the flame colder (approach blowout), this mode dominates, apparently caused by partial flame extinction.

Longitudinal modes are in the intermediate-frequency range, nominally from 100 to 1500 Hz, and produce a humming sound (Fig 4). Transverse oscillations, either radial or azimuthal, are in the high-frequency range from about 500 to 5000 Hz and particularly destructive.
4. **Longitudinal modes** produce a humming sound; transverse oscillations, either radial or azimuthal, are characterized by screeching.

They are characterized by screeching, which is attributed to the minimal film cooling of DLE combustors.

**Why instabilities occur.** Lieuwen said two important mechanisms in DLE combustors that cause instabilities are these: (1) Equivalence ratio of the reactive mixture oscillates and disturbs the flame, and (2) vortices in the combustor distort the flame. The first is impacted by premixer velocity, fuel injection location, fuel supply line characteristics (length, fuel temperature, etc), and flame location (standoff distance, length, etc).

The key effect of fuel and/or operating conditions on dynamics is through alteration of flame shape and/or location. In some cases dynamics is made worse, in others better. Changing the fuel does not change the susceptibility to dynamics (either for better or for worse); rather it moves islands of instability around as shown in Fig 5. Lieuwen noted that some condition exists where every combustor is unstable.

**Mitigation strategies**

The turbine designer has several options to minimize the impact of combustion dynamics. These include varying the combustor geometries, changing fuel-supply system acoustic response characteristics, installing resonators, and beefing up the components known to be vulnerable. However, the design and fabrication

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**2. CDMS hardware and how it works**

A portion of Tim Lieuwen’s course notes concerning the hardware aspects of combustion dynamics monitoring systems, as well as some case histories illustrating the value of CDM in identifying the root causes of combustion instabilities, were based in part on materials provided by Marcus Turner and John Brooks of Control Center, the Gas Turbine Efficiency (GTE) company focusing on this business sector.

To dig deeper, the editors met with Turner at the fall 2008 meeting of the CTOTF—Combustion Turbine Operations Task Force. By way of background, Orlando-based Control Center provides integrated process control solutions for electric power generation sector, among others. It was established in 1963 and became part of GTE in 2007. To date it has designed and installed more than 100 CDMSs for gas turbines.

Reflecting, Turner said that when dry, low-emissions (DLE) combustion systems were first introduced, the gas-turbine OEMs recognized that there was an issue with combustion dynamics and offered a “seasonal tuning” service. Typically, specialists would visit a plant in the spring and fall and tune the engine for best balance between NO\(_x\) and dynamics based on site conditions.

Tuning complete, the technicians packed up their diagnostic equipment and data and left. Users were not equipped to monitor dynamics or to make additional tuning changes and they were blind to any component distress that might be occurring in their engines.

CDMSs were developed to respond to this market need, Turner continued. Briefly, they provide both the ability to tune for emissions compliance as necessary and to warn of damage to combustion hardware, or of impending damage.

There are two types of systems that allow operators to run their turbines at optimum settings: portable and permanent. The latter includes systems designed for monitoring only and others that tie into the control system for active control of the engine.

**Portable tuning systems,** Turner said while pointing to the photo on his computer screen (Fig A here), allow owners to take advantage of CDMS benefits without investing in hardware for each engine. These might make most economic sense in low-hours peaking facilities. He explained how this equipment is arranged and works:

Sensors are connected to some, or all, combustors to monitor pressure fluctuations. Data are fed to a PC analyzer that breaks down the information into amplitude versus frequency. The frequency range typically is subdivided into narrow bands, each with their own amplitude limit. Goal of the technician doing the tuning is to minimize dynamics amplitudes while maintaining emissions below permit limits.

**Permanent monitoring systems**
2. CDMS hardware and how it works

But this has not yet been confirmed. The jury also is still out on the life expectancy of the new sensors.

Intermediate-temperature (IT) sensors (rated up to 700°F) also are another option. They offer the advantages of high-temperature sensors but require a special mounting system that moves the sensor to a cooler location (Fig B). Turner thinks the IT system is a good compromise between cost and maintenance while still maintaining desired performance.

Active control. Turner changed subjects and looked ahead. The promise of controlling the GT based on input from the CDMS—so-called active control—is the direction industry leaders are moving, confirming what Lieuwen said in the workshop. But as the professor stressed, this requires a database of engine behaviors to guide “decision-making” by the CDMS. The gathering of information for that database is on-going and GE/Control Center is participating in the process.

Active control, for those unfamiliar with the term, means that the CDMS is linked to the turbine DCS and combustion dynamics are displaced on the DCS screen along with other system variables. Turner says this allows for continuous tuning as the fuel/air ratio varies, thereby adjusting automatically for changes in fuel quality and ambient conditions. The benefits: Optimal balance between emissions and dynamics, and longer parts life.

With the CDMS speaking directly to the DCS, a stepped run-back—among other changes—would be initiated if dynamics exceed a preset threshold, thereby giving you a better chance of avoiding engine damage. This action is virtually instantaneous, saving the valuable seconds it would take a top operator to respond to a high-dynamics alarm condition.

of combustion systems involves multiple tradeoffs, including:

- Physical constraints, principally axial length of the combustor and area within the chamber.
- Cooling and coating requirements that must be balanced with the overall air flow.
- Thermal expansion considerations. Consider that the metal temperatures experienced by an F-class transition piece range from ambient temperature while the unit is on turning gear to approximately 1500°F when the unit is at full-fire. For resistance to intermediate-frequency dynamics, the likely design solution is to make affected components more robust, in order to withstand low-cycle fatigue mechanisms. To combat higher frequency dynamics, the likely design solution requires keeping the amplitudes of the dynamics low enough to avoid high-cycle fatigue.

Remember, it’s not just large amplitudes that the designer must evaluate, but also resonant frequencies. Each pilot-nozzle assembly, for example, may have a different natural frequency because of slight differences in diameter, wall thickness, and length.

Complicating the designer’s challenge is the fact that any one combustion component may have several natural frequencies. For example, the panels of a transition piece may exhibit relatively low natural frequencies (100 to 200 Hz), while the end-rail assemblies of that transition piece may have higher natural frequencies (typically greater than 500 Hz).

Passive control approaches used when dynamics problems are identified, Lieuwen said, include the following:

- Increase pilot fuel. Usually, more pilot fuel helps mitigate dynamics. Essentially pilot fuel is used as a “knob” to make a flame more stable by making it hotter. However, NOx emissions increase along with flame stability.
- Resonators. Effective control of combustor dynamics also has been achieved with the installation of Helmholtz resonators; they attenuate specific frequencies in the combustion system (Fig 6). The resonators are tuned for specific frequencies where dynamics are known to occur.
- Decouple fuel-line acoustics by choking/detuning.
- Symmetry breaking. Use of multiple fuel systems to vary the fuel/air profile among the burners. For example, in a large frame engine with five burners per combustor, one fuel system might supply two burners; another, the remaining three burners. The goal is to make the acoustic response of each set of injectors different. There may be a small NOx penalty using this approach.
- Vary the convective time lag for the equivalence-ratio oscillation mechanism.

Eliminating instabilities

Case history #1. Dynamics in the intermediate-frequency range (defined here as 100 to 1500 Hz) are what damaged the lower panel of a transi-
Robust software and skilled analysts can interpret the data collected by the CDMS. The latest versions of these systems even provide protection logic to automatically unload and protect the GTs during excursions of combustion dynamics. So-called “active systems” are said to provide the best level of protection against damaging amplitudes and frequencies.

Value proposition

The CDMS offers considerable value beyond preventing a unit trip because of combustion instability. Think of it as a GT health monitoring tool that alerts plant staff to a possible hardware problem that should be addressed at the next scheduled outage to correct a condition that could cause a forced outage and the need for expensive repairs.

Lieuwen suggested that if you observe combustion instabilities in most cans, you probably have a tuning issue, but if the instability is confined to one can, or a few adjacent cans, you may have a part failure to deal with. The CDMS is a “first alert” to problems such as pilot-nozzle weld cracking, transition-piece cracking, flow obstructions, etc.

Two case studies were presented, one on a flow obstruction in the premixer and the other on combustion-liner cracking; both were taken from the book referenced in Sidebar 1. The first was identified by occasional spikes of low-frequency mode above the alarm threshold in one can. Coincident alarms came from spikes in the flashback thermocouple below the threshold that would initiate a unit trip. Investigators found a piece of wire across the swirler.

The second case presented was particularly instructive. The user reported, “During the week prior to the failure, combustion dynamics levels doubled. It is believed that the [combustion liner] crack had been propagating during the week, and then opened up around midnight, marked by a sudden step change in dynamics levels.”

Lieuwen urged all users to notify
him of combustion instabilities that point to hardware issues. He is working with EPRI to build a database containing “normal” and “anomalous” behavior from which failure precursors can be extracted and back-tested against (for more detail, access www.combinedcyclejournal.com/archives.html, click 2Q/2008, click “501F Users Group” on issue cover, scroll to “Using advanced CDM analysis to improve reliability” on p 22).

Consistency in data sets across different machines is important for guiding “decision-making” by an active CDMS. No owner/operator wants to give the active CDMS control of its units until the user is sure there is a very low probability of spurious trips.

Another area under investigation is detection and control of lean blowout (LBO). Impending blowout can be identified by monitoring of flame acoustics. Work by Lieuwen and others shows that blowout often is preceded by a low-frequency rumble and by sporadic “bursts” in signal that are not at a specific frequency. This information can be used to develop an algorithm that can be incorporated into existing software to prevent lean blowout from occurring.

Much work is ongoing in the field of active control. Example: An idea implemented by one gas-turbine OEM that Lieuwen discussed had to do with using a pressure signal from the CDMS as input to the control system. That signal is used to pulse fuel to the combustor with a secondary injector that is out of phase to the oscillations.

Looking toward the future, Lieuwen next talked about the promise of real-time determination of combustor stability margin. Today, he said, CDMSs are only used to tell you how big the dynamics is. It doesn’t provide information on stability margin when the turbine is “quiet.”

Knowing the stability margin would allow you to forecast when dynamics will appear as average seasonal temperatures change and understand how changing fuel composition (for example, when LNG is added to the pipeline) impacts dynamics.

Lieuwen suggested a method of doing this in an ASME paper, “Online Combustor Stability Margin Assessment Using Dynamic Pressure Data” (GT2004-53149). He briefly explained the mathematics involved and said that Alta Solutions Inc, San Diego, experts in machinery diagnostics, had already programmed a software module to calculate stability margin and was looking for demonstration sites.

Compressor surge/stall detection is another “farther out” potential use of CDMS. Lieuwen said that all noise sources upstream of the combustor can be “heard” in the combustion chamber. He reasoned that CDMS could be used to achieve the following:

- Optimize compressor pressure ratio by monitoring surge/stall precursors.
- Detect anomalous blade vibrations to identify failure precursors and prevent engine damage.

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