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AIR FLOW MODULATION FOR REFINED CONTROL OF THE COMBUSTION DYNAMICS USING A NOVEL ACTUATOR

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ABSTRACT

A specific actuator able to modulate the air feed of a gas a burner at a given frequency and amplitude is presented.

The Combustion Department at the Institute for Thermal Turbomachinery and Machine Dynamics at the Graz University of Technology has experience on the study of combustion instabilities in gas turbines using a flow excitor. The stability of an industrial burner is tested at elevated pressure and temperature conditions in the frame of the NEWAC project. For practical matters of operation among which the possibility to induce progressively a perturbation when the flame conditions are all set, the need was expressed to design, construct and validate a flexible actuator able to set an air flow modulation at a given frequency and at a desired amplitude level, with the possibility during operation to let these two factors vary in a given range independently from each other. This device should operate within the 0-1 kHz range and 0-20 % amplitude range at steady-state, during transients, or follow a specific time sequence. It should be robust and sustain elevated pressures.

The objective is to bring a perturbation in the flow to which the combustor will respond, or not. For elevated levels of pulsation, it can simulate the presence of vortex-driven combustion instabilities. It can also act as a real-time actuator able to respond in frequency and in phase to actively damp a "natural" combustion instability. Other issues are a better and quicker mixing due to the enhanced turbulence level, and pushing forward the blow out limits at lean conditions with controlled injection dynamics.

The basic construction is the one of a siren, with an elevated pressure side where the air is throttled, and a low pressure outlet where the resulting sonic jet is sheared by a rotating wheel. A mechanism allows to let vary the surface of interaction between the wheel and the jet. Two electro-motors driven by Labview set both frequency and amplitude levels.

This contribution describes the actuator's principles, design, operation range and the results of the characterisation campaign.

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NOMENCLATURE

Main scripts

c	[m/s]	Sound velocity
f	[Hz]	Frequency
$\dot{m}$	[g/s]	Air mass flow rate
λ	[m]	Length, wavelength
n	[rpm]	Rotational velocity of the shaft
P_o	[bar abs]	Head pressure
r_{crit}	[m]	Radius of the sonic hole
T_o	[K]	Head temperature
u_{ref}	[m/s]	Average flow velocity through the pipe
z	[-]	Number of teeth on the sprocket
λ	[m]	Pipelength of the resonator
τ	[s]	Response time of the regulation

Acronyms

DEHS	Di-ethil-hexyl-sebacat
LDA	Laser Doppler Anemometer
NEWAC	NEW Aero-engine Core concepts
ONERA	The French Aerospace Lab
RMS	Root Mean Square
rpm	revolutions per minute
TTL	Transistor to Transistor Logic
TU Graz	Graz University of Technology

INTRODUCTION

The background of this study is the understanding of the physics of combustion instabilities, as well as the possibility to damp them actively. A major incentive for research and development is the risk of combustion instability that can damage the whole machine and/or prevent to reach a given operation. Modern gas turbine combustors operate at elevated conditions of pressure and temperature, mostly at lean combustion conditions with a limited amount of cooling air, in compact combustor frames where the density of energy is high. The flame must remain steady-state, and this over the whole operation enveloppe of the machine.

The Combustion Department at the Institute for Thermal Turbomachinery and Machine Dynamics at Graz University of Technology (TU Graz) relies on laboratory actuators to simulate the presence of combustion instabilities, or to observe the impact of a given dynamic change of an inlet component (typically air or fuel mass flow rates) on the flame shape for control purpose. A device such as the ONERA siren [1, 2] presented in previous contributions triggered much technical questions from conference attendees or paper readers. This is the reason why a deepened technical description of the latest actuator from TU Graz is proposed. It is an improved version of the ONERA siren that offers the possibility not only to vary the frequency of modulation of the air flow, but also to vary the amplitude of pulsation.

There was a need expressed in the NEWAC project to check out the robustness of a given combustor versus inlet disturbance. The design is an industrial configuration operating at realistic conditions. The fact that the previous actuator provided a fixed pulsation amplitude appeared to be a problem especially at low frequencies where the flame would easily be blown out at elevated pressure conditions. Therefore there was a need to be flexible on the amplitude level of the modulation. In other words, the amplitude of pulsation should be set independently from the pulsation frequency, from 0 to a given percentage of the average mass flow. That was the starting point of this work. Other wishes were established such as high precision on the modulation, precise feedback for control purpose, and possibility to program transients or batch operation.

This paper describes the design of the siren, its characterisation at ambient conditions as well as the methodology for use on the stability of combustion, on an industrial configuration.

TECHNICAL ASPECTS

The Rayleigh criterion defines a condition on the settlement of a combustion instability, and is based on both acoustic pressure and unsteady heat release acting more or less in phase. The perturbation responsible for the unsteadiness may have several origins (a specific acoustic mode of the cavity excited by the compressor's noise, or the inlet turbulence, or the flame dynamics) and its energy is just a small fraction of the energy levels in the combustor. The philosophy of active control is to act at the resonant frequency and force both pressure and heat release to act in phase opposition, resulting in a strong reduction of the thermoacoustic coupling. In theory, low-energy actuators can be efficient.

For research purpose, a list of actuators is established by K. Yu [3]. They include the acoustic devices (compression drivers, loudspeakers), the mass-flux modulation devices (fast valves, siren), heat modification devices (electrical discharge, spark flame actuator), and moving surfaces and boundaries (mechanical shakers). Successful industrial application can be found for power gas turbines in [4,5]. Reference [6] discusses real-time control aspects.

Constraints, and choice of technology

For the NEWAC project, the constraints were defined as follow: operate at high pressure and temperature, cover the 0-500 Hz frequency domain and even higher if possible, be able to augment progressively the amplitude of the perturbation during operation. The perturbation should operate at fixed frequency with a high precision, and offer flexibility for the investigation of transients.

An object that fits these conditions is the ONERA siren [2]. It consists in a sonic jet being periodically sheared by the passage of teeth of a sprocket wheel. The design is straightforward concerning the essential parts of the flow exciter (basically the combination of a sonic throttle with a rotating sprocket wheel, see figure 1). The rotational velocity of the sprocket wheel sets the pulsation frequency. The mass flow pulsation travels streamwise through the pipes at the sound velocity c plus the average flow velocity u_{ref} [7]. Despite the pressure drop due to the sonic nozzle, this system allows to modulate the whole air mass flow entering the combustion zone through the injector and therefore simplifies the acoustic modelling (no by-pass, reflections can be neglected in a first step). The pair sonic nozzle / sprocket wheel can be changed very easily and thus be adapted to the requested air flow.

The air mass flow rate $\dot{m}$ [g/s] at rest is a function of back-pressure P_o [bar abs] and temperatures T_o [K] when for instance operating at ambient conditions. The mass flow rate at the sonic hole is derived from the balance equations for compressible flows.

$$\dot{m} = \frac{0.685}{\sqrt{R\,T_o}}\,P_o\,\pi\,r_{crit}^2 \qquad (1)$$

For instance, if the nozzle diameter is 10 mm, as soon as the nozzle is choked the air mass flow $\dot{m}$ is proportional to the head pressure P_o so that at ambient conditions $\dot{m} \simeq 18.5 P_o$.

In theory, the peak-to-peak amplitude of the perturbation is proportional to the fraction of nozzle surface covered by a tooth when the sprocket wheel rotates. In practice, there is a strong dependency on the rotational velocity of the shaft that induces secondary air flow (air put in rotation with the wheel in the siren's casing) that blocks the average mass flow and results in a lower fluctuation amplitude at higher frequencies. This is also why it is important to be able to vary the pulsation amplitude on a large frequency bandwidth.

Hardware

Like the previous design the new siren is capable of handling air flows at elevated pressure. All parts are therefore designed to withstand pressure levels up to 10 bar. A cooling system, by use of pressurised air, was further implemented to raise the temperature levels the siren can withstand.

The frequency range is given by the revolution speed of the electro-motor linked to the siren shaft and the number of teeth used on the sprocket. The main difference to the ONERA siren, aside from the cooling system and the regulation on the motor, is the possibility to adjust the amplitude of excitation during operation. Therefore the relative position of sprocket wheel to the sonic nozzle can be changed by a servo drive.

The used hardware for the controlling system contains: 2 Maxon EPOS 24/5 Digital Position Control Devices, 1 Maxon Motor EC45 250 Watt and an Encoder HEDL9140 (for the frequency), 1 Maxon Motor EC-max30 40Watt with one Encoder HEDL5540 and a gearbox GP32C (for the amplitude).

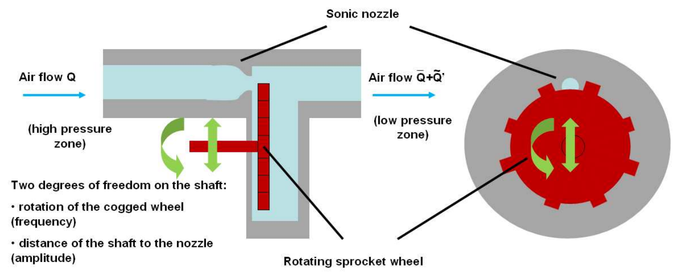

Figure 1. Principles of the TU Graz siren for modulation of air supply, with tunable frequency and amplitude

Combination sonic nozzle / sprocket wheel Several sets of sonic nozzles and appropriate sprocket wheels with varying number of teeth were manufactured to serve a wide range of air flows. Therefore a system to change these two parts very quick and easily had to be defined. The siren was thus designed in two major parts. The part where the air is entering the device is housing the sonic nozzle, which is fixed by a snap ring. The main casing for the sprocket wheel is also attached to this side of the siren. The other part or right side of the siren is attached to the left side by attachment bolts. On the right side the bearing for the siren's shaft is located as well as the sprocket wheel (see figure 2). The sprocket wheel is attached to the siren' shaft by three alignment pins and a snap ring. When the attachment bolts are removed the siren is dismounted and both nozzle and sprocket can be exchanged very easily.

Cooling of the siren's shaft When hot air shall be excited with the siren a proper cooling system has to be used especially to cool the bearings for the shaft and the positioning of the sprocket in respect to the nozzle. So that pressurised air is first pushed into the outer bearing case. Its direction of flow is against the main flow direction to enhance heat transfer. To cool down the bearings of the siren's shaft as well as the axle itself a hole at the front bearings is drilled into the eccentric tappet. The air is entering through this hole into the inner zone of the siren and transports heat away from the bearings to the back of the baring case and leaves the siren through an exit port at the back end.

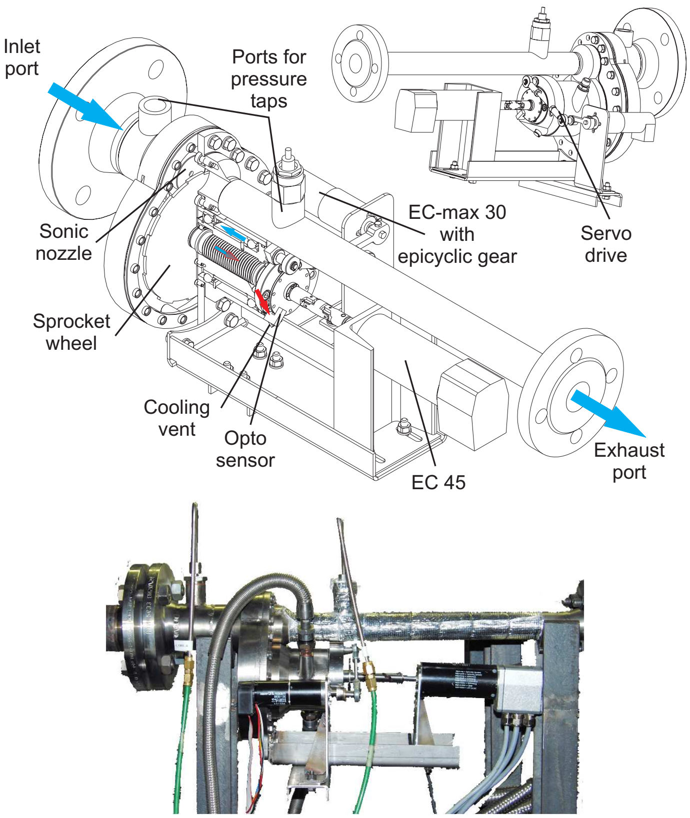

Figure 2. Design of the siren. Top: sketch of the siren. Bottom: picture while mounted on the combustion test facility. Thermal protections and separate air-cooled casing for motor cooling are missing.

Frequency range The frequency of the flow excitation can be set by adjusting the rotational speed of the direct current motor.By changing the number of teeth used on the sprocket wheel the upper bound of frequency can be set. The maximum rotational velocity n set by the motor itself is limited to 6000 rpm with the specific type used herein and $z = 10$ teeth are used on the sprocket. So by using equation 2 the upper limit of frequency with this combination is 1000 Hz.

$$f = \frac{n}{60} z \tag{2}$$

Due to the use of a digital encoder and positioning control the precision in frequency is function of the response time of the regulation. The regulation makes sense in comparison to the previous siren model, so that no frequency drift happens because of flow perturbations coming from upstream. For the set of experiments that follows, the response time τ is 50 μs. So that the uncertainty on the frequency is $\Delta f = f.\tau$, e.g ± 1 % at 214 Hz pulsation.

Amplitude range As said above the amplitude of excitation can be changed during operation of the siren. The blocked area of the sonic nozzle can be varied by changing the relative position of nozzle and sprocket. The bearing of the siren's shaft is eccentric bedded to the rotation axis of the servo drive by 5 mm. A second servo motor is linked to the accentor by a strut. Thus by revolving the servo drive the sprocket is shifted as can be seen in figure 2 as function of angle of tilt of the servo motor.

Figure 3 shows the blocked area as function of the tilt angle given by the second motor. The blocked area is computed iteratively as a function of the geometry of the mechanical transmission, of the eccentricity between the sprocket and the rotating chassis (5 mm) and of the nozzle and sprocket dimensions. For this application, a 10 teeth-sprocket of inner/outer diameter 122/126 mm with a 10 mm diameter sonic hole is computed. An effort is done during the settings to keep the trend of blocked area as a function of the tilt angle monotonic, and as linear as possible. This approximation is satisfied on figure 3 when turning the amplitude motor from position 115 down to 40^o angle thus rising the amplitude of fluctuation from 0 to 55 %.

Augmenting the amplitude provokes a drop of the average mass flow rate. In the TU Graz combustion facility, each feed line is separately regulated with an ensemble massflowmeter (V-Cone type) and electro-pneumatic valve on the high pressure side [8], so that the mass flow rate can be automatically adjusted to a setpoint.

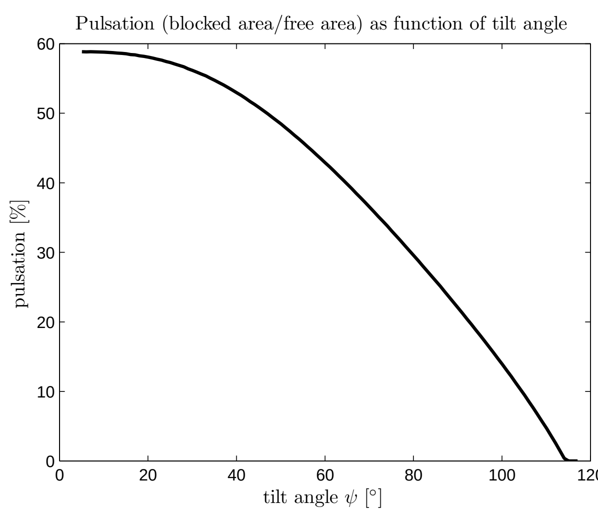

Figure 3. Variation of amplitude of the pulsation, proportional to the blocked surface of the nozzle, as a function of the tilt angle set by the positioning motor

Controls

Command A LabView program controls the siren by manipulating the frequency of the sprocket wheel and the depth of coverage between the nozzle and the sprocket wheel.

Two parameters are controlled by two separate LabView 8.2 routines from National Instruments. The first one is the frequency of the siren. The program allows a continuously adjustable regulation of the frequency up to 1000 Hz with free adjustable acceleration and deceleration. A programmed overload protection prevents the siren from damage through overheat. The second parameter is the amplitude of the siren. The program allows a continuously adjustable setting of the tilt angle of the positioning e-motor between a defined "0"-position and the maximum admissible angle (figure 3). Both programs are designed to report onscreen the translated physical units, or suitable vernier units. The frequency routine converts the revolutions per minute of the motor shaft into Hertz of the sprocket wheel. The amplitude routine reports the angle of tilt based on the gearbox output shaft.

Feedback Each motor is equipped with an Hall-effect detector allowing the EPOS-Controller to measure in real-time the revolution speed and report on the angular position. This information is reproduced on the Labview control panel.

However, in order to verify the information as well as to drive separate instruments, a separate analog trigger signal is required. This electronic is freely inspired from the original control box of the ONERA Siren. This circuit, installed in a compact control unit, reports on the pulsation status of the air flow under the form of a TTL signal. A second output line provides the same signal with an adjustable phase shift for driving phase-locked instruments, e.g. a stroboscope. A third port displays the original reference signal directly derived by the incremental position encoder for operation check.

An increment wheel with as many cutouts as teeth on the sprocket wheel is assembled on the shaft of the primary electric motor, as shown in figure 4. A photoelectric barrier HOA 2005 is able to produce a correct reference signal by detecting the passage of the cutouts. To advance the quality of the detector's TTL a so called Inverting Hex Schmitt Trigger SN74HC14 was added. This electronic component has two special threshold levels that switch between two specific voltage levels (in this case 0 V and 5 V) [9]. By using this Schmitt Trigger the edge steepness of the square wave signal is improved dramatically. Furthermore rotational high speed stability up to 1 kHz is granted.

The second line issuing a phase-shifted trigger has the requirement to shift a whole period length at 50 Hz. A Dual Monostable Multivibrator SN74LS221 connected to a potentiometer [10] for manual phase adjustment was therefore added to the feedback box.

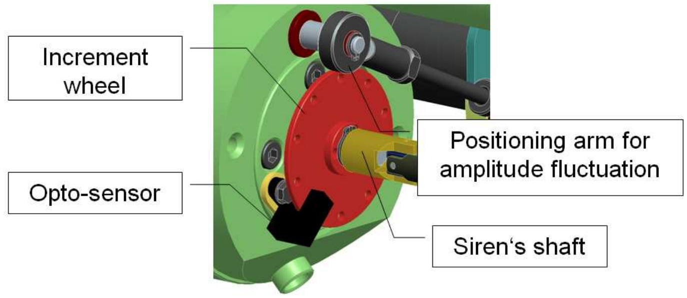

Figure 4. Detail of the feedback sensor and increment wheel

VALIDATION CAMPAIGN

Tests of operation

The tests of operation are realised on the siren blowing in free-jet in the ambient. The siren head pressure is set to 1.3, 1.8 and 2.8 bar, corresponding to an average mass flow rate of 15, 32 and 52 g/s. The first operation point reports on the siren's behaviour when the nozzle is not choked. Both other points can be used with the approximation of equation 1. The length λ between the nozzle's outlet and the end of the pipe is 1.71 m, with 26 mm inner diameter. A microphone type PCB106B50 (PCB Electronics, signal conditionner 482A22) is flush-mounted at distance 1.34 m from the siren's nozzle plate to report on the noise generated by the actuator. The microphone has a diameter of 15.7 mm and a sensitivity of 72.5 mV/kPa. At operation 15 g/s, the air velocity u_{ref} is 23 m/s. Provided the ensemble siren plus pipelength acts as a quarter-wave resonator, the fundamental frequency for resonance is $f_0 = \frac{c+u_{ref}}{\lambda} = 53.5\,\mathrm{Hz}$.

Steady state The signals are recorded by a NI-PXI 1033 chassis with an analog-digital NI4551 PC board with 200 kHz sampling rate, over three lines connected via BNC to a NI-BNC2110 signal acquisition board: clock voltage, TTL signal emitted by the siren, and microphone voltage. Since the frequencies of interest are situation in the low frequency range, the acquisition frequency is set to 10 kHz per line, over a total acquisition duration of 100 s. A subsampling with a factor 10 on a moving window is realised, so that the spectra can be averaged. The resulting frequency step is 1 Hz and the cut-off frequency 500 Hz

The three acquired signals are displayed in figure 5. A signal generator provides a "clock" signal, a triangle wave set at 1 Hz to check wether the signal acquisition is continuous or not. A discontinuity due to a memory swap of the acquisition card is detected by a jump on the slope of the clock signal, or a sudden peak on the time derivative of this clock signal (called "continuity check"). Such incidents provoke errors in terms of phase analysis, and the time segments containing such events are to be rejected.

Both TTL and microphone signal are displayed over a shorter period. One notices the synchronicity between the perturbation (TTL) and the resulting noise (microphone). The TTL could be used for instance for phase-averaging the microphone signal (not shown).

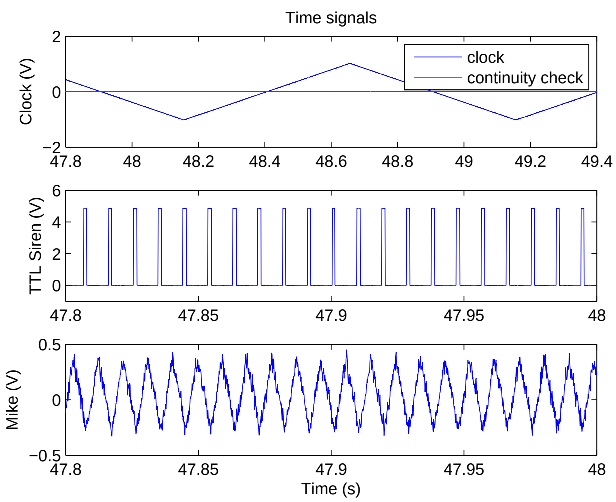

Figure 5. Time-signals. Operation: $P_o = 1.8$ bar, $\dot{m} = 32$ g/s, $f = 107$ Hz, amplitude=20 %

Transients Figure 6 displays the siren operating in transient mode. The recording starts at frequency 230 Hz and then the pulsation frequency goes down progressively until the siren stops. It is expected to meet during this process the resonant frequency 53.5 Hz and its sub-harmonics. Indeed, ”bulks” centred on the expected frequencies 214, 107 and 53.5 Hz appear on the microphone time-signal, or peaks of RMS of the same signal.

To establish the correspondance between frequency, peaks and time-signal, it is interesting to rely on the 3D plot displayed at the bottom of the same figure. Amplitude spectra computed on short signal time windows with a resampling are displayed as a function of time. So that not only the excitation frequency and the response of the resonator can be followed, but also the sub-harmonics. In this experiment, the siren’s amplification achieves +40 dB (SPL) at 214 Hz.

Amplitude modulation Figure 7 shows the use of the positioning motor and its effect on the amplitude of pulsation. In this test, the excitation frequency is set at 107 Hz. During the recording, the positioning motor will act back and forth, augmenting progressively the tilt angle in comparison with the start position. The ”bulks” of the microphone line see their width be-

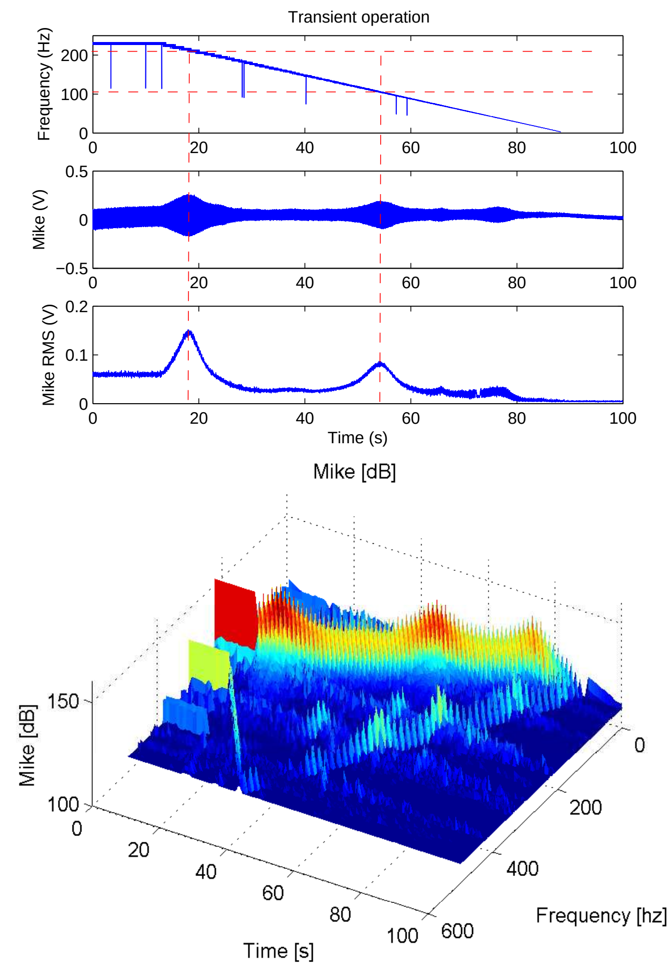

Figure 6. Transient operation. Up: time signals. Bottom: 3D amplitude spectra as a function of time. Operation: $P_o = 1.3$ bar, $\dot{m} = 15$ g/s, $f = 230$ Hz down to 0 Hz with an approximate 3 Hz/s deceleration, amplitude=20 %

ing decreased. The test ends at a position where the amplitude is half of the one at start position. The 3D plot shows as expected a -10 dB noise level reduction. Observe also the effect on the first harmonic at 214 Hz where the reduction is more dramatic. Not only the pitch but also the tessitura of the noise changes when decreasing the amplitude, since the subharmonic quickly disappear.

Batch sequence The last demo is a batch sequence, where both amplitude and frequency are varied. Figure 8 shows starts and stops of the siren, as well as the effect of maintaining the sprocket out of the sonic hole and then augmenting the pulsation’s amplitude.

This mode is programmable, and offers the possibility for

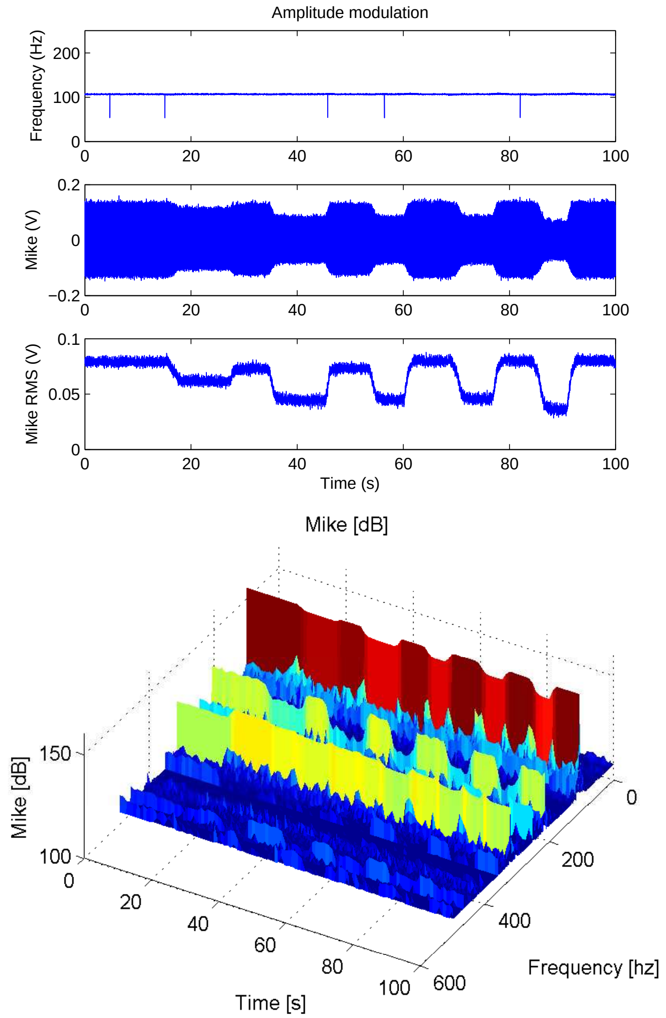

Figure 7. Amplitude modulation. Up: time signals. Bottom: 3D amplitude spectra as a function of time. Operation: $P_o = 1.3$ bar, $\dot{m} = 15$ g/s, $f = 107$ Hz, blockage=20 % start position stepwise down to approximately 10 %

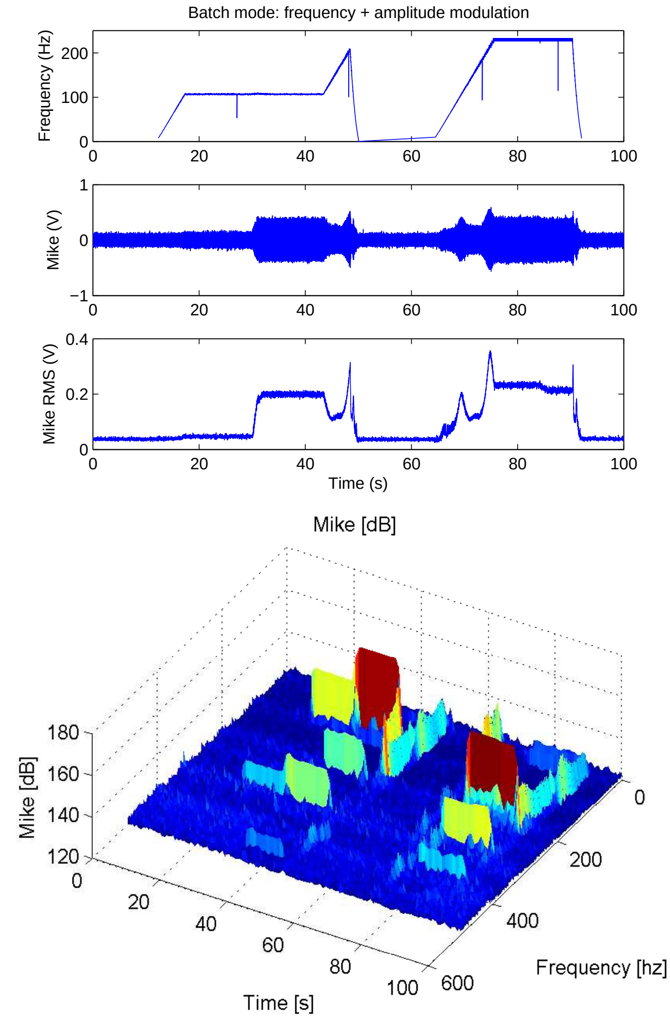

Figure 8. Batch sequence. Up: time signals. Bottom: 3D amplitude spectra as a function of time. Operation: $P_o = 1.8$ bar, $\dot{m} = 32$ g/s

instance to avoid to pass through a critical point such as a strong resonance that could blow a flame out by retracting the sprocket, augment the frequency, and get the sprocket in front on the sonic hole again.

LDA Measurements

The fluctuation of density is measured with a LDA system (Fiber Flow with Burst Spectrum Analyser from DANTEC, DANTEC Dynamics, Roskilde, Denmark. Laser from Coherent Inc.). The air flow is seeded with DEHS aerosol particles (size approx. 0.3 μm).

Figure 9 shows two LDA measurement performed to measure the mass flow rate fluctuation. A first measurement is performed on the axial dimension at the outlet of the siren for a 30 Hz pulsation at 20 % amplitude. A second measurement performed in the flow jet of the test cell at a higher frequency (450 Hz) and higher amplitude is also shown. In the second case, the perturbation flows through a complex air system including among others a plenum and a swirler. Both data sets have been processed with a phase-averaging routine (the trigger signal defines the start of each pulsation period, all events are sorted over one single period and then averaged on a given number of subperiods). The effect of the siren is in both cases visible, and effective for low as well as intermediate frequency range. In both cases, the phase-averaged velocity can be approximated with a sine wave.

When connected to a sudden expansion such as a bulk body burner, the siren generates a specific ring vortex detachment around the injection jet, and if combined to a swirl, the swirl number is also greatly modulated [1].

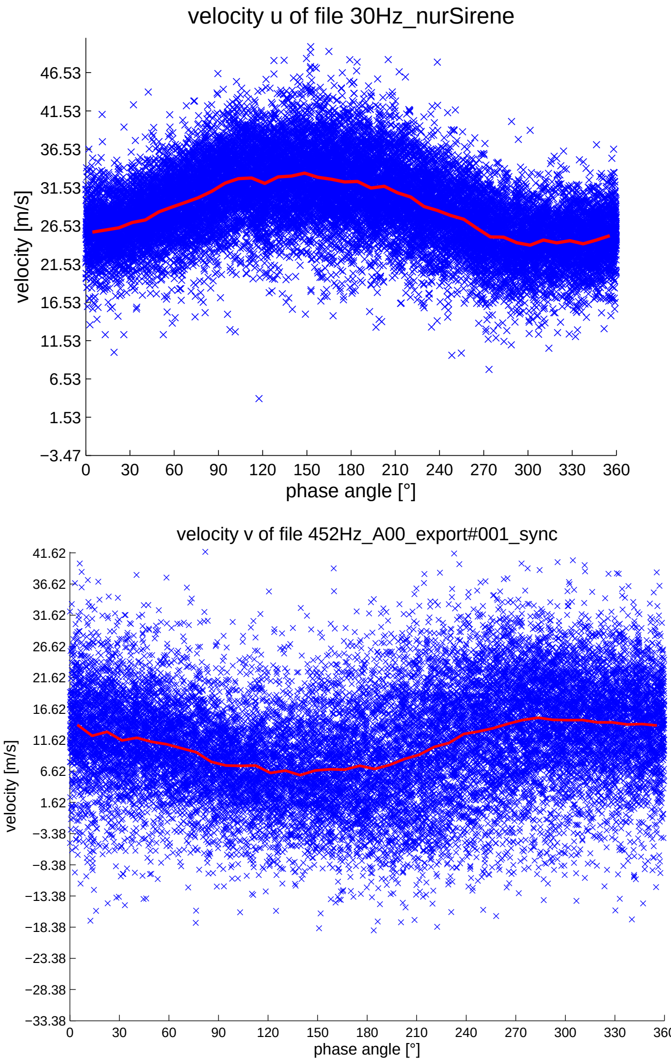

Figure 9. Phase averaged LDA measurements for two excitation frequencies, at 30 and 452 Hz

DISCUSSION

This actuator was designed for research purpose, since it provides a modulation of air flow at precisely controlled frequency and amplitude levels. This section discusses the applicability to real combustion systems.

The choice of its design makes it robust versus hot flows and allows operation at elevated pressure. Other laboratory equipments such as loudspeakers are usually unfit to face real gas turbine flow conditions. The amplitude and frequency levels can be much higher than what could be typically generated with a solenoid valve. The design allows the flow of elevated mass flow rates as a function of the nozzle's dimension, and no bypass is required to separate the average flow from its cyclic component. The actuator is a compact object, of relatively simple construction, and can be directly mounted on the air feed of a burner. It could therefore be used on real systems.

Regarding integration in a real gas turbine, the main drawback of this design is the use of a choked nozzle. This leads to an elevated pressure loss, or a need to further compress the air send into this actuator. Provided only a limited amount of main air is being actuated, the work extracted for further compression of this same air is still manageable on a real gas turbine. The integration of such a device is feasible on power gas turbines where the actuator's added weight and volume are tolerable. The philosophy of actuation would be then similar to the works done by Hermann et al. on the fuel line [4], but acting this time on the air flow. Regarding aeroengines, the integration of a similar actuators is still speculative at this level of technology readyness.

The application of interest of this device is the test of real combustion systems on a test bench, where a wide domain of frequencies and excitation levels is being scanned, and this for several amplitudes of modulation.

CONCLUSIONS AND PERSPECTIVES

An actuator designed and built at TU Graz able to modulate separately the pulsation frequency and amplitude of an air flow was presented. Its specifics and testing have been detailed. This actuator can simulate the presence of an instability by generating a certain air flow modulation at the wished frequency and amplitude, as well as it can be used for control purpose. Steady-state modulations are possible, as well as programmable transients. It is designed to operate at high conditions of pressure and temperature.

A crucial point for control purpose is the definition of the phase reference. The current system provides a TTL signal issued from a separate wheel. If this situation is comfortable from a design point of view, it presents two disadvantages: the TTL does not reflect the "start" of the passage of a tooth in front of the sonic hole, it arbitrarily sets the "beginning" of the cycle. This can be improved by getting the reference signal directly from the main wheel at a position diametrally opposed to the sonic hole. Secondly, since the reference wheel is mounted on a rotating chassis, the reference 0-phase angle is lost when modifying the amplitude of pulsation and thus rotating the chassis. This can be corrected by the reporting the angle set on the chassis, however it has a positioning error in the 2^o angle range (implying a 20^o phase angle error on a cycle, provided the sprocket wheel has 10 teeth). There again, a direct measurement on the sprocket wheel would help. A built-in sensor such as a microphone or a hot-wire anemometer is recommended to provide a second reference signal.

The future electronic box should report on the angle position of the rotating chassis, so that not only the effective frequency but also the amplitude has its analog signal. This will be done with help of an angle position sensor mounted on the chassis' shaft.

Acknowledgments

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REFERENCES

[1] Giuliani, F., 2002. “Analysis on the behaviour of an aero-engine air-blast injection device with forced entries”. PhD thesis, ENSAE No 346, Toulouse, France, June.

[2] Giuliani, F., Leitgeb, T., Lang, A., and Woisetschläger, J., 2010. “Mapping the density fluctuations in a pulsed air-methane flame using laser-vibrometry”. *Journal of Engineering for Gas Turbines and Power,* ***132***, Mar. GTP-031603.

[3] Yu, K., 2001. “Fundamentals and fluid dynamics (experiments)”. In Active control of Engine Dynamics, RTO AVT - VKI Special Course, pp. 59–65. RTO-EN-020.

[4] Hermann, J., 2001. “Application of active instability control to heavy duty gas turbines”. In Active control of Engine Dynamics, RTO AVT - VKI Special Course, pp. 287–302. RTO-EN-020.

[5] Garay, M., Kokanovic, S., Guidati, G., Torchalla, S., and Schuermans, B., 2006. “Active control system for reduction of NOx and pulsation levels in gas turbines”. In ASME Turbo Expo 2006: Power for Land, Sea and Air, Barcelona, Spain. GT2006-90895.

[6] Evesque, S., Park, S., Riley, A., Annaswamy, A., and Dowling, A., 2004. “Adaptive combustion instability control with saturation: theory and validation”. *Journal of propulsion and power,* ***20***(6).

[7] Hirschberg, A., and Rienstra, S., 1994. “Elements of aero-acoustics”. In Applied Aero-acoustics, Von Karman Institute for Fluid Dynamics. LS 1994-04.

[8] Leitgeb, T., Giuliani, F., and Niederhammer, A., 2009. “Computer aided dimensioning and validation of a versatile test facility for combustion chambers and turbines”. In ASME Turbo Expo, Gas Turbine Technical Congress & Exposition. GT2009-59592.

[9] Sautter, Dieter und Weinerth, H., 1993. *Elektronik und Mikroelektronik*, 2. ed. VDI Verlag Düsseldorf.

[10] Wüst, K., 2003. *Mikroprozessortechnik*, 2. ed. Vieweg Verlag, Wiesbaden.

