ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

TOWARDS ACTIVE STABILIZATION OF THERMO ACOUSTIC INSTABILITIES IN LAMINAR COMBUSTION

J.D.B.J. van den Boom*, I. Lopez, K.R.A.M. Schreel, L.P.H. de Goey, and H. Nijmeijer

Department of Mechanical Engineering, Technische Universiteit Eindhoven
P.O. Box 513, 5600 MB Eindhoven, The Netherlands
J.D.B.J.v.d.Boom@tue.nl

Abstract
Modern gas-fired household boilers have one persistent problem: they tend because of thermo acoustic instabilities to make noise. In order to make any further advance in condensing boiler technology this problem has to be solved. Therefore the possibility of active suppression and stabilization of these instabilities is investigated using boundary control. A model-based approach is used for the synthesis of the controller. For that reason first a model for the system is derived based on the acoustic network approach. Special attention is paid to the flame dynamics. A stability analysis based on the eigenvalues of the system is performed. In this analysis the dynamics of the actuator, a loudspeaker, have also been taken into account. The obtained knowledge about the damping or amplification of an acoustic instability is used in the control design. The performance of the controller is validated during simulations and experiments. In the experiments the heat released by the flame is used as a sensor and a comparison is made with stabilization of the system using proportional control.

INTRODUCTION

In this paper, we address the problem of (active) boundary control of thermo acoustic instabilities in a modern gas-fired household boiler. These instabilities originate from the interaction between the combustion process and the system in which the burner is mounted. Nowadays ceramic surface burners are often used in order to reduce the emission of NO_x. All flames stabilized on these surface burners are sensitive to acoustic instabilities. This noise problem has to be solved in order to make any further advance in condensing boiler technology.

The objective is not only to stabilize the thermo acoustic instabilities but also the ability to suppress the disturbances which are present in the system. This objective differs from most of the large number of literature dealing with control of combustion instabilities, for example Annaswamy[1], Campos-Delgado[3], Heckl[4], Mcmanus[6] or Lang[8].

In order to model and control the thermo acoustic interaction in a gas-fired household boiler the transfer matrix method described in Munjal[7] is used. Subsequently two different approaches are possible to implement the control strategy along the border of the system: the introduction of an extra (volume) velocity source or modifying actively the acoustic impedance. In this paper boundary control has been applied to (actively) modify the acoustic impedance.

A MODEL FOR THE BOILER

A mean flow of a methane-air mixture through an open-ended duct, with a premixed flat flame stabilized on a surface burner at an axial location $x = a$ is considered as a representation for the gas-fired household boiler and is shown in Figure 1. The following assumptions have been

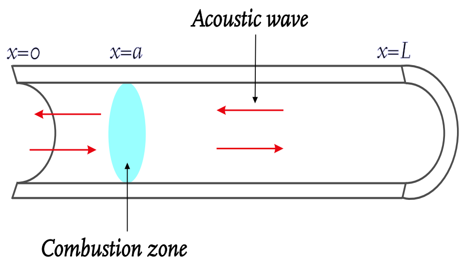

Figure 1: Schematic representation for the gas-fired boiler geometry

made:

- The flame length is small compared to the acoustic wavelength, thus the region of heat release may be approximated as a thin sheet at $x = a$;
- The mean flow Mach number is small;
- The acoustic field can be described by one-dimensional waves, since in a duct system the cross flow dimensions are much smaller than the wave lengths present in the system. This allows the use of the transmission matrix approach, Munjal[7].

The part upstream of the surface burner ($0 \leq x < a$) has a non-reacted gas density of ρ_{u} and a sound speed c_{u}. Analogous the section downstream of the surface burner ($a \leq x < L$) has a reacted gas density of ρ_{u} and a velocity of sound c_{u}. Only plane waves are assumed to be present in the system. In each of the two sections there is a forward and backward traveling wave, represented by their complex amplitudes: A, B, C and D. The relation for the pressure, p, and the particle velocity, u, can be expressed as:

$$p_{\mathrm{u}}(x,t) = A \exp^{ik(x-a)-i\omega t} + B \exp^{-ik(x-a)-i\omega t}\ ,\ u_{\mathrm{u}}(x,t) = \frac{1}{\rho_{\mathrm{u}} c_{\mathrm{u}}} p_{\mathrm{u}}(x,t) \qquad (1)$$

$$p_{\mathrm{d}}(x,t) = C\exp^{ik(x-a)-i\omega t} + D\exp^{-ik(x-a)-i\omega t}\ ,\ u_{\mathrm{d}}(x,t) = \frac{1}{\rho_{\mathrm{d}} c_{\mathrm{d}}} p_{\mathrm{d}}(x,t), \tag{2}$$

where $k = \omega c$ is the wavenumber. In transfer matrix notation this will be for the upstream part of the tube:

$$\begin{bmatrix} p_{\mathrm{u}}(a_-,t) \\ u_{\mathrm{u}}(a_-,t) \end{bmatrix} = exp(-i\omega t) \begin{bmatrix} \cos(ka) & -i\rho_{\mathrm{u}} c_{\mathrm{u}} \sin(ka) \\ -\frac{i}{\rho_{\mathrm{u}} c_{\mathrm{u}}} \sin(ka) & \cos(ka) \end{bmatrix} \begin{bmatrix} p_{\mathrm{u}}(0,t) \\ u_{\mathrm{u}}(0,t) \end{bmatrix} \tag{3}$$

Reflection will take place at both ends of the tube. This can be characterized by the reflection coefficients, R_{u} and R_{d}:

$$A\exp^{ik(x-a)-i\omega t} = R_{\mathrm{u}} B\exp^{ik(x-a)-i\omega t} \tag{4}$$

$$D\exp^{ik(x-a)-i\omega t} = R_{\mathrm{d}} C\exp^{ik(x-a)-i\omega t} \tag{5}$$

Performing a continuity of pressure at $x = a$ results in:

$$A + B = C + D \tag{6}$$

Unfortunately due to the fact that combustion acts as a velocity source, at $x = a$ the velocity is discontinuous. In order to quantify this the linearized acoustic equations for a reacting flow (Rankine-Hugoniot relations) are used:

$$u'_{\mathrm{d}}(a_+,t) - u'_{\mathrm{u}}(a_-,t) = (\gamma - 1)\frac{\dot{Q}'_{rel}}{\rho_{\mathrm{u}} c_{\mathrm{u}}^2}, \tag{7}$$

with Q'_{rel} the fluctuations in the heat release and γ the ratio of the specific heats.

Flame dynamics

In burner-stabilized flames there exists a coupling between the heat loss of the flame to the burner and the particle velocity. Induced by a fluctuation in the particle velocity (denoted as u'u) a variation in standoff distance of the flame, ψ_{f}, will create a displacement of the complete flame structure apart from the temperature. The standoff distance is the distance between the burner deck and the flame front. An oscillating flame position will result in traveling enthalpy waves towards the flame front. If there is a right phase relation between the wave and the movement of the flame front, amplification or damping of the motion of the flame front can occur. This behavior can be described with the following equation:

$$\frac{\partial Q'_{\mathrm{rel}}(\tau)}{\partial \tau} + \frac{Z}{\tau_{\mathrm{f}}} Q'_{\mathrm{rel}}(\tau') = \frac{Z}{\tau_{\mathrm{f}}} \frac{\rho_{\mathrm{u}}}{c_{\mathrm{p}}(\overline{T}_{\mathrm{b}} - \overline{T}_{\mathrm{u}})} u'_{\mathrm{u}}(\tau'), \tag{8}$$

with c_{p} is the specific heat, Z the 'flame feedback' coefficient, τ_{f} the 'flame time, and a time lag $\tau' = \tau - \psi_{\mathrm{f}}/\overline{u}_{\mathrm{u}}$. This time delay is induced by the fact that it takes time for the enthalpy waves to reach the flame front. For more details see van den Boom[2] and the references herein.

For burner-stabilized flat flames the transfer matrix has the following form, after a Laplace transformation has been performed on equation(8):

$$\begin{bmatrix} p'_{\mathrm{d}} \\ u'_{\mathrm{d}} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1+(\gamma-1)\frac{1}{c_{\mathrm{u}}^2 c_{\mathrm{p}}(\overline{T}_{\mathrm{b}}-\overline{T}_{\mathrm{u}})(s\exp(s\psi_{\mathrm{f}}/\overline{u}_{\mathrm{u}}+1))} \end{bmatrix} \begin{bmatrix} p'_{\mathrm{u}} \\ u'_{\mathrm{u}} \end{bmatrix} \tag{9}$$

After multiplying the matrices from equation (3), (9) and the matrix notation for the downstream part of the tube a characteristic equation can be derived. With this equation it is possible to determine the system's poles. The acoustic impedance functions play an important role in determining the roots of the system. The acoustic impedance is defined as $Z = p/u$ and the reflection coefficient is as $R = \frac{Z_{\mathrm{rad}}-\rho c}{Z_{\mathrm{rad}}+\rho c}$.

Since the tube is open at $x = L$, the radiation impedance, Z_{rad} is assumed to be that of a unflanged pipe, see Munjal[7] and equals the acoustic impedance $Z_{x=L}$ at that point:

$$Z_{x=L} = \rho c(\frac{1}{4}kr^2 + 0.61kr), \tag{10}$$

with r the radius of the tube, assuming that the area is constant.

At $x = 0$ a loudspeaker is mounted in order to be able to modify actively the acoustic impedance, $Z_{x=0}$. The acoustic impedance of a loudspeaker is determined by two control parameters Γ_{u} and Γ_{p}, because of the fact that a loudspeaker can be modeled as a relation between pressure and velocity on the one side and a voltage, V, at the loudspeaker and current, I, through it, Lissek[5]:

$$\begin{bmatrix} p \\ u \end{bmatrix} = \begin{bmatrix} L1 & L2 \\ L3 & L4 \end{bmatrix} \begin{bmatrix} V \\ I \end{bmatrix}, \tag{11}$$

where $L1$, $L2$ $L3$ and $L4$ are described by the type of loudspeaker used. The voltage used to drive the loudspeaker is equal to

$$V = \Gamma_{\mathrm{u}} u + \Gamma_{\mathrm{p}} p \tag{12}$$

The acoustic impedance is then equal to:

$$Z_{x=0} = \frac{\Gamma_{\mathrm{u}}}{\Gamma_{\mathrm{p}}} \tag{13}$$

In order to check when the system is unstable, the poles of the system are derived by the following characteristic equation:

$$A + \frac{B}{Z_{x=L}} - CZ_{x=0} - D\frac{Z_{x=0}}{Z_{x=L}} = 0, \tag{14}$$

where A, B, C and D originate from the transfer function matrix of the total system. Figure 2 shows the solution of the characteristic equation. Solutions with a negative damping ratio will result in amplification of the thermo acoustic instability and have to be canceled.

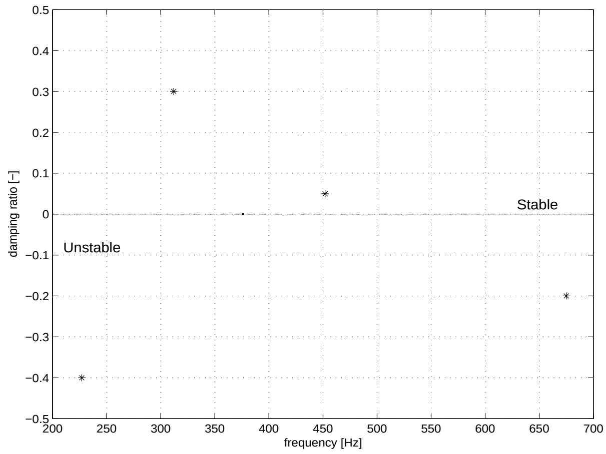

Figure 2: Solution of the characteristic equation for $Z_{x=0} = \infty$, (no control)

CONTROL DESIGN

A $\mathcal{H}_\infty$ controller is derived based on the model from the previous section and is designed only to stabilize the first unstable mode at 227 Hz (performance aim) (see Figure 2). The μ-toolbox of Matlab is used for control design. In order to use this toolbox the system is transformed into a state space form. This can only be done when equation (8) is linearized around an operating condition (with an equivalence ratio of 0.8 and a mean flow velocity of 0.14 m/s) and the time-delays are approximated by a (sixth-order) Padé-approximation. More details on $\mathcal{H}_\infty$ controller can be found in Skogestad[9]. In advance is known which type of loudspeaker, a two inch transducer from *Tang Band*, is used as an actuator. Several experiments are conducted on the loudspeaker in order to find the correct characteristic (cone mass, stiffness and damping), which can be translated into a weight on the control signal. The simulation results are shown in Figure 3, in which band-limited white noise is used as an external disturbance.

EXPERIMENTS

For the experimental validation of the synthesized $\mathcal{H}_\infty$ controller the set-up described in van den Boom[2] is used. A schematic representation is shown in Figure 4. The experimental set-up is modified on three places: the tube is extended, the mixture enters the duct from the side through little holes, the loudspeaker used for actuation is directly mounted at the bottom of the tube. The heat released by the flame is measured by a photo-multiplier equipped with an UV-filter. The emitted light (ultraviolet) of excited OH molecules is sensed, because the concentration of excited OH molecules is considered to be a quantitative measure for the heat-release. These measurements are used as an input for the control strategy. The controller is implemented with a *National Instruments* I/O board using a real-time Linux/Matlab envi-

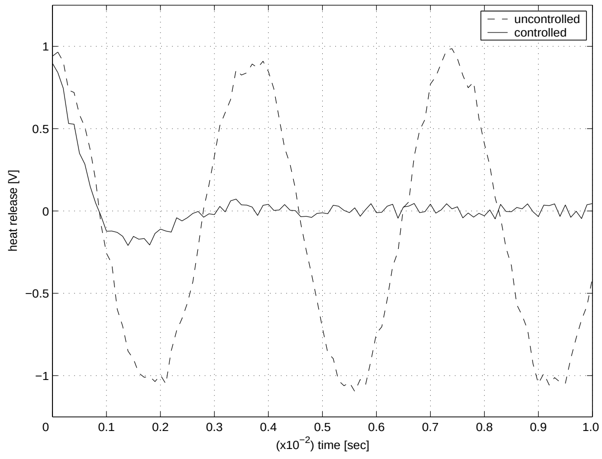

Figure 3: Results of the simulation, (x-axis times 10^{-2})

ronment. An additional amplifier based on the *National Semiconductor* LM3875 was needed to drive the loudspeaker.

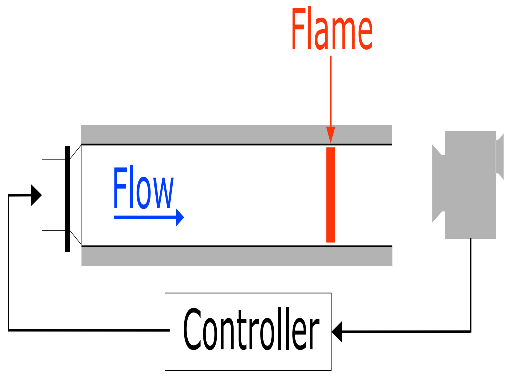

Figure 4: Schematic representation for the experimental set-up

A comparison between the $\mathcal{H}_\infty$ and a proportional controller derived by empirical tuning. Stabilization by pole placement using proportional control (sometimes combined with an additional phase shift) is performed often in literature, for instance Heckl[4] and Lang[8]. Nevertheless this type of control can not perform its task whenever there are (external) disturbances present in the system.

Figure 5 shows the stabilization of the first unstable mode at frequency of 227 Hz by both controllers ($\mathcal{H}_\infty$ control the straight line and proportional control the dashed line). A second side mounted loudspeaker was used to introduce a sinusoidal disturbance (160Hz) to the system. At $t = 0$ both controllers are turned on. The experiments are not performed at the same time. It can be noticed that it takes six cycles before the fluctuations is heat-release are stabilized by the $\mathcal{H}_\infty$ controller. This delay compared to the proportional controller is probably caused by the saturation of the actuator, which is still under investigation.

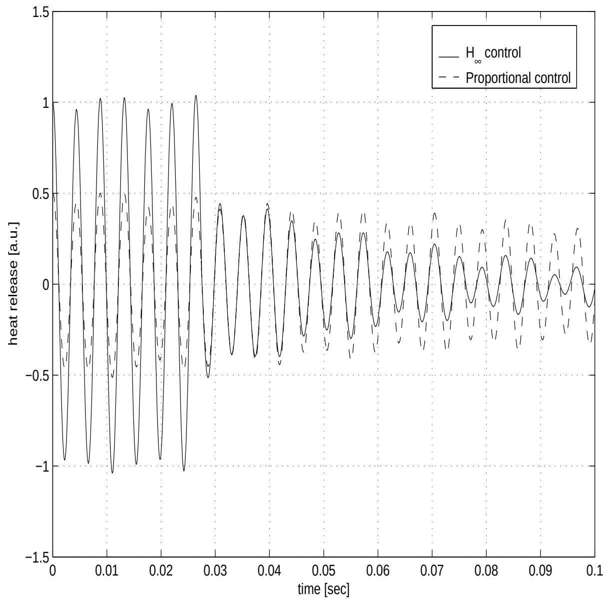

Figure 5: Results of the experiments

CONCLUSIONS

A simulation and experimental study has confirmed that boundary control, in the appearance of changing actively the acoustic impedance, used in a modern gas-fired household boiler is able to stabilize the thermo acoustic instabilities. Beside it is shown that the controller is capable of suppressing additional disturbances in the system, which is not possible with a proportional controller often used in literature.

ACKNOWLEDGEMENT

This research is supported by the Technology Foundation STW, applied science division of NWO and the technology programme of the Ministry of Economic Affairs.

References

[1] A.M. Annaswamy, M.Fleifil, J.W. Rumsey, R. Prasant, J.P. Hathout, and A.F. Ghoniem, 'Thermo acoustic instability: model-based optimal control designs and experimental validation,' IEEE Transactions on control systems technology, 8(6), p. 905-818, (2000).

[2] J.D.B.J. van den Boom, I. Lopez, K.R.A.M. Schreel, L.P.H. de Goey, and H. Nijmeijer, 'Towards active suppression of thermo-acoustics instabilities in laminar combustion,' Proc. *12th ICSV*, Editors: J.L. Bento Coelho and D. Alarco, Lisbon, Portugal, (2005).

[3] D.U. Campos-Delgado, B.B.H. Schuermans, K. Zhou, C.O. Paschereit, E.A. Gallestey, and A. Poncet, 'Thermo acoustic instabilities: Modeling and Control,' IEEE Transactions on control systems technology, 11(4), p. 429-447, (2003).

[4] M. Heckl, 'Active control of noise from a Rijke tube', Journal of Sound and Vibration, 124, p. 117-133, (1988).

[5] H. Lissek, and X. Meynial, 'Active impedance control for room acoustics,' Proc. *12th ICSV*, Editors: J.L. Bento Coelho and D. Alarco, Lisbon, Portugal, (2005).

[6] K.R. McManus, T. Poinsot, and S.M. Candel, 'A review of active control of combustion instabilities', Prog. Energy Combustion Science, 19, p. 1-29, (1993).

[7] M.L. Munjal, *Acoustics of ducts and mufflers*, (John Wiley & Sons, New York, 1987).

[8] W. Lang, T. Poinsot, and S. Candel, 'Active control of combustion instability,' Combustion and Flame, 70, p. 281-289, (1987).

[9] S. Skogestad, and I. Postlethwaite, *Multivariable feedback control: Analysis and Design*, (John Wiley & Sons, New York, 1996).