

Waveform Inversion in Acoustic Pyrometry

Helmut Sielschott, Dr. Frank Wübbeling

Institut fuer Numerische und instrumentelle Mathematik
Einsteinstr. 62, D-48149 Muenster
Phone: ++49(0)251 83-33795, Fax: -32714
E-mail: helmut.sieschott@math.uni-muenster.de
Frank.wuebbeling@math.uni-muenster.de

Abstract – Acoustic pyrometry is a measurement technique for the temperature of flue gas inside large scale combustion chambers. Detection of first arrival times of acoustic signals leads to coarse reconstructions of the velocity of sound which is directly related to gas temperature. In addition these data contain information about the velocity of flue gas.

Waveform inversion makes use of the time resolved data recorded by the microphones and detects a more detailed model for the speed of sound by solving the inverse problem of the appropriate wave equation.

Keywords: Waveform inversion, acoustic pyrometry, inverse problems, process tomography

1. INTRODUCTION

Acoustic pyrometry is one of only a few techniques that can give information about temperature and flue gas velocity in a large scale furnace of a coal fired power station.

Several acoustic transducers, each consisting of a sound source and a microphone, are fixed at the walls of the furnace at one horizontal layer, see figure 1.

For each measurement, one of the transducers sends an acoustical signal that the others receive. From the signals recorded by the microphones we can compute the travel time resulting in a standard tomography problem or the whole signal can be used for reconstructing the velocity profile in the boiler via waveform inversion.

For the purpose of temperature measurement we can describe the flue gas as an ideal gas because the temperature is high ($>1.200\text{ }^{\circ}\text{C}$) and the pressure is low ($\sim 0.9\text{ bar}$). This gives us a simple relation between temperature T and speed of sound c :

$$T = g c^2$$

The number g depends on the gas composition which is known. At full load only 7 of the 8 burners at a height of 25 m (see figure 1) are operational. This results in an asymmetric temperature profile. Acoustic pyrometry can detect this asymmetry and control the effect of operational parameters like burner arrangement, recirculated flue gas etc.

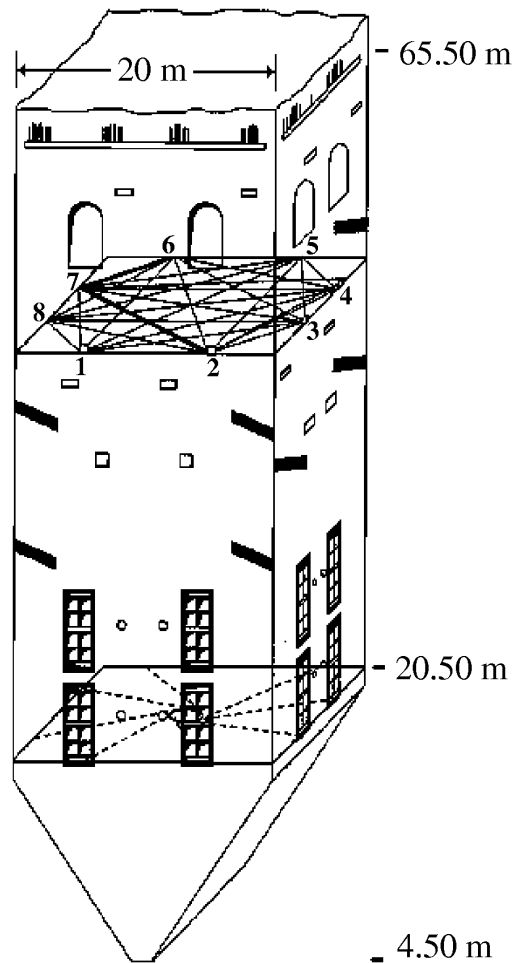


Figure 1: Tangentially fired 600 MW furnace.

2. DATA COLLECTION

We are interested in the temperature distribution in one horizontal layer at the end of the combustion chamber of a coal fired power station.

Eight transducers are installed outside the furnace. Acoustical signals are lead by a pipe with a diameter of about 7 cm through the walls of the furnace.

For a measurement one of the transducers sends a very loud acoustical pulse that the others receive. Next, the second transducer "fires" while the seven others receive. The signals are produced by a sparc discharge. As it takes about 40 seconds to load the capacitor, the eight transducers "fire" at a time distance of 5 seconds. Without this technical restriction it would be possible to collect one set of measurements in less than one second, as the speed of sound is around 650 to 800 m/s. The signals vanish in less than 1/8 second. Figure 2 shows the background noise that is measured during the time of flight and the signal to be measured. The signal to noise ratio is good enough for our purpose.

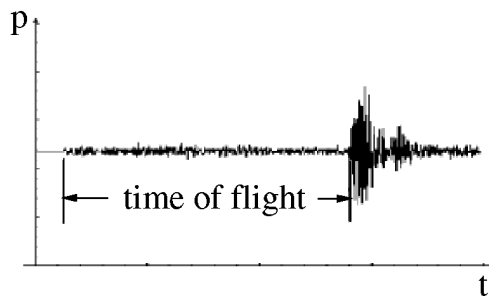


Figure 2: Typical signal recorded by a microphone.

Two ways of exploiting the data are possible. First, we can make use of merely the time-of-flight information, see figure 2. This leads to stable algorithms giving both the velocity of sound and thereby the temperature and the horizontal velocity of the flue gas, see section 3. Second, the whole signal recorded by the microphones can be used. In this case the propagation of sound has to be simulated on a computer and a model for the speed of sound, c , is looked for that leads to a simulated wave propagation giving the measured data at the microphone positions. This is called *waveform inversion*.

There is a number of problems with waveform inversion in this application.

1. To get a good signal to noise ratio 25 m from the microphones, the initial signal must be very loud. It is so loud that the linear wave equation does not model wave propagation close to the sender.
2. Signals are produced by a sparc discharge. Two cathodes with a voltage of 10.000 Volts are moved towards each other until the sparc discharge takes

place. We do not know what the initial signal leaving the pipe into the furnace looks like.

3. Before being recorded by the microphones the acoustic wave has to travel through another pipe. The additional reflections here once again change the received signals.

We hope that the first two problems can be solved using an artificial source for the reconstruction, see section 4. Measurements in march 1998 showed that the available hardware cannot measure data that can be used for waveform tomography. The third problem will be solved within the re-development of the hardware.

3. TIME OF FLIGHT TOMOGRAPHY

Having measured the time of flight of acoustic signals in both directions between one pair of transducers, we can directly compute the mean velocity of sound on the straight ray between these transducers. We now have to solve a scalar tomography problem. Our algorithm is based on a series expansion method, see [1]. The assumption of the fastest part of the wave taking approximately the rectilinear line between the transducers is not always fulfilled, but in our case it is a very good approximation, see [2].

As we also know the difference of time of flight between each pair of transducers we can compute the horizontal part of the velocity of flue gas in the boiler at the measurement height, see [3].

4. WAVEFORM INVERSION

The expression *waveform inversion* is the geophysical name for what mathematicians call the solution of an *inverse problem to the wave equation*. In our case, the wave equation takes the form

$$\frac{\partial^2 u}{\partial t^2} + 2\mathbf{v} \cdot \nabla \frac{\partial u}{\partial t} - c^2(x)\Delta u = q_j(x)\mathbf{a}(t) \quad (1)$$

The term containing \mathbf{v} expresses the influence of the velocity of gas \mathbf{v} . The gas is blown in with a speed of about 20 m/s while the velocity of sound takes values up to 800 m/s. The influence of \mathbf{v} therefore is rather small and there is no need to reconstruct \mathbf{v} from time resolved data. We can use the reconstruction of \mathbf{v} from time of flight measurements for the solution of (1).

The index j in (1) belongs to the number of the source. Currently we assume that the time dependence of the acoustic source is the same for all transducers, so has no index.

Having an approximation for $c(x)$ we can solve the wave equation (1) using an explicit finite dif-

ference scheme and compare the results of this simulation with the time resolved data measured by the microphone. The idea of waveform inversion is to improve our model for c until the solution of (1) gives results similar to the measured data.

A coarse description of our propagation-backpropagation algorithm is given in [2], it is based on a multi purpose algorithm for inverse problems presented in [4]. This technique is known and has been applied successfully in geophysics (see [5, 6]) and works well in 2D-experiments (see [2]) with simulated data.

For waveform inversion as it is described here we need to know the function q . This is a problem as q is a complicated function because of the reflections inside the pipe belonging to the sender. In addition wave propagation is nonlinear close to the sender. We hope that these problems can be overcome by using an artificial source for the reconstruction: using a propagation-backpropagation method we can solve the inverse problem for equation (1) with c and q unknown. This means that we can compute an artificial source that leads to the same data as the real nonlinear one.

5. NUMERICAL RESULTS

Figure 3 shows a phantom (a) that reflects the temperature distribution near the ceiling of a combustion chamber that is fired through 5 burners in the ceiling. Below you see the reconstruction from time of flight tomography (b). Because of ray bending effects the fastest part of the acoustic signal does not travel through the cold areas. This means that the first arrival times contain no information about these cold spots and they can not be found in the reconstruction, see [2].

Picture (c) shows the reconstruction of c with q and t known. Without knowledge of t we get the reconstruction (d) if we assume q to be known. If we only have an approximation to q (see figure 4) and no knowledge of t , we get the reconstruction (e).

The cross section (f) shows that even with inexact knowledge of q and the reconstructed version of t we get much better results from waveform inversion than from time of flight tomography.

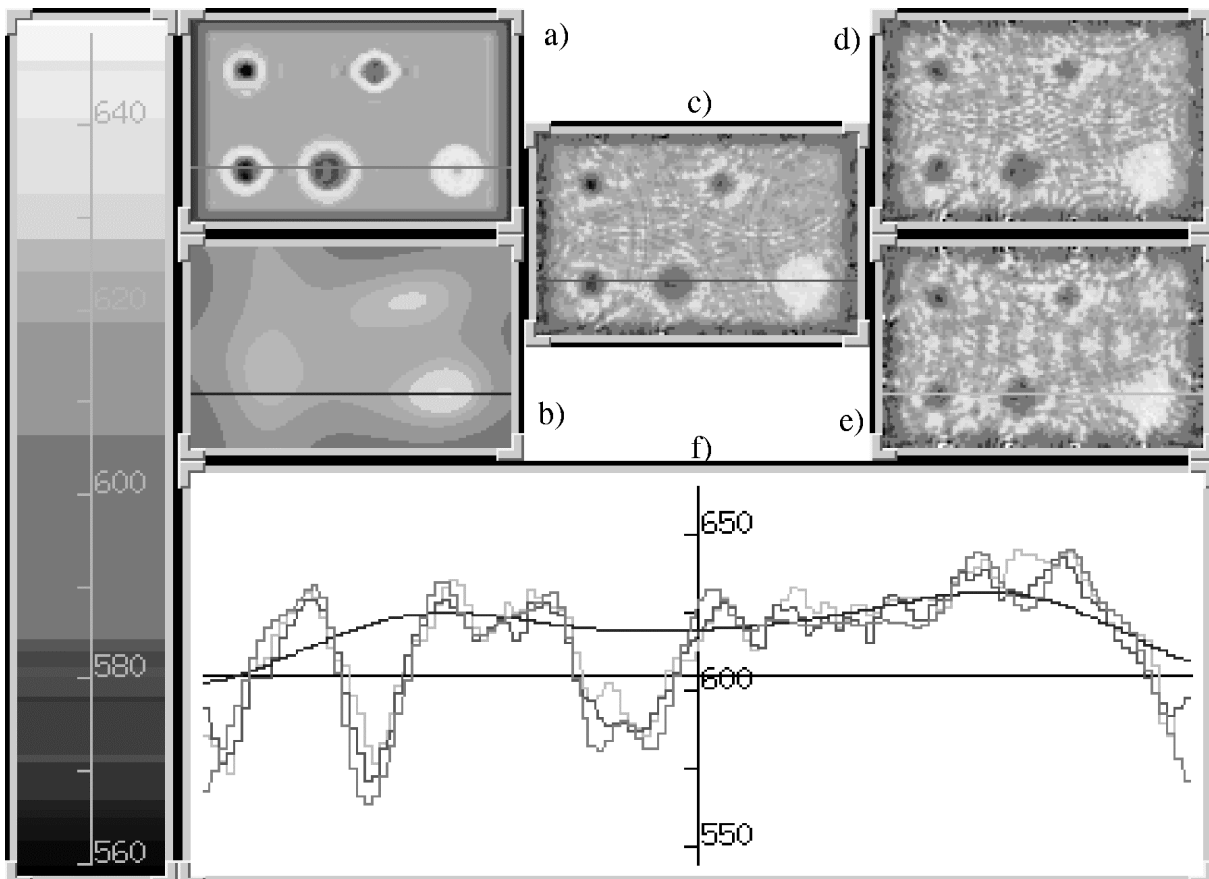


Figure 3: Numerical results for reconstruction of c with and without knowledge of t . The phantom (a) is reconstructed via time of flight tomography (b) and via waveform inversion (c)-(e). The cross section (f) shows that even without knowledge of t and an inexact model of q the reconstruction via waveform inversion (e) is much better than the TOF-reconstruction (b).

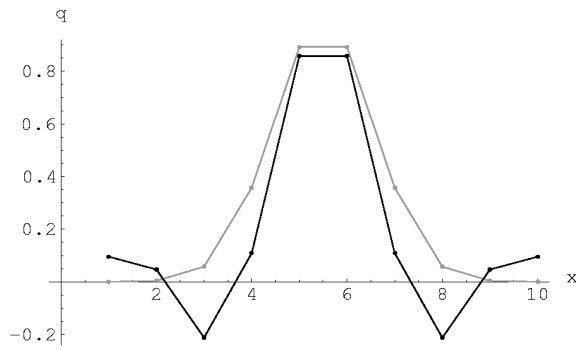


Figure 4: Models for $q(x)$. Grey: original, black: approximative model.

6. CONCLUSION

We have presented a reconstruction algorithm that is the natural improvement of standard acoustic pyrometry. Simulations show that even when the time dependent part of the acoustic source has to be reconstructed from the measurements, the results are much better than results from time of flight tomography.

ACKNOWLEDGEMENT

This work is part of a project supervised by Prof. Dr. F. Natterer, granted by the German "Federal Ministry of Education, Science, Research and Technology", grants: 03-NA7MUE.

REFERENCES

- [1] H. Sielschott and W. Derichs, "Use of collocation methods under inclusion of a priori information in acoustic pyrometry". In: M.S. Beck et al. (eds.), *Process Tomography – 1995, Implementation for industrial purposes*, pp. 110-117, Manchester: UMIST.
- [2] F. Natterer, H. Sielschott, and W. Derichs, "Schallpyrometrie". In: K.-H. Hoffmann et al. (eds.), *Mathematik – Schlüsseltechnologie für die Zukunft*, pp. 435-446, Springer, 1997 (German with English abstract).
- [3] H. Sielschott, "Measurement of horizontal flow in a large scale furnace using acoustic vector tomography", *Flow Meas. Instrum.*, 1997, 8, pp. 191-197.
- [4] F. Natterer, "Numerical Solution of Bilinear Inverse Problems", Tech. Rep. 19/96N, Department of Mathematics, University of Münster, Germany.
- [5] O. Gauthier, J. Virieux, and A. Tarantola: "Two-dimensional nonlinear inversion of seismic waveforms: Numerical results", *Geophysics*, 1986, 51, pp. 1387-1403.
- [6] C. Zhou, W. Cai, Y. Luo, G. Schuster, and S. Hassanzadeh, "High resolution crosswell imaging by seismic travelttime + waveform inversion", *Geophysics*, 1995, 60, pp. 765-773.