Defense Technical Information Center Compilation Part Notice

ADP011146

TITLE: Combination of Active Instability Control and Passive Measures to Prevent Combustion Instabilities in a 260MW Heavy Duty Gas Turbine

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles [Technologies des systemes a commandes actives pour l'amelioration des performances operationnelles des aeronefs militaires, des vehicules terrestres et des vehicules maritimes]

To order the complete compilation report, use: ADA395700

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP011101 thru ADP011178

Combination of Active Instability Control and Passive Measures to Prevent Combustion Instabilities in a 260MW Heavy Duty Gas Turbine

J. Hermann, A. Orthmann
IfTA, Ingenieurbuero fuer Thermoakustik GmbH,
D-82194 Gröbenzell, Industriestr. 33

S. Hoffmann, P. Berenbrink
Siemens AG Power Generation,
D-45466 Muelheim, Wiesenstr. 35

Abstract

Reducing the output of NO_X pollutants and enhancing efficiency are the two major aims pursued by developers of modern gas turbines. In order to achieve them, lean premix combustion is preferred, turbine inlet temperatures and thus power densities within the combustion chamber system being continuously increased to augment efficiency. Due to this fact, the tendency of modern combustion systems to develop so-called self-excited combustion oscillations keeps increasing.

After briefly discussing the oscillation problems encountered with the annular combustion chamber of a Siemens type V94.3A stationary gas turbine, particular attention will be paid to suppressing these oscillations by passive and active means. The passive measures presented, i.e. extending the burner nozzle, were intended to detune the combustion system by prolonging the time lag required by the combustible mixture exiting the burner outlet to reach the combustion zone. Moreover, to suppress periodic vortex shedding, another possible cause for combustion instabilities, those extensions were inclined in a certain angle with respect to the main flow direction. To prevent the in-phase lock of all 24 burners promoting the excitation of any azimuthal mode, the burners were selected to have different time lags, and were arranged asymmetrically within the annular combustion chamber. In addition to these passive measures, a multi-channel Active Instability Control (AIC) system was implemented to achieve further damping. With the AIC system presented, any burner oscillations occurring are measured by p-ressure sensors; their signals are processed by means of a multi-channel controller, and then transmitted to actuators designed to damp down combustion oscillations. The points of intervention selected to do so were the gas supplies of the pilot flames. In order to achieve optimum response, every single one of the 24 burners was fitted with its own actuator.

In field demonstrations for various type V94.3A gas turbines, the presented measures were successfully tested and active suppression of combustion oscillations proved to be highly flexible in dealing with various oscillation problems.

1. Introduction

Self-excited combustion oscillations or instabilities are observed in various kinds of industry-type combustion or propulsion systems, reaching from domestic heating devices to gas turbines and rocket motors. The oscillations cause substantial pressure fluctuations at discrete frequencies which, particularly with systems characterised by high power densities, may reach levels leading to mechanical failure of the combustion chamber, or of upstream or downstream plant components.

Developments targeted at reducing NO_X pollution and increasing efficiency levels for modern stationary gas turbines involve lean burning and increased turbine inlet temperatures and thus power densities within the combustion chamber. Since these measures tend to bring about self-excited combustion instabilities, avoiding these instabilities constitutes one of the main tasks in developing modern combustion systems.

2. Rayleigh criterion and time lag

A fundamental element of the driving mechanism of self-excited combustion oscillations is the excitation of pressure oscillations by a fluctuating heat release rate of the flame. Generally speaking, for the heat release rate oscillations to result in amplification of pressure oscillations, heat addition must occur at or around times of high pressure. Lord Rayleigh [1] was the first to state this criterion, now bearing his name, which was developed further by various other authors, e.g. Putnam and Dennis [2].

To evaluate the Rayleigh criterion, the phase shift between pressure and heat release fluctuations can be used. Phase shifts occur because every heat release fluc-

Paper presented at the RTO AVT Symposium on "Active Control Technology for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles", held in Braunschweig, Germany, 8-11 May 2000, and published in RTO MP-051.

tuation produces the corresponding pressure fluctuation only after a certain delay or "time lag" (and vice-versa). Time lags in combustion systems consist of various components τ_i , e.g. acoustic and convective time lags, as well as time lags attributable to the processes of mixing and reacting (see e.g. Hermann et al. [3] or, for a slightly different model, Lieuwen et al. [4]). These chronological components - and thus the system stability - are generally hard to predict. Accordingly, measures to suppress oscillations based on knowledge about time lags can usually only be taken when self-excited oscillations in a combustion system are already present.

3. Feedback mechanisms

For self-excitation of pressure oscillations to occur, it is not sufficient that the Rayleigh criterion be fulfilled. There must also be a suitable feedback mechanism between oscillations of pressure and heat release rate: pressure oscillations caused by fluctuations of the heat release rate must interact with other effects involved in the combustion process that in their turn - directly or indirectly - cause further oscillations of the heat release rate. This can for instance be due to sound pressure waves within the combustion chamber propagating against the flow direction. When these waves interact with the flow at fuel or air feed points or flame-stabilising components (bluff-bodies, wakes, etc), fluctuations of mass flow rate, equivalence ratio or periodic vortex shedding can occur. Subsequently, these disturbances will travel, at convective speeds, into the combustion zone where they cause corresponding fluctuations of the heat release rate. Other possible feedback mechanisms involve variations of the flame front area and periodic break-up, atomization and vaporization of liquid fuel (see e.g. Putnam [5]).

4. Possibilities of avoiding and/or suppressing self-excited combustion oscillations

During the design phase of a combustion system, predictions about its tendency to develop self-excited combustion oscillations are still only of limited validity. Thus, the development of methods allowing to avoid and/or suppress this type of oscillation during system testing is of crucial importance. The means available to do so can be subdivided, in principle, into two groups: passive and active measures.

4.1. Passive measures

The term passive measures refers to modifications of a combustion system that, during system operation, will not be changed any more and/or will require no external supply of energy. Typical passive measures are "detuning" a system by modifying its burners or the acoustics of its combustion chamber, by increasing acoustic damping via Helmholtz-type resonators, or by disturbing the propagation of sound waves via baffles (see e.g. Culick [6]). For passive measures to be successful, it is normally indispensable to do intensive research on system behaviour. Accordingly, any measures thus found are often valid and/or effective for a specific system only.

4.2. Active measures

Additionally, so-called active measures are an interesting alternative, the term active referring to any means of acting upon the current status of any combustion system in a targeted, controlled manner. Normally, an external power supply will be required.

One example of this kind of active system is "Active Instability Control" (AIC) of combustion oscillations. AIC uses an actuator to modulate some suitable parameter of a combustion system. Under ideal conditions, modulation is performed in a manner to have the corresponding system variable fluctuate precisely *in counter-phase* with the fluctuations constituting the combustion instabilities, thus damping them. To do so, some system parameter characterising the corresponding oscillation is measured, and processed via a controller, in order to generate the control signals for the actuators. For industry-type combustion systems, influencing heat release fluctuations by modulating fuel supplies has proved to be an efficient and practicable means of intervention. Because of the high volumes of air to be moved, another type of intervention - via system acoustics by imposing sound waves in counterphase to the sound field in the combustion chamber, e.g. by loudspeakers - is suitable only for low-power combustion systems.

5. Combustion instabilities in Siemens type Vx4.3A gas turbines and ways of avoiding them

5.1. Combustion instabilities and eigenmodes in annular combustion chambers

Siemens type Vx4.3A gas turbines (see Figure 1) feature annular combustion chambers comprising 24 hybrid burners distributed peripherally (see Figure 2). Hybrid burners make it possible to operate gas turbines on either gaseous or liquid fuels. The gas-burning mode offers, in addition to purely diffusion-based or premix operations, the possibility of combining both types of operation. Moreover, so as to stabilise the premixed flame, every burner features a small diffusion-based pilot-flame.

Using the standard hybrid burner within the annular combustion chamber of type Vx4.3A gas turbines resulted in unwanted self-excited combustion instabilities which limited, above all, the maximum achievable power output of the turbine. Moreover, it was found that certain part load operating modes were subject to oscillations. In addition to high sound pressure levels at discrete frequencies, standing sound waves - typical of combustion instabilities - were measured; these are characterised by localised amplitude minima and maxima, also called nodes and antinodes. Owing to their preferred orientation along the circumference of annular combustion chambers, these modes are designated azimuthal. Figure 6 shows a typical azimuthal mode, corresponding to the first harmonic, within the annular combustion chamber.

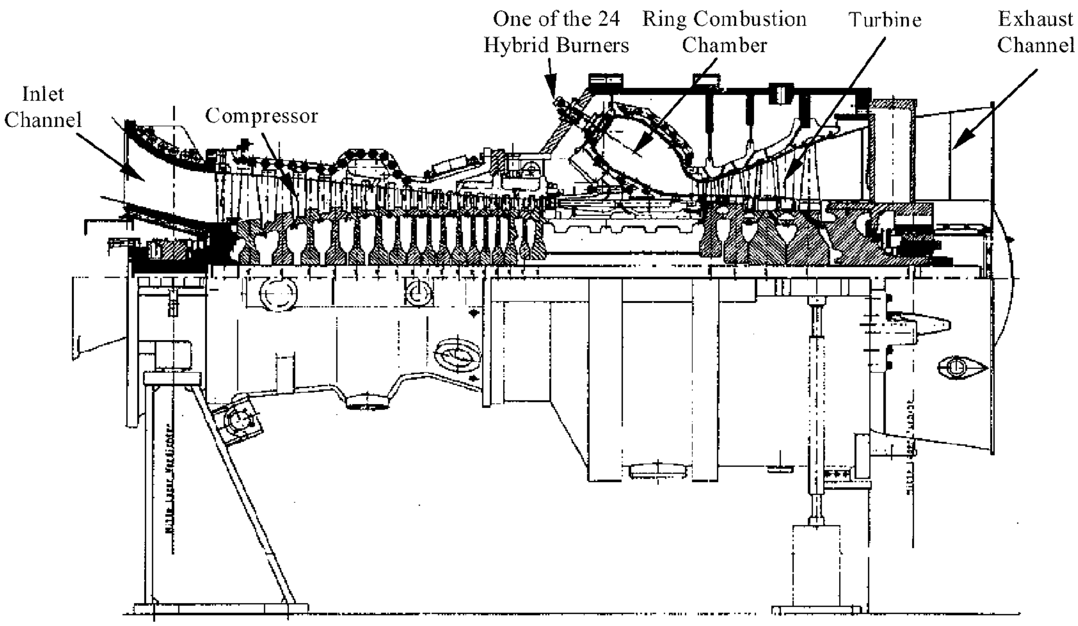

Figure 1: Half-section drawing of the Vx4.3A series gas turbine.

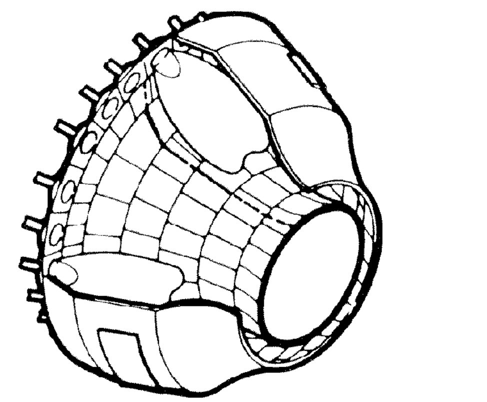

Figure 2: Vx4.3A Hybrid Burner Ring® (HBR) Combustor - One Annular Combustor with 24 Burners.

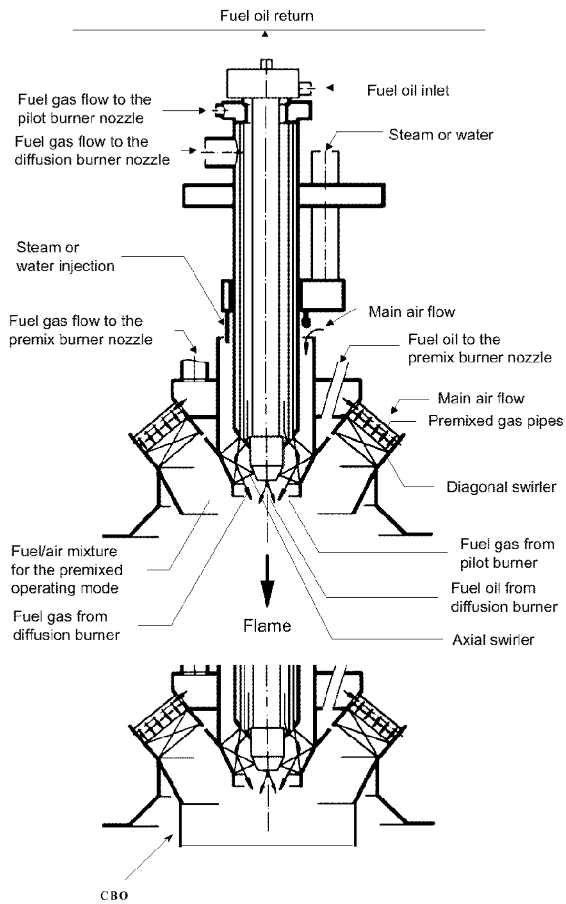

Figure 3: The standard Siemens Hybrid Burner (top) and with schematic CBO extension (bottom).

5.2. Measures used to suppress combustion instabilities

5.2.1 Passive measures

Considering the fact that the generation of self-excited combustion instabilities depends on certain time lags, selectively modifying those time lags is one possible means of suppressing combustion instabilities. The time lag most easily adapted is the convective time lag or the time required to convey the fuel/air mixture into the combustion zone. In order to make it possible to adjust this parameter in a precisely targeted manner, a cylindrical extension - called a cylindrical burner outlet (CBO) - was welded onto the burner nozzle (see Figure 3). The length of this extension was selected so as to prolong the convective time lag by slightly more than one quarter of the period of the self-excited oscillation.

As already mentioned in section 3, one possible cause for fluctuations of the heat release rate of the flame and thus for combustion instabilities are periodically generated vortices, which can be provoked by flow disturbances in the shear layer. To prevent these flow instabilities, the cylindrical extensions attached to the burner nozzles were inclined by 10° in respect to the flow axis on two

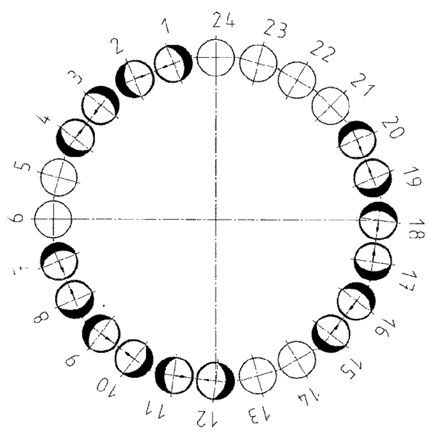

Figure 4: Asymmetric arrangement of 8 ABO pairs along the circumference of the annular combustion chamber.

neighbouring burners. Owing to the angle of inclination characterising these extensions, they are designated asymmetric burner outlets (ABOs). ABOs cause an uneven shear layer distribution around the burner nozzle, thus reducing the formation of coherent structures, and displace the combustion zone downstream of its former position, thus increasing the time lag.

Another passive measure taken is the use of several burner types characterised by differing flame frequency responses and installing burners belonging to the same type asymmetrically, with reference to potential azimuthal modes: if burners belonging to the same type are not precisely located, for example on the potential pressure antinodes of the azimuthal modes to be prevented, they will not be optimally excited to combustion oscillations by the prevailing acoustics. Figure 4 shows an example for an asymmetric burner arrangement using ABOs.

5.2.2 Active measures

The AIC system implemented for V94.3A turbines corresponds, in principle, to the active system developed for V84.3A prototype tests. However, major components, such as controller, actuators and certain methods to implement the system at the turbine, were redesigned comprehensively and developed into a system fully optimised for the power generation industry. Detailed descriptions are to be found in Seume et al. [7] for the first AIC implementation, and in Hoffmann et al. [8] and Hermann et al. [9] for the re-designed version. Figure 5 schematically shows the AIC-set-up for the gas turbine.

Active control was done by modulating the pilot gas supply for the various hybrid burners. The pilot gas was chosen because the pilot flames that stabilise the main premix flames, exert a very high degree of influence on the main flames. Owing to reduced mass flows, control via pilot gas flames is substantially easier than modulating the main gas flow. To obtain optimum control over the system, every burner was fitted with its own actuator, a Moog-made rapid direct drive valve (DDV). The amplitude loss of the used 3rd generation of the DDV valve is less than 3dB up to a frequency of 420 Hz and the valve can be used with a maximum allowed ambient temperature of about 120°C.

The success of AIC strongly depends on a sufficiently high modulation of the heat release rate of the pilot flame and thus, indirectly, on a high modulation of the mass flow rate in the pilot gas system by the actuator. Since the mass flow rate modulation on the other hand is strongly dependent on the acoustic field in the pilot gas system or rather its resonant behavior, the pilot gas system was tuned so as to allow for maximum mass flow rate modulation at the frequencies to be damped. Details about the tuning of a fuel system for AIC can be found in Hermann et al. [10] and Hantschk et al. [11].

Since any individual burner can excite combustion oscillations, each of the 24 burners has to be controlled. This requires, in addition to 24 actuators, a multi-channel AIC system providing the same number of control loops. However, the number of sensors and control units needed can be reduced by taking advantage of the

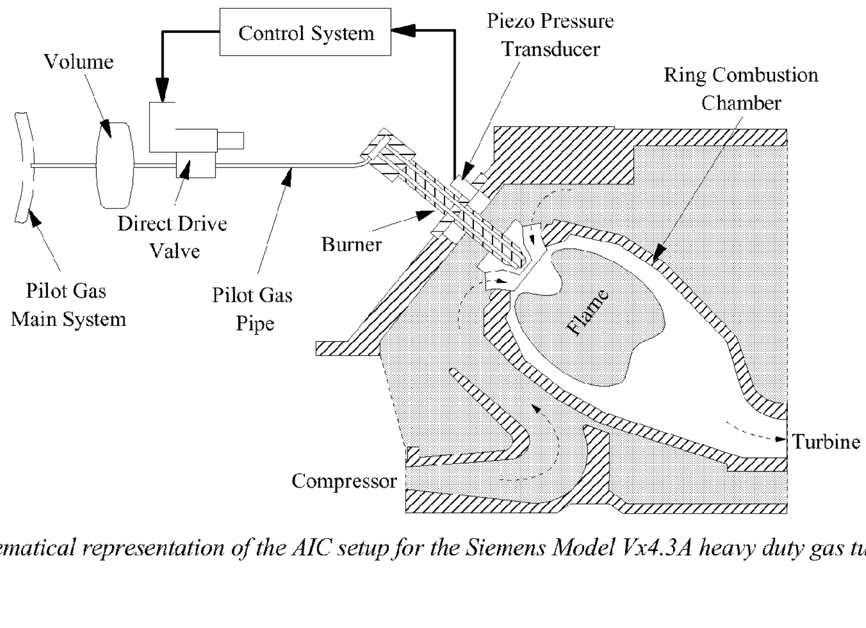

Figure 5: Schematical representation of the AIC setup for the Siemens Model Vx4.3A heavy duty gas turbine.

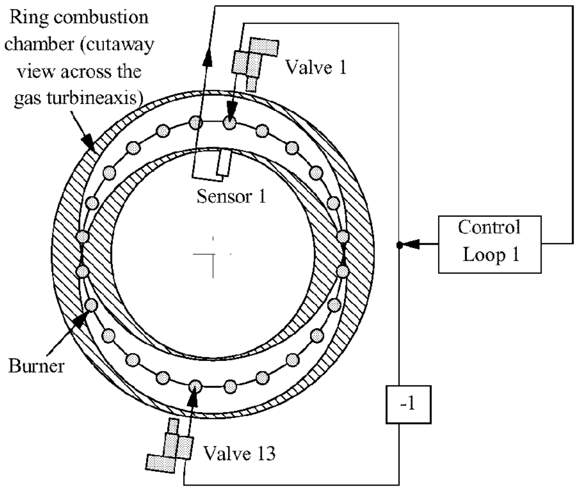

Figure 6: Use of the symmetry of azimuthal modes, e.g. for the first harmonic. One sensor and one controller provide the input signals for two DDVs.

symmetry of the excited azimuthal modes. As described by Seume et al. [7] it is possible to use a signal measured at a certain circumferential location of the azimuthal mode - or the annular combustor - to determine not only the actuator input signal for this particular location but also those for several other locations. Depending on the possible excitable azimuthal modes in the V94.3A, a total of 12 control loops were used, with each loop comprising a pressure sensor and 2 valves as actuators (see Figure 6).

The multi-channel controller is a self-contained modular industrial system and fully integrated into the gas turbine control system. In addition, the hard- and software set-up is optimised with respect to short commissioning and implementation time scales. The main control work is done by 6 digital signal processors, each of them handling two control loops. The control algorithm used works in the frequency domain and allows, in its latest version in combination with new expanded hardware outputs, simultaneous processing of any two oscillation frequencies.

As input signal for the control loops, the sound pressure value measured at the burner flange by high temperature piezoelectric transducers is used. As shown by Seume et al. [7], these signals are sufficiently correlated with sound pressure levels prevailing within the combustion chamber. For this purpose, a total of 12 transducers was installed along the circumference of the gas turbine.

5.2.3 Combining passive and active measures

Gas turbines are often operated over a wide range of power levels, ambient temperatures and in different modes of operation. This makes it a difficult task to protect all operating points against potential combustion instabilities by passive measures. Furthermore, implementing passive measures may bring about, beside any successful suppression of combustion oscillations at formerly unstable operating points, instabilities at points formerly quiet.

In contrast to that, the active control of combustion oscillations is a very flexible measure. At any operating point, AIC can easily be used to suppress unexpected new instabilities as well as those that cannot be overcome by passive measures.

The successful implementation of the passive and active measures described, as well as various combinations of these measures for different gas turbines with nominal power output levels between 233 MW and 267 MW at ISO conditions will be described in the following section.

6. Results

6.1. Application of passive measures

The first tests, using the passive measures developed, were designed to research several variants of installing asymmetrical burner extensions. 3, 5 and 8 pairs were used, the 8-pair arrangement being installed both symmetrically and asymmetrically (see Figure 4) along the circumference of the annular combustion chambers. The impacts of the various arrangements in terms of combustion oscillations were verified by running up the turbine to its new stability limits and/or a new level of maximum achievable turbine power. As the number of ABO pairs was increased, damping results improved; more particularly, asymmetrical arrangements given identical numbers of ABO pairs resulted in significant improvements (see Figure 7). With the best arrangement, it was possible to increase maximum turbine power by 7 percentage points. A further increase of ABO pairs to a total of 9 failed to produce any further improvement.

A further series of experiments was run to test various combinations of CBOs installed in a similar, i.e. asymmetric, manner as the ABO arrangements. Just as with ABO experiments, an increasing number of CBOs resulted in shifting stability limits towards higher levels of achievable maximum turbine power (see Figure 8). The best result achieved amounted to an increase of turbine power by 9 percentage points, with 20 CBOs.

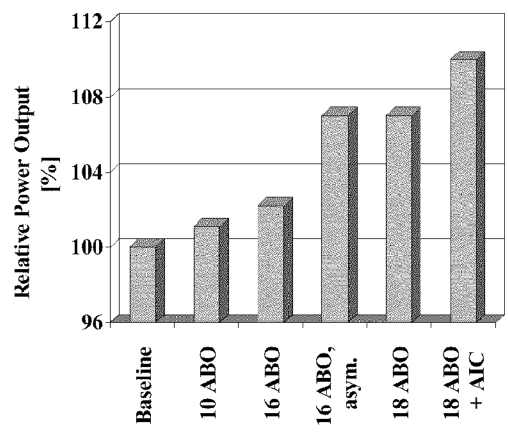

Figure 7: Stability limit at different ABO arrangements.

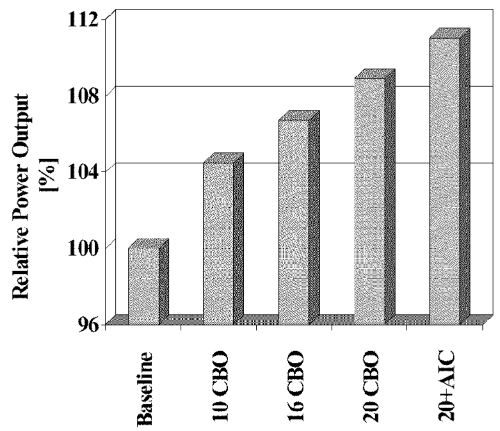

Figure 8: Stability limit at different CBO arrangements.

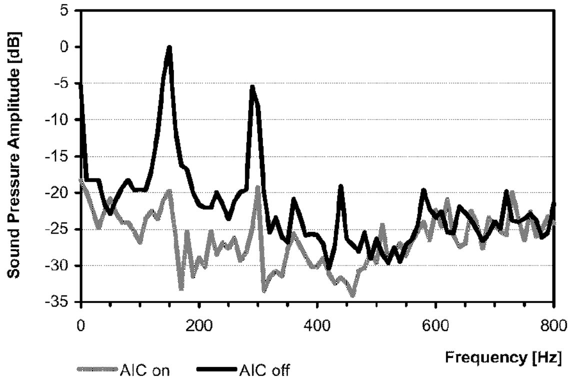

Figure 9: Suppression of two frequency peaks during part load operation by AIC.

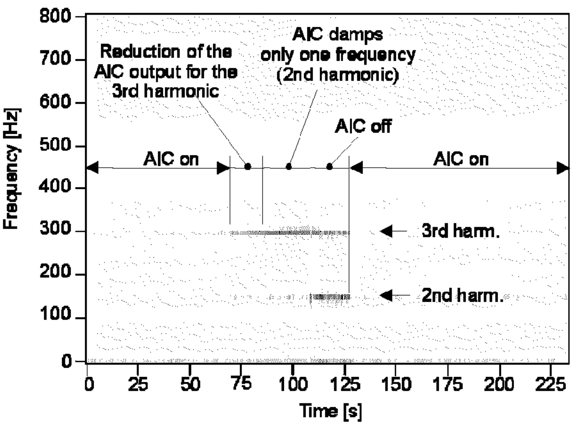

Figure 10: Separate damping of two dominant eigenmodes of a combustion instability by AIC.

6.2. Combination of passive and active measures

The good results achieved by passive measures were further improved by using an Active Instability Control system. Furthermore, in situations where implementing passive measures causes instabilities at points formerly stable – which can occur in some configurations – AIC was successfully applied to overcome these problems. More particularly, short-term stability problems at part load operations were dealt with successfully. In the process, AIC once again proved its high level of flexibility with regard to solving oscillation problems of various kinds.

6.2.1 AIC during start-up and part load operations

Using CBOs with a special burner configuration unexpectedly lead to increased oscillation tendencies during the start-up phase. During this phase, operation of the hybrid burners is ensured by means of diffusion-type flames since combustion chamber temperatures are still too low to stabilise a premix flame. Subsequent to start-up, and while loads increase up to the switch-over point towards mixed operation (combining diffusion and premix operations), the second and third harmonics of the annular combustion chamber were excited. Due to the strenuous commissioning schedule, there was no more time left for optimisation of the start-up sequences. Therefore it was decided to use the AIC system in order to resolve this issue. Even though, in view of its control via pilot flames, AIC was designed for premix operations, additional pilot gas was introduced during diffusion operation, while simultaneously the AIC was activated. This resulted in very good damping of the combustion oscillations, thus allowing the system to run up through the start-up and part load phases to mixed-mode operation without any problem. Figure 9 shows the sound pressure spectrum (the overlapped spectrum of the 12 AIC sensors) with and without AIC at a certain operating point. By activating AIC for both dominant frequencies, a damping by 20 dB (second harmonic) and 15 dB (third harmonic) was achieved. In order to allow the simultaneous damping of the second and third harmonics within the annular combustion chamber, the AIC system was improved in terms of its independence in controlling valves located on opposite points of the combustion chamber. With this improvement the limitations on damping for certain frequencies described by Hermann et al. [9] were eliminated.

The individual damping of the two dominant eigenfrequencies of the combustion instability by the AIC system can be seen in Figure 10. It shows the frequency spectrum of the sound pressure versus time in a kind of contour plot: dark regions signify high pressure amplitudes. The two grey horizontal streaks at 145 Hz and 290 Hz belong to the two dominant frequencies of the prevailing combustion instability. It can be seen that by slowly reducing the AIC output signal used to suppress the 3rd harmonic this mode resurges step by step (line darkens for 70s < t < 85s). During the next 23 seconds only one of the self-excited frequencies - the 2nd harmonic at 145 Hz - is damped by AIC. After switching off the complete control loop at t = 108 s also the 2nd harmonic resurges to higher amplitudes: at that time a dark line appears at f = 145 Hz. After another 19 seconds, at t = 127 s, the AIC system is reactivated to damp both frequencies which leads again to a complete suppression of the combustion instability. This example shows that in the prevailing case the two modes are excited independently of each other and therefore every mode must be suppressed separately by AIC to achieve a good damping of the combustion instability.

6.2.2 *Increasing base load operating levels*

In addition to part load operations, AIC demonstrated its high levels of flexibility in suppressing oscillations also for peak load operations. In combination with passive measures, it was thus possible to edge up stability limits for most applications by a few percentage points. For example, by using AIC in combination with the best arrangement of ABOs (9 pairs), it was possible to increase maximum turbine power by 3%, and in combination with the best CBO arrangement (20 CBOs) by 2%. In the latter case, further load increase was not possible because the maximum permissible turbine inlet temperature had already been reached. In addition to these improvements, with the AIC system active, the NO_x emissions could be reduced significantly by reducing the mean pilot gas mass flow rate: in premix mode, the pilot flames are the primary source of NO_x emissions.

6.2.3 *Problems with frequency shifts*

Near base-load operation, arising combustion oscillations did not only increase the pressure amplitude but simultaneously also led to a substantial shift of the oscillation frequency from 155 Hz to about 170 Hz (see Figure 11). During the tests it was observed that damping of these oscillations depends on synchronised modification of AIC set-up parameters. The determined set of parameters allowing optimum AIC performance indicates that, when this frequency shift occurs, the combustion zone will simultaneously be shifted towards the burner nozzle. To allow efficient compensation of the changes in boundary conditions thus produced, the AIC control algorithm was complemented by an appropriate frequency tracking feature. Taking this measure substantially improved long-term stability at base-load levels.

6.2.4 *Failure tolerance and long-term AIC use*

During the different tests, valve failures were simulated in order to test their impact on the overall AIC performance. A maximum of four valves was switched off during AIC runs resulting in no noticeable degradation of the system performance, regardless of the valve position. Switching off more than four valves were not tried out due to time constraints.

The Active Instability Control system presented here is currently being used for base load, with several V94.3A gas turbines featuring 20-CBO configurations. Two of the systems, in operation since January 1999, have demonstrated outstanding long-term stability. Up to now the AIC-Systems have operated for approximately 6,000 hours each. In co-operation with the gas turbine control system, the AIC system provides fully automated, stable gas turbine operations over the entire operating range. Moreover, inspection of some of the actuators used demonstrated that the wear and tear of the moving parts is negligible.

7. Summary

Self-excited combustion oscillations occurring within the annular combustion chamber of the Siemens type V94.3A stationary gas turbine featuring 24 hybrid burners limited, above all, the maximum achievable turbine power output. To avoid or suppress these oscillations, various passive and active measures were developed and successfully implemented. Stability improvements achieved by every single measure were demonstrated on various gas turbines.

In a first step, burner nozzles were equipped with cylindrical extensions whose length was adapted to extend the time lag between the flow entering the combustion chamber and the combustion zone. In order to avoid fluid-dynamic instabilities and change the time lag of the flames, the cylindrical extensions of neighbouring burners were inclined towards each other in an angle of 10° with reference to the main flow direction. By using an increasing number of burner pairs featuring these extensions, it was possible to increase turbine power in steps by suppressing the excessive flame oscillations. It was found to be highly effective to use an asymmetrical arrangement for 8 to 10 pairs. As compared to the standard configuration, these pairs allowed turbine power to be increased by 7%. Similar results have been achieved for the not inclined cylindrical extensions. These extensions were likewise installed asymmetrically within the combustion chamber. The best arrangement totalling 20 modified burner nozzles improved the stability limit by 9 percentage points, as compared to standard burners.

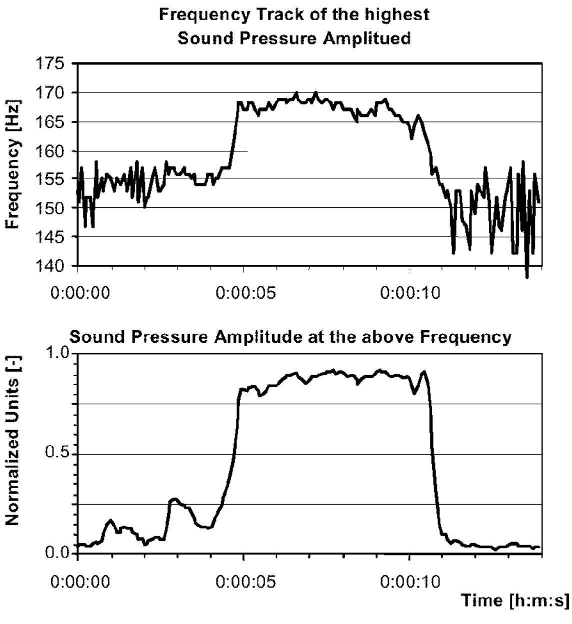

Figure 11: Frequency shift during arising sound pressure amplitude (without activated AIC-System).

The results achieved by means of passive measures were improved even more by employing an Active Instability Control (AIC) system. For the best burner configuration having ordinary, i.e. straight, extensions, AIC made it possible to increase the stability limit by 2%, as well as by 3% for the best configuration having inclined nozzle extensions. Moreover, at base load operations, AIC allows a reduction of NO_X emissions by more than 60% by lowering the pilot gas mass flows necessary for stable operation. Problems entailed by substantial frequency shifts whenever combustion instabilities occurred at maximum turbine power were rectified by rapidly and automatically adapting the appropriate control parameters. In addition to stabilising base load operations, the AIC system successfully dealt with stability problems occurring under part load conditions in diffusion operation of the gas turbine. At this point AIC reduced the two dominant frequency peaks by 20 dB (2^{nd} harmonic at 145 Hz) and 15 dB (3^{rd} harmonic at 290 Hz). To allow - in contrast to former AIC set-ups - the control of two modes with an even and an odd mode number, the AIC system was improved in terms of its independence in controlling any two modes.

The successful damping of combustion instabilities in various operating points of the gas turbine demonstrates the high flexibility of the employed active measures in dealing with this problem and allowing stable gas turbine operation over the entire range. The presented AIC system is currently being used with several V94.3A gas turbines. The field leading installation, implemented in January 1999 in a base loaded machine, has been operating for approximately 6,000 hours and continues to demonstrate its excellent long-term stability.

8. References

1. Rayleigh, Lord J.W.S.: The Explanation of Certain Acoustical Phenomena. Nature, pp. 319-321, 18. July 1878.
2. Putnam, A.A., Dennis, W.R.: Burner Oscillations of the Gauze-Tone Type. The Journal of the Acoustic Society of America, Vol. 26, No. 5, pp. 716-725, 1954.
3. Hermann, J.; Zangl, P.; Gleis, S.; Vortmeyer, D.: Untersuchung der Anregungsmechanismen selbsterregter Verbrennungsschwingungen an einem Verbrennungssystem für Flüssigkraftstoff. 17. Deutscher Flammentag, Hamburg-Harburg, VDI-Bericht Nr. 1193, S. 251-260, 1995.
4. Lieuwen, H.T.; Torres, H.; Clifford, J.; Zinn, B.T.: A Mechanism of Combustion Instability in Lean Premixed Gas Turbine Combustors. ASME paper 99-GT-3.
5. Putnam, A.A.: Combustion Driven Oscillation in Industry. Elsiever.
6. Culick, F.E.C.: Combustion Instabilities in Liquid-Fueled Propulsion Systems – An Overview, AGARD CP 450, pp. 1-1 – 1-73, 1988.
7. Seume, J.R.; Vortmeyer, N.; Krause, W., Hermann, J.; Hantschk, C.-C.; Zangl, P.; Gleis, S.; Vortmeyer, D.; Orthmann, A.: Application of Active Combustion Instability Control to a Heavy Duty Gas Turbine. ASME Paper No. 97-AA-119, 1997
8. Hoffmann, S., Hermann, J. and Orthmann, A.: Active Flame Instability Control for Heavy Duty Gas Turbines. PowerGen Europe 99, Frankfurt, Germany.
9. Hermann, J.; Orthmann, A.; Hoffmann, S.: Application of Active Combustion Control to a Heavy Duty Gas Turbines. 14th Int. Symposium on Airbreathing Engines, Florence, Italy, 5-10 Sep 1999.
10. Hermann, J., Gleis, S., and Vortmeyer, D.: Active Instability Control (AIC) of Spray Combustors by Modulation of the Liquid Fuel Flow Rate, Combust. Sci. and Tech., Vol. 118, pp. 1-25, 1996,.
11. Hantschk, C., Hermann, J., and Vortmeyer, D.: Active Instability Control with Direct Drive Servo Valves in Liquid-Fuelled Combustion Systems, 26. Int. Symp. on Combustion, Naples, 1996.

PAPER -3, J. Hermann

Question (B. T. Zinn, USA)
When you do active control, you basically change the manner in which the total fuel is supplied to the system. This, in turn, *may* affect the primary process that drives the instability. Thus, it is important to determine the relative damping of the instability provided by "redistribution" of the fuel injection and by the active instability control (AIC).

Reply
The mean gas mass flow is not changed by AIC. Because of this and the fact that we only modulate the pilot gas mass flow, which is about 5-10% of the total gas mass flow, around its mean value, we do not expect any damping of the instabilities by "redistribution" of the fuel injection. Furthermore, having been able to damp two different frequencies independently of each other is another proof that the damping is achieved purely by AIC.

Question (V. McDonell, USA)
What is the cost effectiveness of AIC? You are gaining an additional 1-2% in the total output, but at what relative cost of the AIC system. It is reasonable that costs will come down if more systems are installed/developed.

Reply
If you can produce some percent more electric power over some years, the cost of an AIC-system easily pays off.

Question (M. N. Nina, Portugal)
How much fuel was used in the pilot burner to control the oscillations?

Reply
About 5-10% of the total gas mass flow.

This page has been deliberately left blank

Page intentionnellement blanche