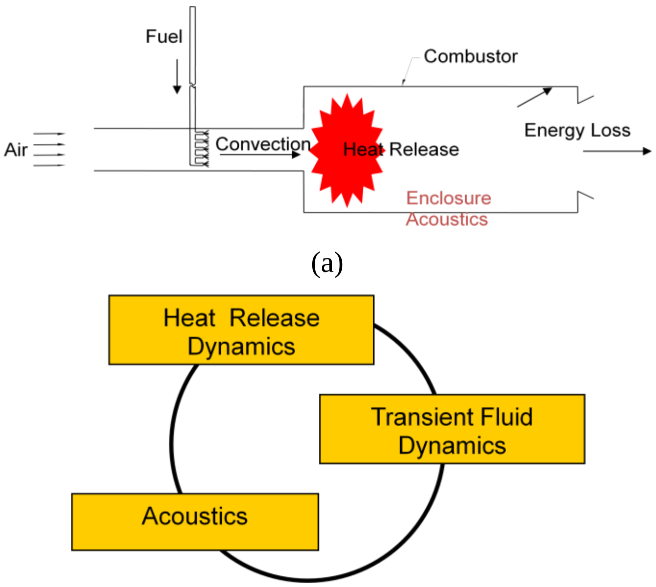
Mitigating Combustion-driven Oscillation (Thermoacoustic Instability) in Industrial Combustors

Combustion processes generate a band-limited pseudo-random sound that is often referred to as "combustion roar." Although combustion roar sound is moderately intense but it is rather straight forward to quiet to a non-objectionable level by properly applying sound absorbing material around the burner area. In addition to the 'roar' sound which almost always exists in any confined combustion, on occasion a very intense, narrow-band (frequently single-frequency/tonal) noise is generated in a combustion chamber resulting in a high-amplitude, self-sustaining pressure oscillation. This phenomenon originates from a coupling between the flame's heat release dynamics, the combustor acoustics, as well as transient fluid dynamics in the combustor and is referred to by many names including, but not limited to, 'combustion-driven oscillation', 'combustion dynamic instability', and , 'thermoacoustic instability'. The excited acoustic oscillation causes large pressure fluctuations (high combustor noise levels), poor combustion, increased emissions and even catastrophic combustor failure (structural damage). 'combustion-driven oscillation' has been reported in all types of combustion systems including industrial combustors (heaters, boilers, etc.), propulsion systems (rockets, afterburners) and gas turbine combustors.

Under favorable conditions, a flame in a confined space (combustion chamber) can couple with an acoustical mode of the combustor and produce strong combustion oscillations (Rayleigh 1945; Feldman 1968; Culick 1988; Hersh 1989; among others). This coupling mechanism becomes self-sustaining, resulting in large amplitude pulsations, if a favorable phase between unsteady heat release and acoustic pressure is maintained over the whole oscillation cycle.



(a)

(b)

Figure 1 Schematic (a) and block diagram (b) of a thermoacoustic system

'Combustion-driven oscillation' be mitigated by either putting less acoustic energy into the combustion system or removing more acoustic energy from it, at the frequency corresponding one (or multiple) natural frequencies related to the acoustic mode(s) of the combustor. The former approach, typically accomplished in an experimental (trial and error) manner, include changing the location or velocity of fuel injection or change the resonant frequency of the combustion chamber by changing the operating temperature or geometry. Such modifications must be passed up if they change the functionality of the system beyond the acceptable level. In addition, once the combustion system is built and commissioned, such remedies will be extremely costly and time consuming. The latter approach is based on adding

acoustic damping to the combustion environment. Acoustic liners commonly used in aero-engine applications are notable examples of such remedies for mid and high-frequency combustion instability problems.

Some combustors, mainly the ones used in propulsion systems, are designed with an acoustic liner that allows for suppressing a certain level of combustion instability by adding acoustic damping to the combustion chamber. These liners are typically arranged in such a way that the perforated skin of the liner combines with the volume of the 'backing' to form what can be considered as small Helmholtz resonators with short necks arranged around the combustor. In addition, the flow of cooling air thru the liner perforation (to protect the liner itself) provides the additional benefit of improving the effectiveness of the liner thru enhancing its energy dissipation effectiveness. Because of the small backing volumes and short neck lengths (typically the thickness of the liner skin) these liners are tuned to relatively high frequencies (> 1000 Hz). Because of the geometry limitations, stated above, the liners have proven to address the high frequency combustion oscillations.

Helmholtz resonators and quarter-wave tubes have been proposed and used as solutions to 'combustion-driven oscillation', (Putnam, 1971). The geometric and weight requirements of such solutions become cause for concern in weight sensitive applications such as aerospace propulsion systems. For industrial applications (heaters, boilers, etc.) weight and space requirements are not as critical as they are in propulsion applications. Nonetheless, quarter wave tubes and Helmholtz resonators might still not be the most suitable treatments for industrial applications; this is mainly because a) such passive devices have a fixed tuning frequency and cannot be re-tuned (automatically or manually) to track combustion instability frequency if and when it varies with time[1], and b) they might be unacceptably large and massive for very low-frequency industrial applications, as well.

In recent years active control techniques have been proposed to eliminate combustion oscillations by either modulating a portion of the fuel or pulsating the combustion air, via their corresponding actuators, i.e. a servo-valve or a loudspeaker, respectively. The signal generated by a sensor measuring the dynamic pressure inside the combustion chamber drives the control algorithm which in turn actuates the actuator.

Fuel modulation can be induced by means of a servo-valve. The air pulsation can be induced by a loudspeaker installed on the combustion air duct, downstream of the fan, to produce pressure pulsation inside the duct and consequently inside the combustion chamber. The servo-valve or the loudspeaker is mounted outside the combustion chamber upstream of, but close to, the burner head. The signal activating the actuator (either a servo-valve or a loudspeaker) is realized (computed) by a high-speed control computer housing the control algorithm. In either control strategy, the pressure pulsation inside the combustion chamber will be measured by a dynamic pressure sensor and will be used as the input signal to the controller. Excellent control performance, in terms of quieting the combustion-driven oscillation (noise), is anticipated by pulsating either the combustion air using a loudspeaker or the combustion fuel using a servo-valve. DEICON promote the pulsation of the combustion air as the active control mechanism of choice.

In the following pages the mitigation of combustion-driven oscillation in two different combustion systems are reviewed.

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[1] In many applications, the unstable frequency varies with time, depending on the operating conditions of the combustion system. This is either because heat release dynamics couples with different acoustic modes (with different frequencies) depending on the operating conditions or despite the fact that the sympathetic mode does not change but its frequency changes due to variation in the combustor temperature (and thus the speed of sound in the chamber) caused by load variation. In either case, passive tuned damping would not serve instability mitigation purpose effectively. Under these circumstances, DEICON promotes semi-active/ active acoustic damping solutions.

Case 1: Combustion-driven Oscillation Abatement of an Industrial Heater

A large gas fired oil heater is used to heat a liquid in a process. While in operation a low frequency, tonal rumbling sound is being emitted from the heater. Figure 3 depicts a rendering of the heater. A large forced draft fan runs the combustion air thru a heat exchanger, pre-heating the air prior to introducing it to the gas burner located at the bottom of the heater.

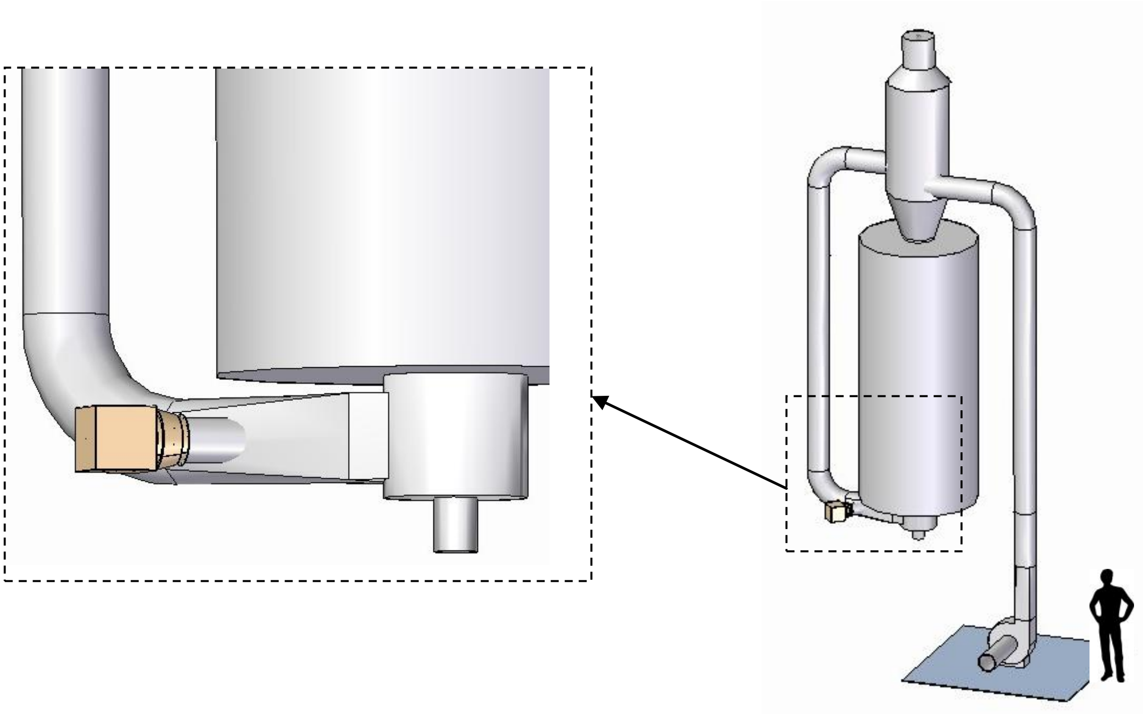

Figure 3 An industrial heater equipped with an active mitigation of combustion-driven oscillation system

Figure 4 depicts the A-weighted sound pressure level spectrum measured at the vicinity of the heater, at the 100% load on the heater, revealing the tonal rumble occurring at 45 Hz. The spectrum clearly has the sign of a combustion-driven oscillation, i.e., one very distinct peak, overshadowing all the other peaks by many dBs, at a certain frequency. Although at a lower frequency and magnitude, the tonal sound was also present at lower loads (than the maximum) on the heater.

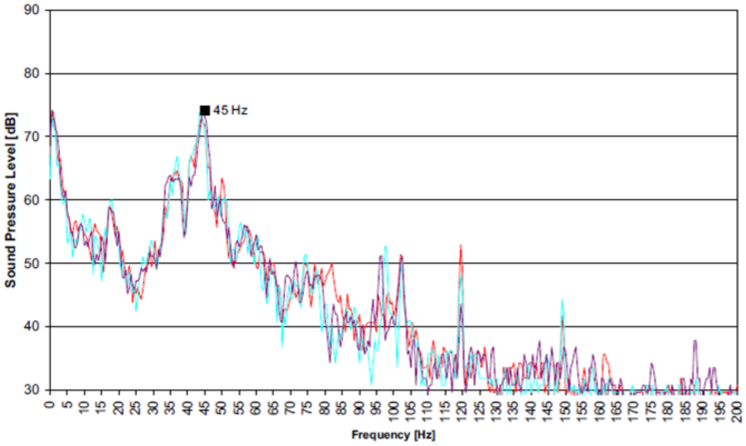

Figure 4 SPL spectrum of the heater at 100% capacity

Figure 5 shows the axisymmetric representation of the acoustic standing wave believed to be the one at the root of the 45 Hz combustion-driven oscillation problem of the heater. Although there are a number of lower frequency modes, mainly shaping up in the outer passes of the heater, the 45 Hz mode seems to be the one corresponding to the first closed-closed acoustic standing wave shaping up in the inner core of the combustion chamber; see the segment of Figure 5 encircled in dashed lines.

As expected, and predicted by finite element analysis, the shell of the heater has a number of structural modes (resonances) around the frequencies where the tonal rumble is being emitted. Thus coupling between the combustion-driven oscillation and the structural modes of the heater may well be contributing to the radiation of rumble, although this coupling is not the source.

An active acoustic damping solution was implemented to abate the above-mentioned undesirable tonal rumble. Figure 6-a depicts the schematic of the active control arrangement, including the sensor and loudspeaker actuator placements. Figure 6-b shows the speaker and the pressure sensor installed on the heater. As stated earlier and shown in Figure 6 (a and b) the loudspeaker exciting the combustion air upstream of, and yet close to, the burner head is actuated by the controller. The pressure transducer mounted in the combustion chamber, close to the burner, provides the feedback signal to the controller.

A hardware-in-the-loop laboratory simulator was used to test the active control system prior to implementing on the actual heater; see Appendix A for more detail.

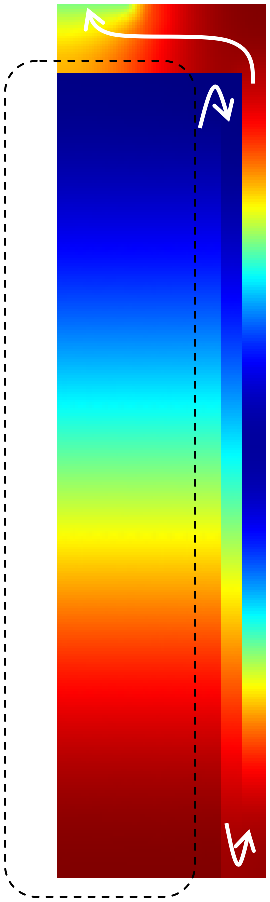

Figure 5 The first closed-closed mode in the main part of the heater

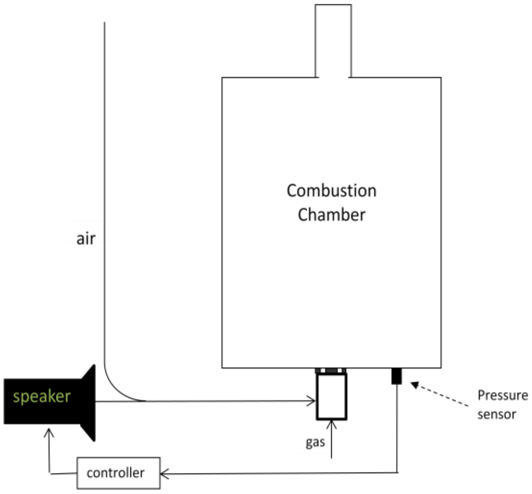

Figure 6-a The schematic of the proposed control scheme

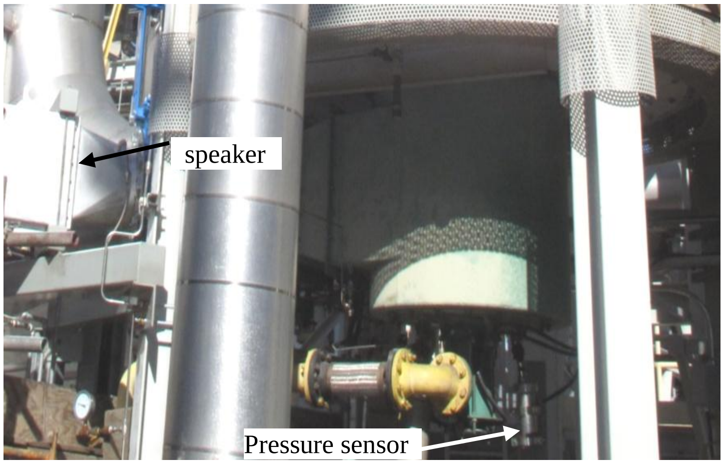

Figure 6-b The actuator (speaker) and pressure sensor installed on the heater

The instantaneous pressure inside the heater, measured by the pressure sensor highlighted in Figure 6-b, had an amplitude of around 50 Pascals which translates to the sound pressure level of about 120 decibels. Considering such high level of sound pressure as well as the large size of the combustor, the original design of the active instability mitigation system called for 2 actuators, but due to the limitation of space only one actuator was used on the intake air duct; see Figures 3 and 6-b.

Figure 7 shows the linear spectrum of sound measured outside the heater by a microphone and inside the heater by the pressure sensor. The measurement is done with the sound abatement system off (the blue traces) and on (the red traces). The actuation level generated by only one speaker proved less than enough to add a substantial abatement to the 45 Hz tone. Although the reduction in noise level, both inside and outside the heater, were realized but the level of reduction outside the heater was not high enough to be substantially perceptible. Nonetheless, the limited reduction of sound level achieved, *indicates the validity of the physics of the active control solution*.

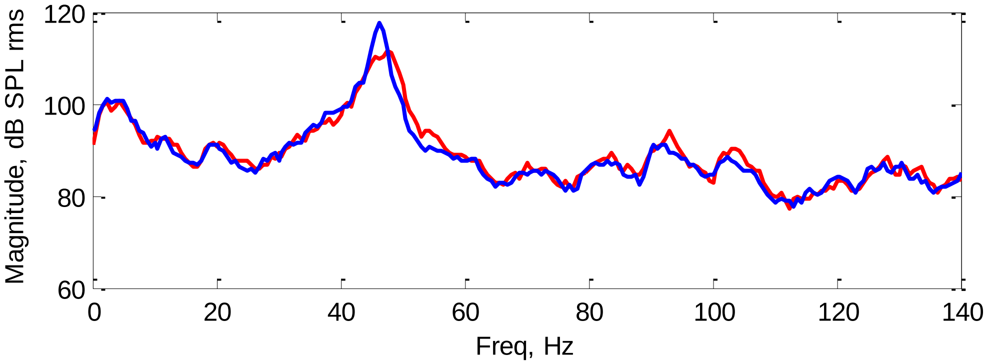

Figure 7 Linear spectrum of acoustic pressure measured inside the combustor with the control system off (blue traces) and on (red traces)

Case 2: Thermoacoustic Instability Mitigation of a Gas-fired Combustion Rig

Under certain sets of conditions, an experimental propane/air premixed combustion rig, made up of a 6ft long air cooled duct with the cross-sectional area of 4inch by 6 inch exhibited thermoacoustic instability. Figure 8 shows an image of the rig.

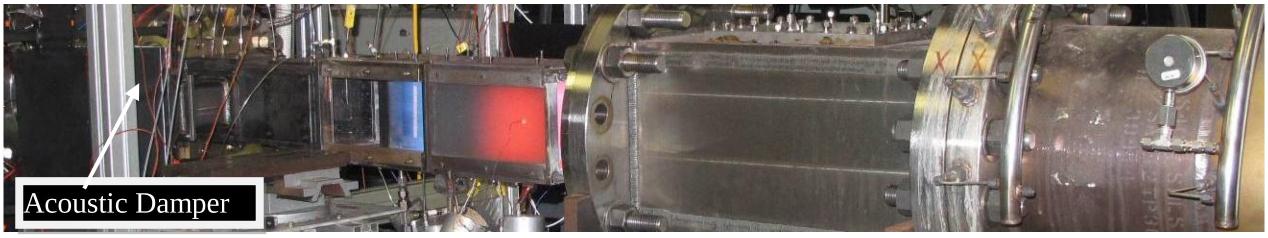

Figure 8 The experimental combustion rig with an acoustic damper installed on it

Although the instability in the rig always corresponded to the first acoustic mode of the duct, but its frequency was varying depending the set of conditions under which the combustion system became unstable. Note that various conditions resulted in different change temperature in the duct varying the speed of sound. That, along with the varying velocity distribution caused the frequency of instability change. Because of this variation, one of the tunable acoustic dampers of DEICON was used to mitigate the thermoacoustic instability.

The blue trace in Figure 9 depicts the power spectrum of pressure measured in the combustor with thermoacoustic instability occurring at 100 Hz; note the sharp peak in 100 Hz. The red trace shows the same power spectrum when the combustor was treated by one of DEICON's tuned acoustic damping devices. Comparison of the two power spectrum traces together clearly indicates the effectiveness of DEICON's acoustic damping treatment in mitigating acoustic instability.

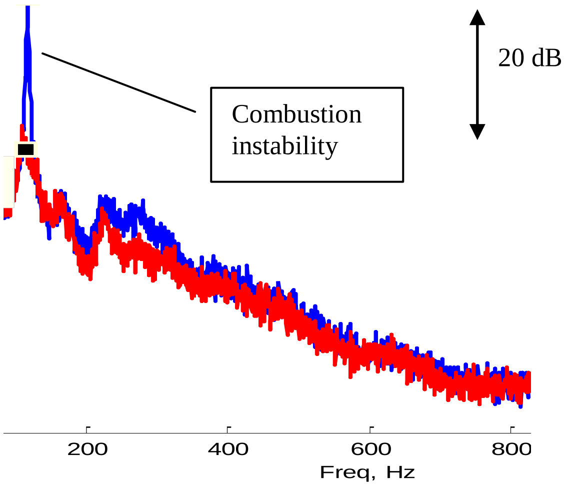

Figure 9 Power spectrum traces of pressure without (blue) and with (red) treatment

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Appendix A

Experimental Hardware-in-the-loop Thermoacoustic System (Cold Rig)

A hardware-in-the-loop laboratory simulator (called test cold rig) was used to test the active control system prior to implementing on the actual heater. The physical traits of the test cold rig constitute the acoustics of the combustion system. The thermal aspects, the coupling of which with the acoustics would realize the thermoacoustic system were synthesized into the rig via feeding back the acoustic velocity, through the dynamic model of the heat release running in real-time, to a loudspeaker (dobbed flame loudspeaker) placed inside the test cold rig at the location that the flame is expect to be. The acoustic sensor and the flame speaker are nearly collocated with (placed very close to) each other. This arrangement makes the speaker to behave as the flame, realizing heat release perturbation, coupling with the acoustics of the rig. By changing the convection delay in the active heat release perturbation, the rig could be made unstable at the frequency of interest.

Figure A1 depicts the fan supplying air to the system and the mock up of the burner as well as the control speaker installed upstream of the burner.

Pressure at 2 locations, one outside the laboratory model and one inside the laboratory model (at the center of the wall facing the burner), were measured.

The ease of modifying the cold rig, if need be, and running numerous tests on it in a short period of time is invaluable in finalizing the design of the combustion instability mitigation solution and gaining a wealth of experience with it prior to installing in on the real combustion system at the plant.

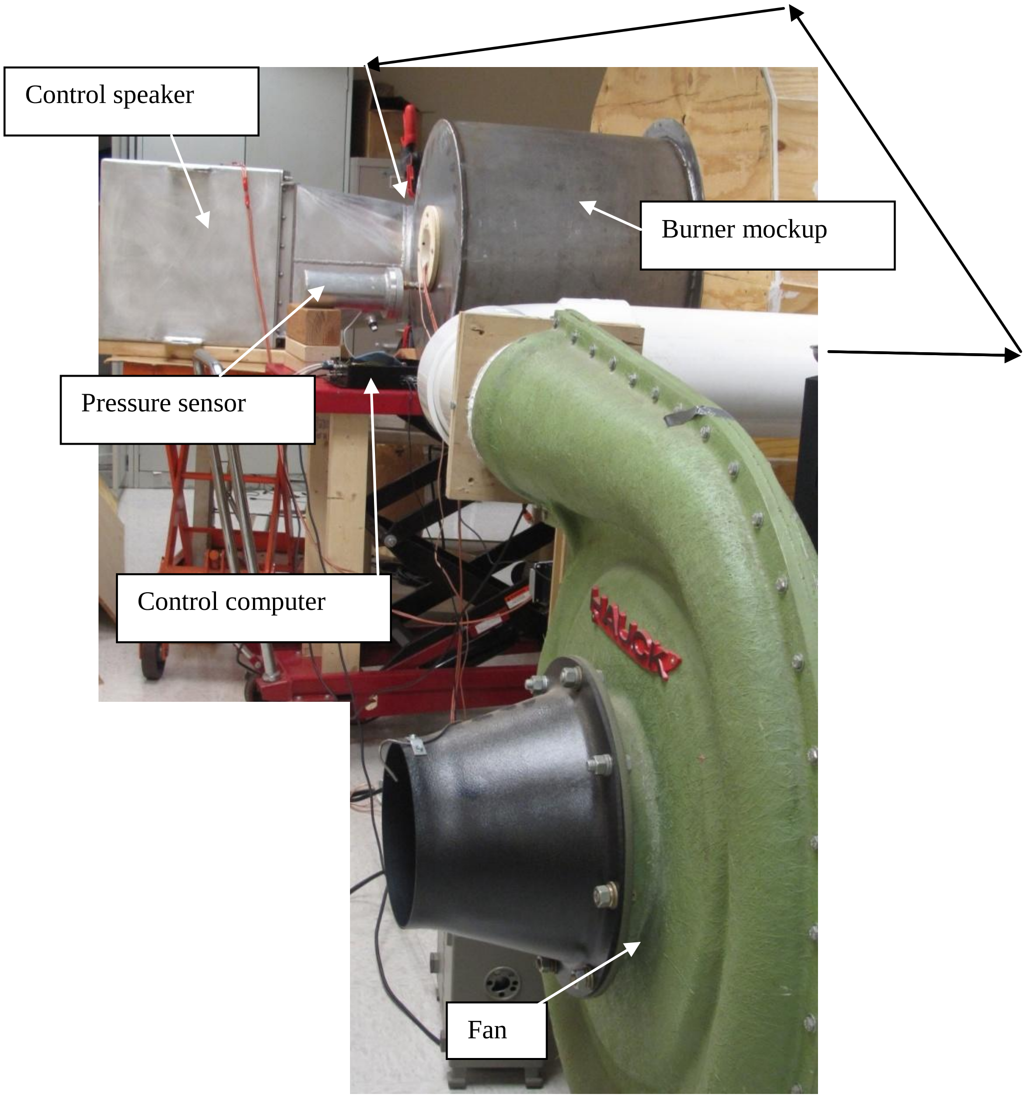
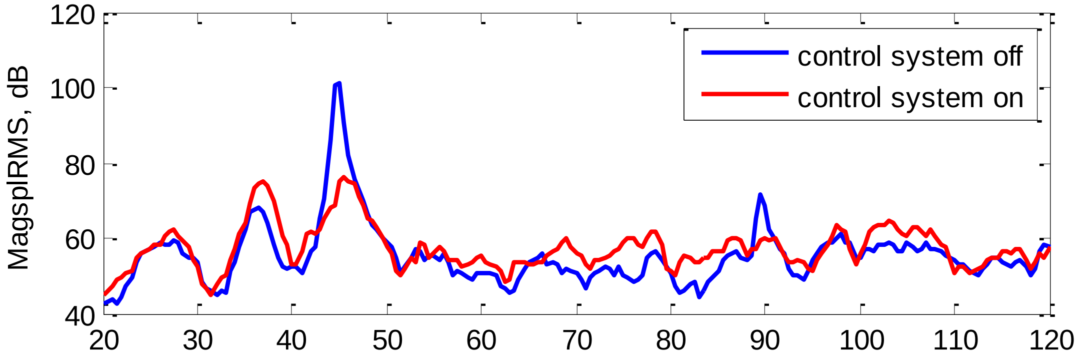


Figure A1 The burner side of the laboratory model

The traces shown in Figure present the linear spectrum of pressure measured inside and outside of the laboratory model. Comparison of red and blue traces in Figure A2 clearly shows the effectiveness of the system in mitigating the 45 Hz noise.


(a) Linear spectrum of sound outside the lab model

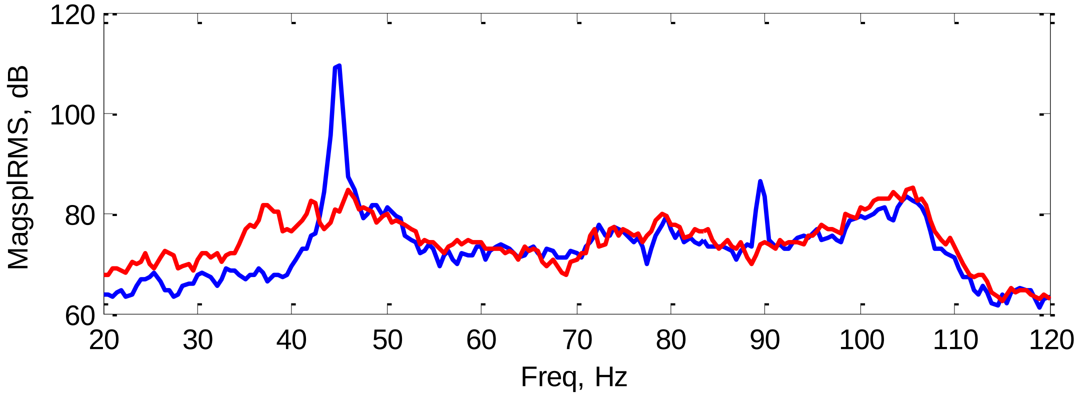

(b) Linear spectrum of sound inside the lab model

Figure A2 Linear spectrum of sound pressure level measured inside and outside the cold rig