A sonic approach for the measurement of gas temperature in power generation boilers

Une approche sonique pour la mesure de la température des gaz dans les chaudières de grande puissance

Ambrogio Ceserani
Luca Gregori
Gian Antonio Zanetta
CESI S.p.A.
Via Rubattino 54
20134 Milano
Italy
http:// www.cesi.it
E-mail : zanetta@cesi.it

Angelo Farina
Università degli studi di Parma
Dipartimento di Ingegneria Industriale
Parco Area delle Scienze 181/A
43100 Parma
Italy

La mesure de la température des gaz dans la chambre de combustion des chaudières de grande puissance a un intérêt remarquable pour le personnel d'exploitation, puisqu'elle peut avoir un impact immédiat pour un fonctionnement correct, et sur les coûts durant la vie du composant. On comprend facilement que la rudesse extrême de l'environnement rencontré empêche d'appliquer n'importe quel genre de système intrusif de mesure, qui ne pourrait pas être employé sauf pendant des périodes très courtes et qui ne pourrait en aucun cas être considéré comme un moyen de surveillance à long terme. En outre, les techniques optiques n'ont pas donné jusqu'ici les résultats espérés, en raison des problèmes d'opacité de gaz aux distances industriellement intéressantes ; qui plus est, ces systèmes sont très coûteux, et entraînent des problèmes considérables d'entretien.
La méthode sonique est basée sur la mesure du retard d'un signal acoustique le long d'un certain nombre de trajets entre des capteurs faisant face aux parois de la chaudière. Une température moyenne sur chaque trajet est d'abord obtenue ; une carte thermique sur la section de mesure peut alors être tracée. Actuellement, la pyrométrie acoustique s'est avérée être la seule solution possible pour la surveillance à long terme. Mais deux problèmes majeurs n'ont pas encore trouvé une solution satisfaisante :
a) la fiabilité des mesures de la température dans de grandes chaudières n'était pas encore acceptable pour un traitement des signaux non supervisé ;
b) l'installation des sondes sur les parois de chaudière demandait toujours des ouvertures trop grandes, de sorte qu'elle aurait été beaucoup trop encombrante et coûteuse, en particulier pour du ré-équipement sur les usines existantes, et l'entretien aurait été également difficile, sinon impossible, avec l'usine en fonctionnement.
Par conséquent, le travail de recherches décrit dans cet article a porté en particulier sur les deux problèmes mentionnés ci-dessus.
Une nouvelle conception des avertisseurs sonores a débouché sur des sondes complètement non-intrusives et à bas coût, qui pouvaient être installées sur les usines existantes et pouvaient être inspectées et même démontées, l'usine étant en fonctionnement normal, cela de manière à garantir un entretien facile.
En parallèle, un certain nombre d'algorithmes d'analyse de signal ont été développés, certains d'entre eux étant complètement originaux. En particulier, pour l'excitation à balayage sinusoïdal, un filtre numérique de suivi en temps réel a été introduit, avec une pondération particulière de la fonction de corrélation, et un post-traitement par la transformation de Hilbert. De plus, il a été développé une méthode alternative et originale qui fait usage des impulsions temporelles tonales, avec un traitement des données particulier.
En conséquence, l'article illustre d'abord les nouvelles solutions pour les avertisseurs sonores, puis discute en détail l'algorithme de traitement des signaux, et montre finalement quelques résultats obtenus à partir des essais expérimentaux réalisés sur une installation sur la chaudière d'une usine à combustible charbon de 660 MW.

The paper describes the recent improvements of a proprietary system for the estimate of temperature distributions inside gas flows by sonic methods, with special attention to applications in the steam boilers of power stations.
In particular, together with a short review of the original configuration, the problem of installation and maintenance of the waveguides is first discussed and the newly devised solutions are shown. Then the revision of the signal processing algorithms, employedfor the determination of the temperature along the acoustic paths between any two transducers, is described; the aim was to reduce the scattering of the measurements and to improve their reliability, despite of the strong levels of background noise and the highly non-stationary system under measure.
Finally some results obtained by preliminary tests carried out on a coal fired 660 MW steam boiler are documented in some detail.

The measurement of the gas temperature in the furnace of power boilers has a remarkable interest for the plant personnel, since it can have immediate impact on the correct operation and on the life expenditure of the component.

In fact, the gas temperature knowledge is important for fuel and air balancing, for optimizing the burner operation, for keeping the fireball off the walls in order to prevent wall tube fireside corrosion, for the control of the emissions, for pointing out possible reductions of heat exchange caused by dirt on the tubes, for verifying vitrification of combustion residuals due to threshold temperature overcomings and, of course, for the computations of residual life of the materials.

All these aspects assume even more prominence for the innovative "Ultra-Hyper-Critical" (UHC) cycles, with a working range of steam temperature up to 720°C and 400 bar pressures.

It is easily understood that the extreme harshness of the furnace environment prevents from applying any kind of intrusive measurement system, that cannot be applied if not for very short times and that, by no means, can be considered for long term monitoring. Also optical techniques did not give so far the expected results, because of problems of gas opacity over distances of industrial interest; moreover those systems are very costly and entail considerable maintenance problems.

The sonic method is based on the time delay measurement of an acoustic signal on a number of paths between transducers faced to the boiler walls. A mean temperature on every path is first obtained; a thermal map on the measurement section can then be drawn. To the present time, the acoustic pyrometry has turned out to be the only possible solution for long term monitoring. But two major problems did not yet find a satisfactory solution: a) the reliability of the temperature measurements on large boilers was not yet acceptable for unsupervised signal processing; b) the installation of the probes on the boiler walls still requested too large openings, so that it was very much cumbersome and costly, in particular for retro-fitting on existing plants, and the maintenance was once again difficult, if not impossible, with the plant in operation.

Therefore the research work described in this paper addressed particularly the two above mentioned problems.

The paper, after a short review of the original system, first illustrates the new solutions for the emitting horns, then discusses into some details the signal processing algorithms and finally shows some results obtained from the tests performed on an experimental installation on a boiler of a 660 MW coal fired plant.

The original system and the problems of temperature measurement in industrial boilers

In its original configuration, the proprietary system developed at CESI consisted of a number of dual function electro-acoustic transducers, constituted of a compression driver able to emit and receive the signal. Each transducer was provided with local intelligence for signal processing and communicated for control and data exchange with a central server via a field bus. The digital electronic components and the field-bus are by now somewhat obsolete. The waveguides had to be placed beyond the furnace walls and, consequently, they were rather costly, prone to wear, difficult to install and to maintain. A view of the original system is given in Fig. 1.

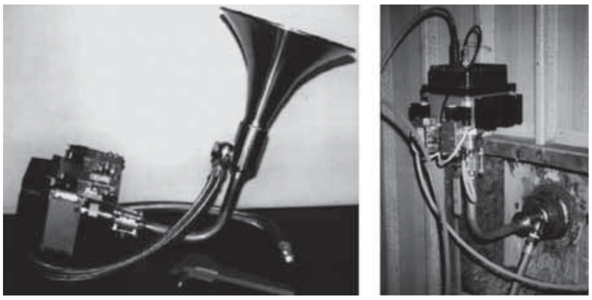

Fig. 1: Hardware of the original system

It is well known that the speed of sound c in a gas is a function of the temperature T, through the following equation :

$$c = \frac{d}{t_f} = \sqrt{\frac{\gamma R T}{M}} \tag{1}$$

where R is the universal gas constant, M is the molar mass of the gas, γ is the ratio of the specific thermal capacities at constant pressure and at constant volume respectively.

The generated signal was a fast (10 ms) sinusoidal sweep (chirp). The flight time t_f on the path d between any couple of transducers was determined as the absolute maximum value of the cross-correlation function between the excitation and the received signal. From equation (1) it is apparent that the uncertainties in the temperature estimates are a quadratic function of the uncertainties in the measured flight time.

Averaging the results of a number of subsequent measurements, it is possible to obtain temperature values within an uncertainty range of ±5% of the expected value. When nearby soot-blowers are in operation the background noise is exceedingly high and the scattering of measurements becomes in general unacceptable.

There are several additional factors affecting the precision of such kind of measurement, tied to the physics of the problem: gas temperature gradients close to the walls and inside the waveguides; gradients in the flow direction causing curved paths; thermal dilatation of boiler; uncertainties in the gas properties. A good summary of the possible errors and of some suggestions for their compensation is provided in [1].

Nonetheless, on the light of the experience gained so far, the greatest source of uncertainty in the measure are likely to be the non-stationary characteristics of the system under measurement, as it is discussed later on. That is due to turbulences of the gas flow, planar component of the gas speed, variable content of impurities.

The new design of the waveguides

The original waveguides (illustrated in Fig. 1) offered a satisfactory acoustic efficiency, with an exponential profile and geometric dimensions optimized for the range of emitted frequencies. On the other hand, the manufacturing costs were pretty high, the installation cumbersome and the maintenance difficult and by no means possible with the boiler in normal operation.

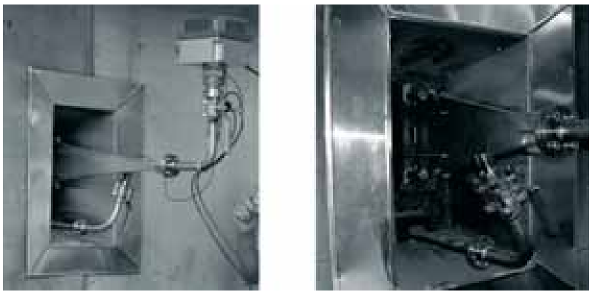

Fig. 2 : The new guide-waves installed for the tests on the plant

Namely, those guides were not well suited for retro-fitting existing plants, because of the obvious difficulties to get the duct from the loudspeaker to pass through the wall tubes, separated from each other by narrow fins, typically as large as 12÷16 mm. By the way, this holds true also for commercially available systems, that have horns with circular section and mouth diameters of about 60 mm.
Therefore, the new horn were designed in order to deal with theses problems. The transverse section is rectangular so that they can be faced to the furnace from outside the furnace walls, with a simple opening in the tube fin equal to the mouth area of the horn. A connecting frame was designed so as to make it easier the installation and removal, in a very simple pug-in mode, for maintenance, repair or substitution with the boiler in operation. A plug was also provided to close the opening in the tube wall in the absence of the horn.

Two profiles were designed, one exponential and another trapezoidal, for further simplification of manufacturing. Some stiffening was introduced to avoid excessive structural vibrations. The cost of such horns was obviously very cheap. An example of the experimental installation of the new horns for the tests on the plant is illustrated in Fig. 2.

The small pipe below the horn is the waveguide of the receiving microphone. In later tests, the length of the microphone pipe was shortened and adapted by spacers for better tuning acoustic resonances.

Of course the above improvements have been obtained at the expense of a reduced acoustic efficiency. Some tests were carried out in the laboratory with a mock-up of the tube wall in order to compare the emissions of two new horns, the original horn and the bare loudspeaker. The comparative values of the sound pressure levels measured in the laboratory at 3 m distance from the mouth of the horns are reported in the diagrams of Fig. 3.

The new guide emission is in fact a 12÷15 dB lower than the original ones in the frequency range from 500 Hz to 2.5 kHz. An unwanted result is also constituted by the repeated acoustic resonances introduced by the new

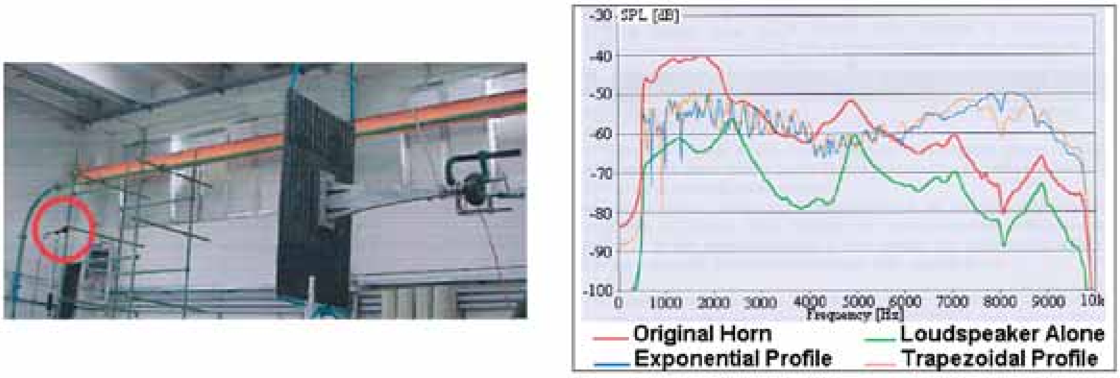

Fig. 3 : Laboratory test of the new horns: experimental set-up and results

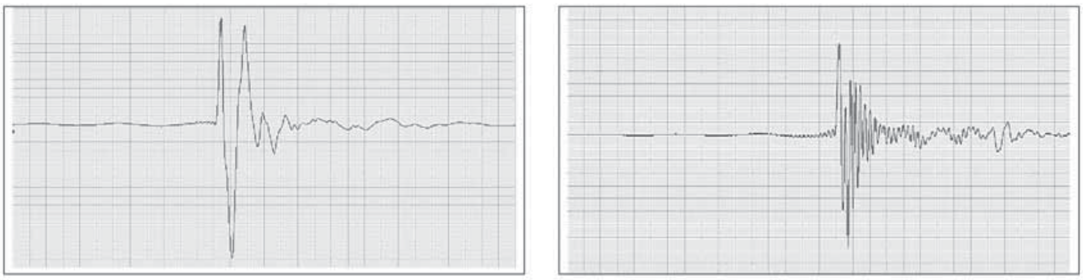

Fig. 4 : Cross-correlation function with original (left) and new (right) horns

guides, that can affect the quality of the cross-correlation function. This effect is clearly demonstrated in Fig. 4.
All the results of the field tests described in chapter 5 of the paper were carried out with use of the new waveguides just described. A further upgrading is currently under development in order to increase the mouth area, to reduce the effect of acoustic resonances, to improve the coupling of the acoustic impedances of the loudspeaker and the horn, while keeping the same advantages of installation and maintenance. This will result in an entirely new design of the horns and of the receiver waveguide.

Some aspects of the signal generation and processing

In the original system the excitation was constituted by a 10 ms burst of a linear chirp with frequency variable between 1.5 kHz and 4.5 kHz and sampling frequency of 100 kHz.
The S/N ratio was pretty low at every frequency of interest. Far better results could be obtained by extending the excitation time to 2 s, that was found to be a good compromise between keeping excitation and processing times as short as possible and having enough useful signal energy in the response.. A logarithmic sweep was preferred, that is somewhat equivalent to pink noise.
The whole buffer of the time samples was then transformed in the frequency domain by subsequent records with an appropriate overlapping. Each record in turn was filtered with a 6 pole pass-band filter, with a central frequency updated each time to match the average excitation frequency of the examined record, identified on the electric excitation signal. The width of the filter has to be calibrated taking into account the sweep speed and the expected delay of the received signal. The spectra obtained by the subsequent transformations are finally averaged. In this way, an original digital tracking filter was introduced, simple to implement, very fast, selective enough and not requiring, by converse, delicate synchronizations between excitation and response, that has an a priori unknown time delay.
The cross-correlation function is obtained from its frequency domain counterpart, the cross spectrum. An option was introduced to normalize the plain cross spectrum by its squared amplitude and, additionally, by the coherence function, before to anti-transform to the time domain.
It must be added at this point that other excitation and processing techniques were tried. One was the convolution with the inverse filter for obtaining the equivalent impulse response of the system [2], as an alternative to the cross-correlation function, but that did not provide better results. The measurement of the impulse response was also tried by means of a MLS (Maximum Length Sequence) excitation signal [3], but the results were absolutely unusable; in fact this technique is known to be performing well only with linear, time-invariant systems.
The system is highly dispersive, given the acoustic resonances introduced by the waveguides and because of the time variance, that causes remarkable distortions of the cross-correlation function. As a consequence, the cross-correlation function obtained by back transformation in the time domain is often difficult to be examined for the search of the maximum. A solution is provided by the Hilbert transform. In particular, the search of the maximum was performed on the squared amplitude of the so called “analytic function”, which is always positive, reduces dramatically the oscillations and enhances the maxima.
Additionally, it was shown that it is not advisable to estimate the flight time by the time delay of the maximum point of the cross-correlation function: the detection of the flight time based on the excedance of a prefixed trigger level improves the stability of the readings and reduces possible effects of reflected paths, which sometimes can produce delayed peaks having larger amplitude than the first one.
An alternative and original approach was also devised, in which the excitation signal is given by very short tonal bursts. The frequency must be properly chosen in consideration of the resonant frequencies of the waveguides and of the background noise. The time delay is determined once again with the Hilbert transform of the cross-correlation functions. The duty cycle (signal and silence) of such excitation is typically set to 200 ms; the optimal length of the signal burst depends on the best compromise between S/N ratio and precision of the readings.
Preliminary numerical simulations demonstrated that it is still possible to obtain usable results with S/N ratio values of –10 dB (that is, the signal is buried 10 dB below the noise).

Results of the test on the plant

Several tests were carried on 660 MW coal plant, employing the new waveguides and the signal processing algorithms described in the previous chapters. Four access points to the boiler furnace were prepared and used; the measurement section was situated in correspondence with the so called “nose” of the boiler, approximately at 24 meters above the last row of burners (Fig 5).

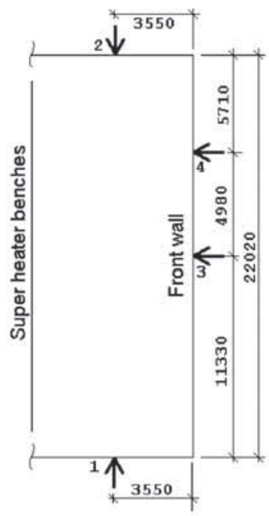

Fig. 5 : Measurement positions on a 660 MW boiler

The tests have been performed by means of portable instrumentation, illustrated in Fig. 6, together with the scheme of the measurement. The loudspeakers were compression drivers with a 50 W nominal output power in “continuous” service and 100 W in “continuous program” service, according to the IEC definitions; the output impedance was 8 Ohm.

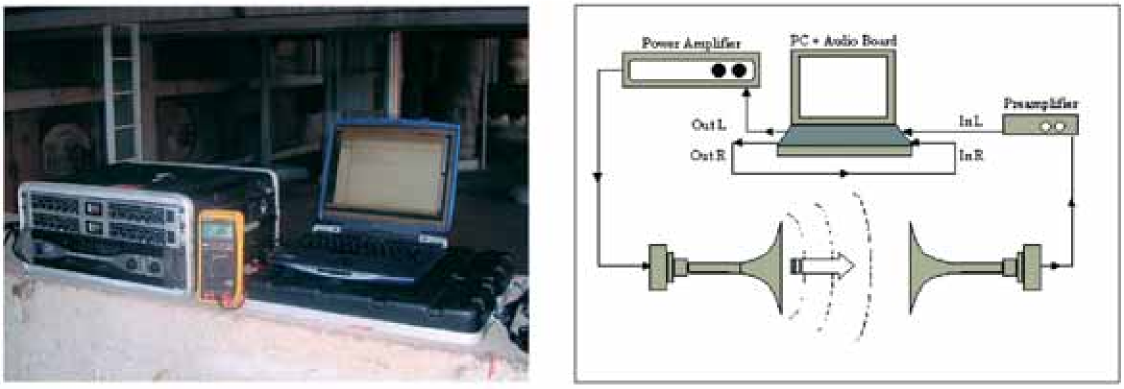

Fig. 6 : Portable instrumentation used and scheme of the measurement

A first set of measurements were taken with the boiler turned off. In those conditions, the only possible problems on the cross-correlation function came from reverberation in the furnace and dispersive effects of the waveguides resonances. To this respect, it is interesting to observe how the selective normalization of the cross-spectrum based on the amplitudes of the auto-spectra of the I/O signals produces a much clearer peak in the Hilbert transform of the cross-correlation function, avoiding ambiguities with delayed peaks, as in the example of Fig. 7 (path 2 >> 1).

With the boiler in normal operation at full load, the measurements of the background noise as received by the microphones at the end of a short pipe plus the spacers at the location 2, without (left) and with (right) soot blowers in action, are illustrated in Fig. 8; blue curves are averaged spectra, while the red curves are peak-hold spectra. The peaks are the acoustic resonances of the microphone waveguides. The soot-blowers determine a 10 to 20 dB increase of the background noise, in the frequency range 500 Hz÷4000 Hz.

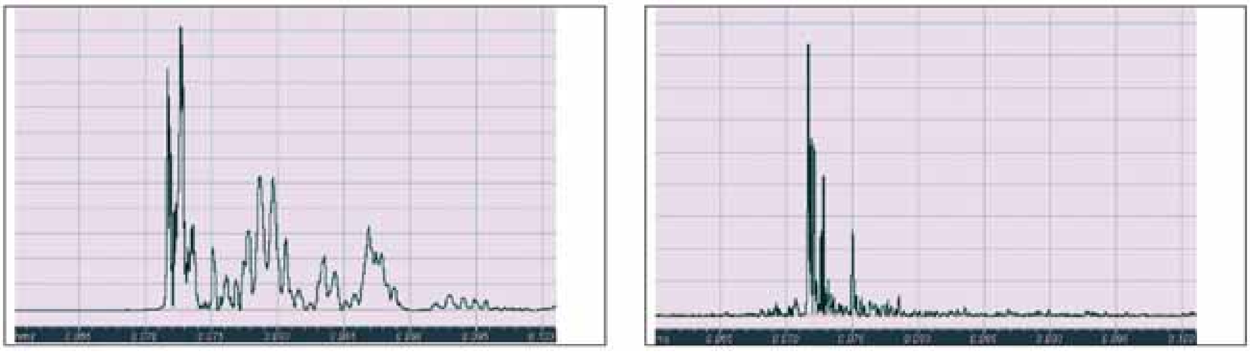

Fig. 7 : Effect of the cross-spectrum selective normalization

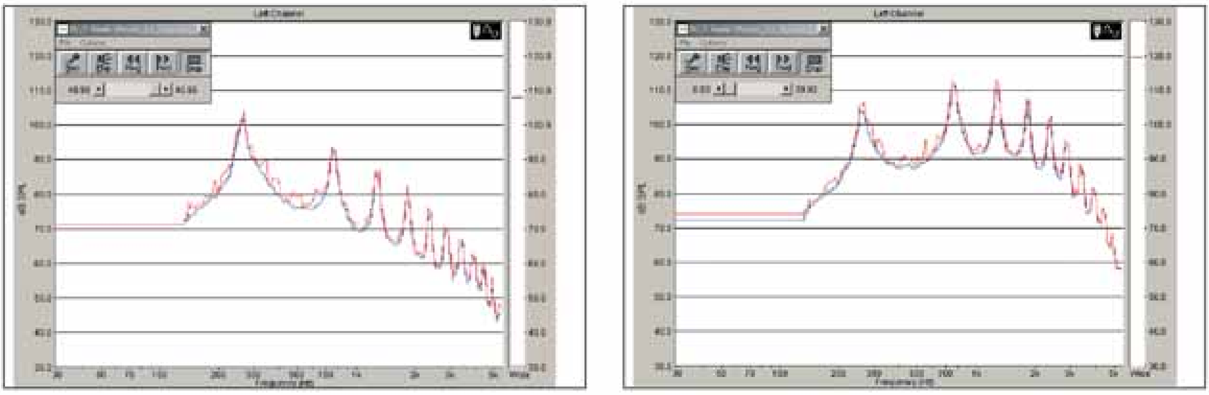

Fig. 8 : Background noise at measurement point 2 without (L) and with (R) soot-blowers

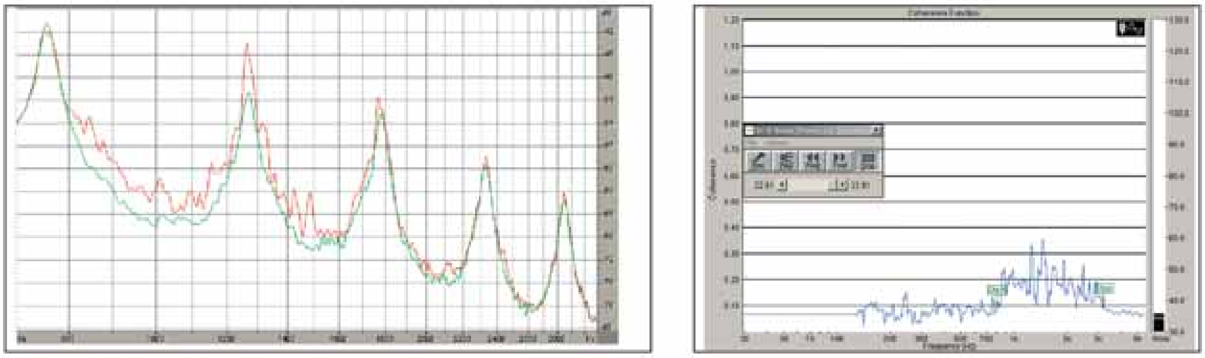

Fig. 9 : Contribution of the test signal to the received signal and coherence function

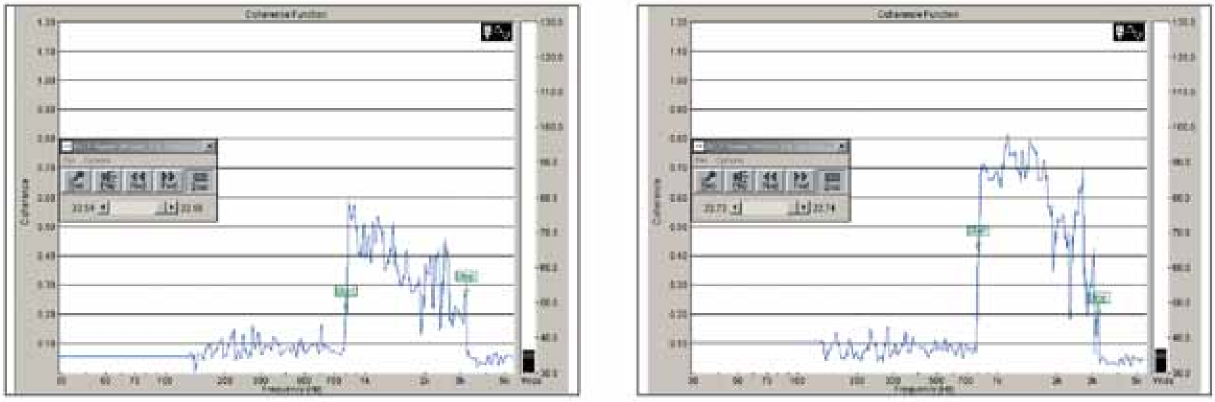

Fig. 10 : Coherence function for the paths 2Æ3 (L) and 2Æ4 (R).

The contribution of the signal against the background noise is documented in Fig. 9 (left), where the peak-hold spectrum (red curve) of a sine sweep in the frequency range 800÷3200 Hz emitted in 1 and received in 2 is reported against the spectrum of the background noise (green curve). The coherence function between emitted and received signal is reported as well in Fig. 9 (right).

The contribution of the excitation in the received signal is hardly distinguishable from the background noise level over 1600 Hz; a 10 dB excess attenuation of the signal between 1 kHz and 3 kHz was estimated, in comparison with measurements performed while the furnace was not operating, and probably caused by additional loss caused by turbulence and gas flow.

The coherence function is very poor all over the frequency range; it improves for the receiver at points 3 and 4, the last one only with emission from point 2 (Fig. 10).

2→3 (L) and 2→4 (R).

The effects of the tracking filter with respect to a 500÷3500 pass-band filter on the signal emitted at point 1 and received in point 2, with a 2 s sweep in the frequency range 800 Hz ÷ 3200 Hz, are illustrated by the sonograms and the Hilbert transforms of the cross-correlation function in Fig. 11.
The tracking filter was effective on noisy signals, but further refinements on the tracking filter quality did not produce any appreciable improvement.

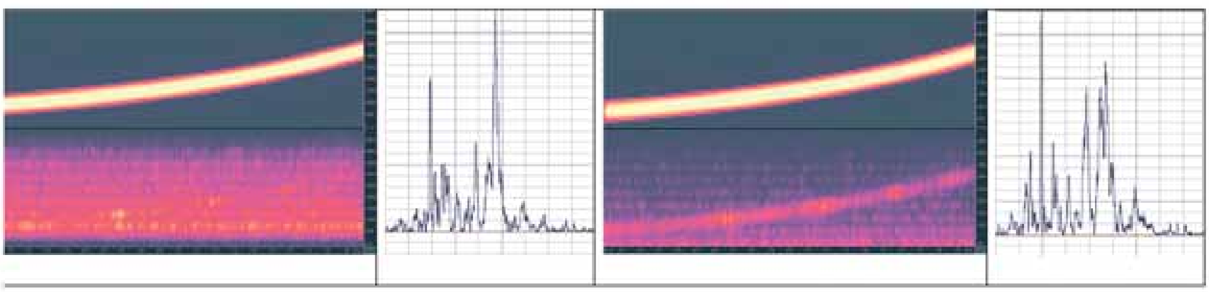

Fig. 11 : Effects of the pass-band (Left) and tracking (Right) filter

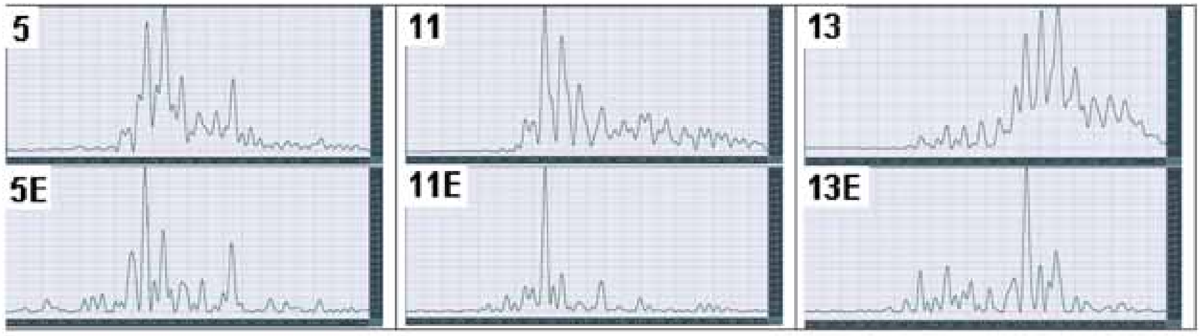

Fig. 12 : Effects of the pass-band (Left) and tracking (Right) filter

Some examples of time delay measurement with the sinusoidal sweep excitation are shown in Fig. 12, with emission from point 2 and receiver at point 1 (path 2→1). The upper diagrams represent the square amplitude of the Hilbert transform of the cross-correlation function; the lower diagrams represent the same results obtained after preliminary "normalization" of the cross-spectrum.

It is clearly observed from these few diagrams that the shape of the Hilbert transform is not repeatable and some results are heavily different from the average value, like the sequence 13 in Fig. 12. This holds true for the generality of the tests carried out so far.
The standard deviation of the time delay on the paths 1→2, 1→4 and 2→1 computed on a sequence of 20 sweeps was equal to 12÷15%; for the paths 1→3 and 2→3 it was equal to 5÷6%; for the paths 2→4 it was equal to 1%. Some of the measurements could be in a 70% error with respect to the average values.
A good post-processing strategy should therefore be adopted for averaging or filtering the raw time delay values. Moreover considerations about the physics of the process and comparison of the results obtained from slightly different approaches (pretrigger or absolute maximum, plain or normalized cross-spectrum) allow for the pre-screening of each new result.

Typical results obtained with the boiler turned-off by means of the tonal burst excitation are illustrated in Fig. 13, where the waveforms of the emitted (upper diagrams) and received (lower diagrams) signals on the path 1→2 and the relevant Hilbert transform of the correlation functions are shown. The effects of reverberation and waveguide resonances are clearly visible in the received signal.

With the boiler in operation, the typical aspect of the waveforms and of the sonograms of the emitted and received signals on the path 1→2 are those of Fig. 14. In the figure the signals are filtered with a 1/3 octave pass-band filter.
Once again, the quality of the results obtained by subsequent bursts can be pretty different from one burst to another. An example is documented in Fig. 15, where the Hilbert transform of the correlation function are illustrated for two distinct sequences of three bursts, with respect to the received signal on the path 2→1.

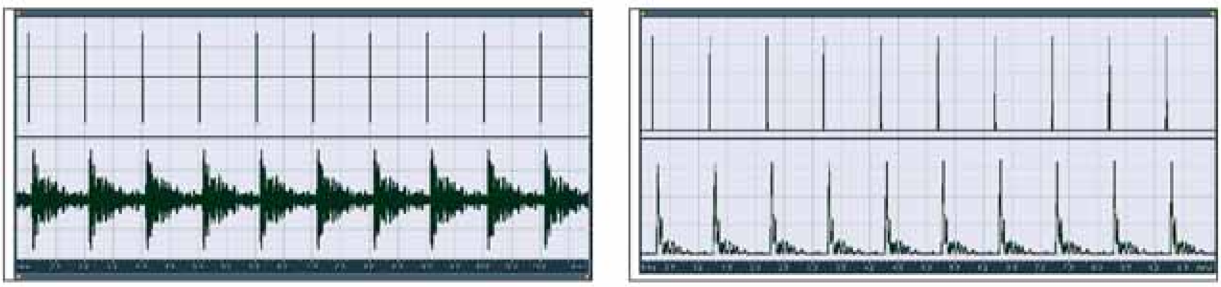

Fig. 13 : Waveforms and Hilbert transforms with tonal burst excitation (boiler turned-off)

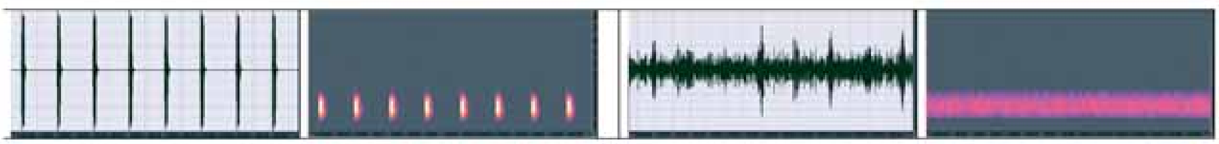

Fig. 14 : Waveforms and sonograms with tonal burst excitation (boiler at full load)

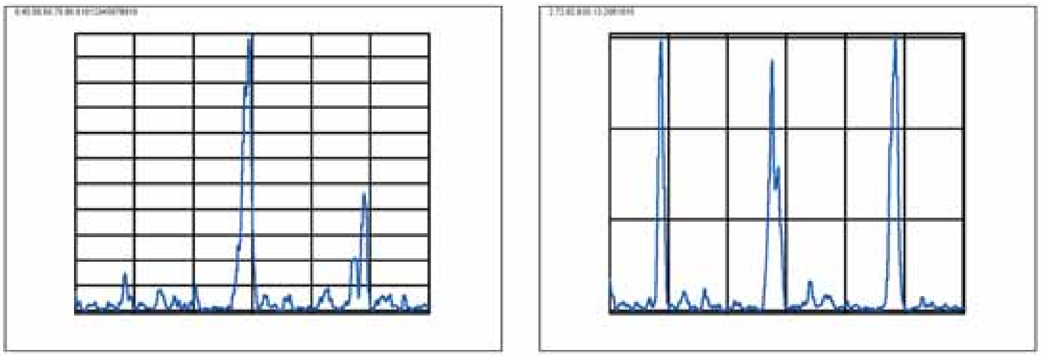

Fig. 15 : Hilbert transforms with tonal burst excitation (boiler at full load)

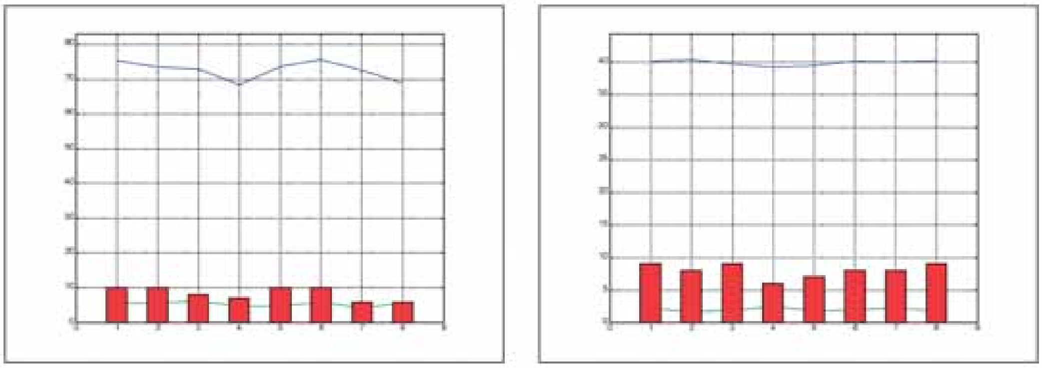

Fig. 16 : Time delays on the paths 2→1 and 2→3 with burst excitation(boiler at full load)

The results obtained in terms of stability of the time delay values for the two paths 2→1 and 2→3 are shown in Fig. 16 by the blue line. These graphics where obtained by selective averages of ten subsequent bursts at a time, all of them belonging to a sequence of 80 bursts.

Conclusions

The paper discussed the measurement of gas temperature in steam boiler of power plants by means of acoustic techniques.
The aim of the research was the updating and enhancement of a pre-existent proprietary system. On one hand, the development of waveguides simple to manufacture and easy to install and to maintain was particularly addressed; on the other hand, the work was focused on the improvement of the excitation and signal processing algorithms so as to arrive at measurements well suited for automatic processing and, therefore, reliable enough for continuous monitoring.
The new design of the emitting horns resulted in low cost and completely non-intrusive probes, well suited for retro-fitting on existing plants and that can be inspected and even disassembled with the plant in normal operation, so as to warrant an easy maintenance.
In parallel, a number of signal analysis algorithms were developed, some of them being completely original. In particular, for the sinusoidal sweep excitation, a real time digital tracking filter was introduced, together with a peculiar weighting of the correlation function and a post processing by the Hilbert transform. Moreover, it was developed an alternative and original method that makes use of short time tonal bursts, with a peculiar data processing.The new solutions were tested on a 660 MW coal fired boiler. The results examined so far confirmed the viability of the new hardware design and the effectiveness of the signal analysis procedures was demonstrated. Nonetheless, the test pointed out that the signal to noise ratio should be further improved and the effects of the acoustic resonances of the new waveguides should be reduced. Further work is in progress to deal with such aspects.
It is then deemed that the major problem is determined by the time variance of the system under measurement. This intrinsic problem can only be relieved by an adequate post-processing of the raw data obtained by the time delay measurements.

Acknowledgments

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