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THERMO-ACOUSTIC CHARACTERIZATION OF CAN-CAN INTERACTION OF A CAN-ANNULAR COMBUSTION SYSTEM BASED ON UNSTEADY CFD LES SIMULATION

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ABSTRACT

Many modern gas turbines are using can-annular combustors. One important feature of can combustors is that the flame reaction zones are separated by walls. Based on this fact it is often assumed that the acoustic coupling between adjacent cans is negligible.

Experimental measurements in can-annular combustion systems however indicate, that a non-negligible coupling between the cans exist and it needs to be taken into account when modeling instability modes. Such can-to-can modes are not easily reproducible in a common single can test rig and are an issue for establishing a reliable acoustic rig-engine correlation.

In the presented work the combustor can coupling at the turbine side is investigated by means of numerical simulations. The possible modes are computed using eigen-mode analysis. The can cross-talk is quantified using a forced response analysis. For this study a generic simplified geometry with 8 cans is used.

INTRODUCTION

Typically can-annular combustion systems are tested in single combustor test rigs. A single can combustor test shows for many combustion phenomena like ignition or NOx and CO emissions a high rig-to-engine correlation since no flame interaction between the spatially isolated burners takes place. For combustion dynamics, establishing this correlation becomes more difficult, when can-can modes need to be predicted. Such modes are not easily reproducible in a single-burner rig. Usually it is tried to reproduce these modes in the rig by introducing an appropriate geometry downstream of combustor outlet that simulates the acoustic characteristics of the neighboring cans. Another approach is to use high fidelity LES simulations on 2 or more cans relying on massive computational power (see e.g. [1]).

For predicting the frequency and stability of acoustic modes which are anchored in multiple combustors a good understanding of the can-can mode shapes is mandatory.

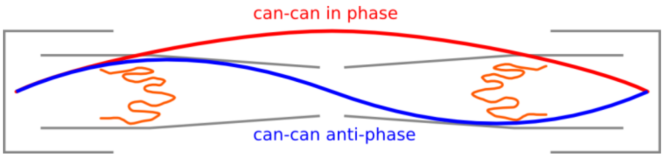

Figure 1 Sketch of can-can pressure modes in a pair of burners

The term can-can mode is used in this paper to describe a modal form, which involves more than a single burner can or a single can mode that synchronizes with other cans in the turbine. A sketch explaining the basic mode shapes based on the pressure in two cans is shown in Figure 1. A pressure node is assumed on the cold side of the burners. The turbine inlet is located between the cans. The red curve demonstrates two coupled single can modes which are in-phase. The blue curve in the image indicates a can-can mode with the cans oscillating with opposite phase. The acoustic condition at the can interface (turbine inlet) changes significantly for both type of modes between

$$\text{grad } p = 0$$

and

$$p = 0$$

in this idealized model.
The present study is limited to the downstream side of the cans. The acoustic path via the plenum is not the scope of the work.

EXPERIMENTAL EVIDENCE

As mentioned before, the existence of can-can modes has been indicated by measurements in can-annular combustion systems. The presented data originates from a system with an even number of cans with a can count higher than eight. Dynamic pressures were measured in all combustor cans at the same location. The signals of adjacent cans have been processed by means of the cross power spectral density function based on the Welch method (Matlab). Figure 2 depicts the phase of the complex result for an exemplary time span of three minutes in the relevant frequency range. The phase relation between the neighboring cans tends to group naturally into in-phase (0 degrees, blue color) and anti-phase (180 degrees, red color) regions. The transition around the normalized frequency of $f_n = 1$ has a steeper transition between the two states compared to the region around $f_n = 2.2$. This fact is most probably attributed to more acoustic activity in the first-mentioned range.

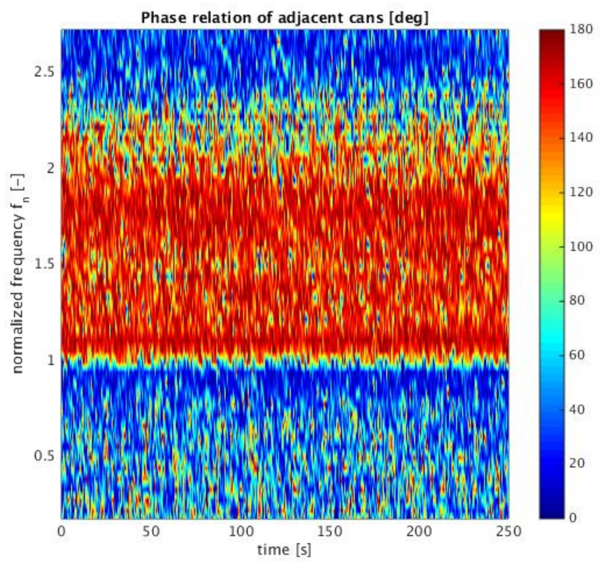

Figure 2 Phase relation between two adjacent cans plotted over frequency and time.

The in-phase region with no phase shift can be linked to the red curve in Figure 1, the one with a shift of π to the blue shape. The phase lock is not amplitude dependent if the signals are above the noise level.

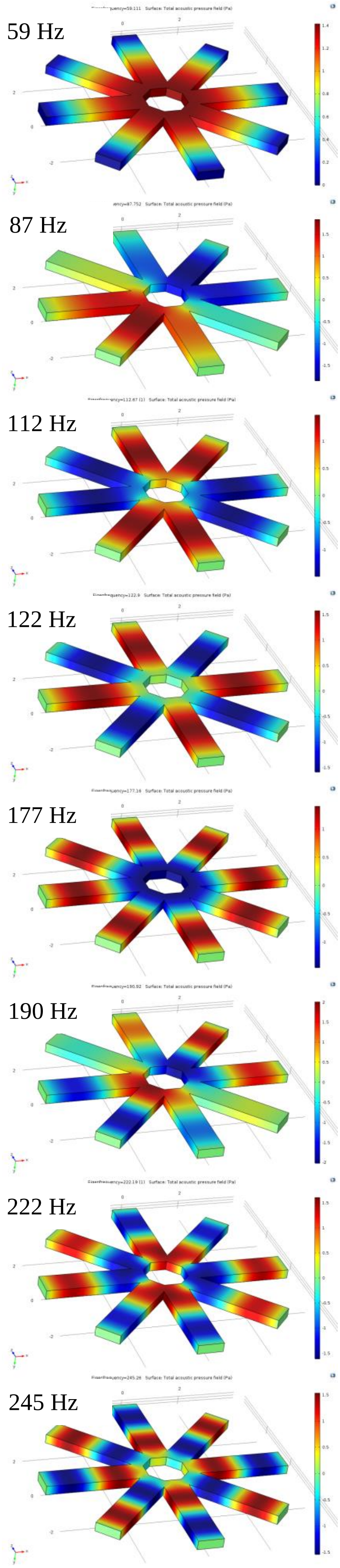

Figure 3 Pressure contours of the first eigen-modes in a system of 8 communicating cans shown in ascending order

EIGENMODE ANALYSIS

To gain some basic insight into the possible mode distributions in a multi-can system an eigen-mode analysis of a simplified geometry has been performed using the commercial software package Comsol. The investigated geometry is depicted in Figure 3. It consists of eight flat channels connected to a star-shaped assembly. The channels represent the combustor cans in the most generic form. Their outer ends are terminated with an "acoustically open" condition "p'=0" imposing a pressure node, a condition often used to model the plenum-can transition. The choice of this boundary is not essential for the formation of can-can modes as long as it is equal for all cans and reflective.

All other boundaries are of the type "wall", implying then the system has no damping and the turbine inlet is modeled as fully reflective. The dimensions and the temperature (can length of about 3.5 m, T=1700 K) have been selected to match roughly the conditions of a large gas turbine and give eigen-frequencies in the correct order of magnitude. The flow has not been considered.

Figure 3 shows the relevant results of the eigen-mode analysis with the normalized pressure used for the contours. The eigen-frequencies, the number of cans in the repeating mode pattern and a description of each mode are given in Table 1. A mode pattern is defined as the pattern of the smallest subset of cans by which the pattern of the complete can system can be obtained by periodical rotation. The modes are described in more details in the following.

The typical equally phased single can modes occur at 59, and 177 Hz. These frequencies form a ratio of 1:3 according to the number of quarter-waves fitting in a single can. These modes can exist in an isolated can. It can only exist in a communicating system when the cans are in synchrony and *grad p* = 0 in the can connection gap.

The all-cans modes at 87 and 190 Hz form a pattern where the waves travel transversally through all cans, comparable to a sloshing motion of a fluid in a cylinder. This mode has to pass the highest number of can gaps.

The results found for the frequencies 112 and 222 Hz show a can-can mode repeating four times in the circumference with an alternating phase alignment of “+−−+”.

This mode can exist in an isolated two-can setup, since the pairs are "separated" from each other with a grad p = 0 condition. Each can has both an open and a close boundary at the can gaps.

The last modal form is represented by the frequencies of 122 and 245 Hz. According to the measurements described before briefly, this mode is the most dominant can-can mode. Here each neighboring can oscillates with an opposite phase pattern of type “+−”. Multiples of a wave length of 1/2L per can or 1L per two cans fit into the acoustic path. Both connecting gaps of each can have an "open" condition.

The last-mentioned oscillation form is dominant in the experimental data. The reason for the absence of the more complex patterns is not entirely clear. If data analysis errors are excluded, a simplified explanation might be a longer “path” of the complex modes involving several gaps. Such can-can gaps allow only a limited transmission of acoustic energy as shown later in this paper.

The formation of single-can and multi-can modes repeats with the same order with rising frequencies and an increased number of quarter-waves fitting into the geometry. Above the first cut-off frequency of the channels transversal modes start to appear.

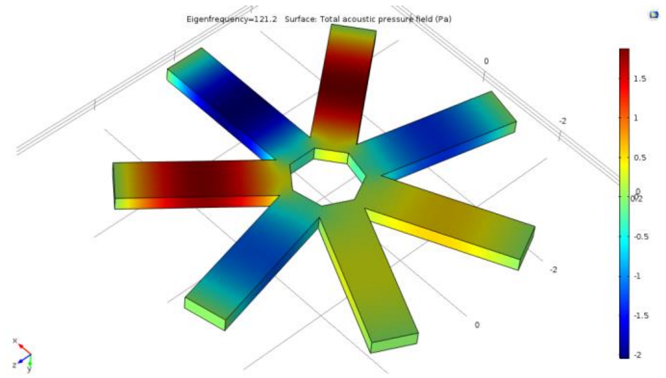

Figure 4 Exemplary mode of a 7-can system

Freq. [Hz]	Cans in pattern	Comment	Wave length
59	1	Single can mode	1/4L per can
87	8	All-cans mode	1L btw opposite cans
112	4	4 anti-phase pairs ++−−++−−	~1L per 2 cans
122	2	Anti-phase from can to can	~1L per 2 cans
177	1	Single can mode	3/4L per can
190	8	All-cans mode	2L btw opposite cans
222	4	4 anti-phase pairs ++−−++−−	~2L per 2 cans
245	2	Anti-phase from can to can	~2L per 2 cans

Table 1 List of eigen-modes and their properties

The even number of channels in the examined setup favors modes shapes involving two cans. Conversely, one could expect that a system with an odd number of cans will be less prone to can-can interaction. An exemplary multi-can mode for a setup with seven cans is presented in Figure 4. As expected, the non-single-can mode shape involves all seven cans. The picture repeats for other frequencies. The longer communication path of such all-can modes might make their excitation less easy.

NUMERICAL INVESTIGATION OF THE CAN-CAN CROSS-TALK

The experimental data showed the existence of can-can modes in the gas turbine. Their possible shapes were investigated by means of an eigen-mode analysis in the previous section. A question that remains is how the size of the connecting gap influences the communication between the cans and from which specific size the communication is suppressed.

To gain more insight into the can cross-talk effect, an isolated system of two connected cans terminated by a stator stage is studied numerically with compressible LES. The sound transmission from one can to the neighboring one is investigated and amplitude ratio is given.

The computational setup is sketched in Figure 5. It consists of two flat channels, the turbine inlet region with the stator and a large buffer zone for flow stabilization and non-echoic acoustic termination. The cans are connected upstream of the vanes via a small gap, which is in focus of the study.

The computational domain consists of about 30000 cells of predominantly hexahedral shape. A detail of the grid is presented in Figure 6. It has a resolution of just one cell in the height direction reducing the problem to two dimensions. Refinements are applied around the curved vanes where high gradients are expected. The solver *sonicFoam* from the OpenFOAM package [2] has been used for the simulation. It offers numerical schemes with an order up to two in space and time. A physical time of several hundreds of milliseconds has been simulated to ensure statistical convergence of the results.

The acoustic behavior is characterized using the forced response approach in combination with wave decomposition applied a posteriori. In the present case, the inlet boundary of one can serves as plane wave sound source and emits a multi-harmonic low amplitude ($U' < U_0/100$) signal in the frequency range of 20-400 Hz. The downstream wave amplitude in the excited can F_1 is put in relation to the upstream amplitude G_2 in the non-excited can. The ratio of these amplitudes is defined as the cross-talk coefficient

$$X = G_2/F_1.$$

The amplitudes for each travel direction have been computed by the multi-microphone method as described for example by Bothien et al. [3]. Several probes located along the axis of each can have been used for the amplitude estimation.

Two geometries are compared in this paper. They are shown in Figure 8 in more detail. In the reference geometry (right) the can gap is completely closed. The cans are connected acoustically via the indirect route through the reflective vane passages. This setup allows to establish the

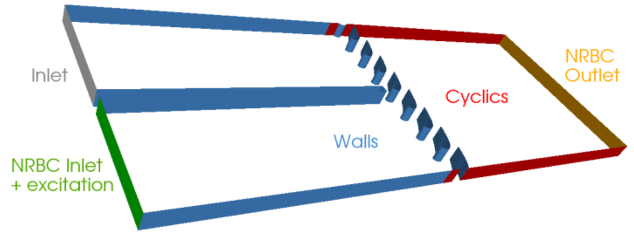

Figure 5 Numerical setup for the can-can cross-talk investigation

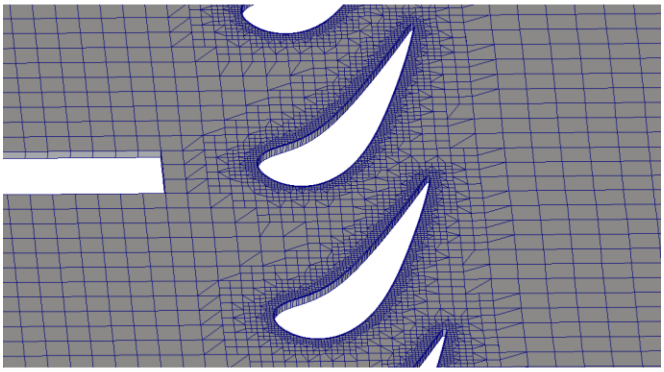

Figure 6 Detail of the computational mesh in the can gap area

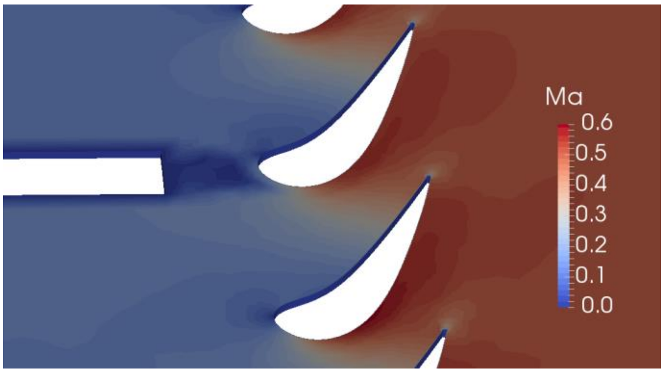

Figure 7 Mach number in the can gap area

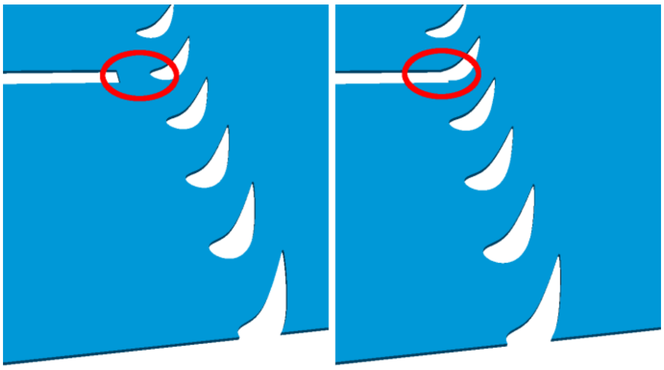

Figure 8 Comparison of the gap geometries. Left: gapped case, right: no gap.

baseline behavior and check if the calculation delivers reasonable results. In the other case (left) the gap is about one half of the vane cord length or one tenth of the can width. Here a direct acoustic route has been added and a higher can cross-talk coefficient is expected. It should be noted that the cyclic boundary condition provides a second gap of the same size at the outer sides of the cans (red marking in Figure 5). Effectively the cans communicate via two gaps with each other.

The highest excitation frequency has a wave length about four times bigger than the can width and is far below the cut-off frequency. The flow conditions in both cans were identical resulting in a maximum Mach number of about 0.6 in the stator section. A random instantaneous Mach number distribution in the stator zone is shown in Figure 7. A low velocity region is visible in the wake of the can wall.

The cross-talk coefficient as a function of the frequency is plotted in Figure 9. The graphs are based on the excited frequencies only and a have a rather smooth behavior. As expected the cross-talk is significantly smaller for the no-gap case, although the value is above zero. The gapped case shows an amplitude ratio of about 0.2 in a broad range with a slow rise towards lower frequencies. In the lowest frequency range below 40 Hz the non-reflective boundary conditions become reflective and the result becomes unphysical.

In general the result seems quite high in relation to the size of the gap. Even higher values can be expected for higher stator Mach number where less acoustic energy is transmitted out of the domain through the outlet. More detailed parameter studies on this topic can be found in the work of Farisco et al. [4,5].

The results in Figure 9 can be transferred easily from amplitudes to the acoustic energy transmission, since the can cross-sections are equal and the Mach number in the cans is low making the calculation of intensity simple.

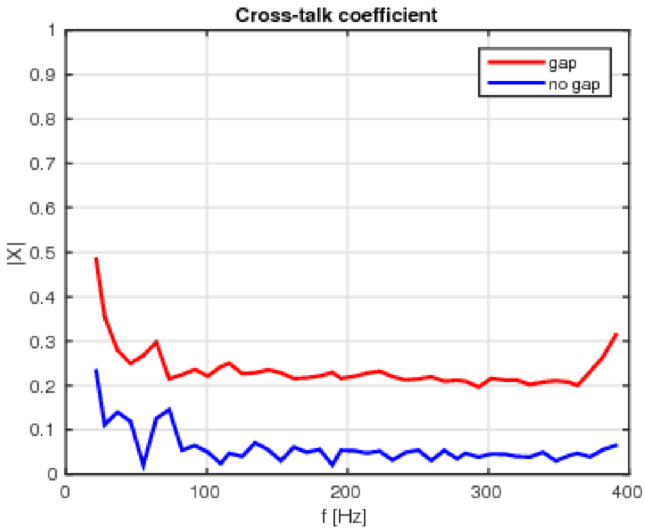

Figure 9 Cross-talk coefficient comparison for the gapped and no-gap case

CONCLUSION

Acoustic oscillations in can–annular engines tend to synchronize or form more complex patterns involving multiple cans. Such modal shapes have been investigated based on modal analysis in a simplified geometry of connected ducts. As expected, the mode shapes from regular patterns repeating with growing frequencies. Mode patterns involving 1, 2, 4 or all 8 can are present in the 8-can setup. A possible explanation for the lack of modes with complex pattern in the experimental data is their long “acoustic route” with a high number of small gaps to pass. If these gaps are regarded as dampers, complex modes are more difficult to excite.

The last part of the paper focuses on the acoustic transmission coefficient between two cans. A generic can pair terminated with a stator vane row has been investigated using LES and the forced response approach. A relatively high cross-talk coefficient was found in comparison to a no-gap case. It can be concluded that the introduction of an even relatively small gap before the stator might have a non-negligible effect on acoustics. Acoustic aspects should be considered during the design of this turbine section.

ACKNOWLEDGMENTS

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