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Phase-locking in post-processing for pulsating flames

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Abstract
A new approach to studying thermo-acoustically driven heat release fluctuations has been developed. By performing a phase correlation of the pulsation signal for each instant in time in post-processing, a number of advantages over the usual online processing technique are obtained: many frequencies can be analysed from the same data set allowing faster recording and introducing fewer errors than performing the phase correlation online. The method does not require complicated trigger and delay line setups and is most flexible. As an example of this technique, two different pulsation modes of a swirl combustor are resolved from only 300 chemiluminescence images. Further use of this method for a wide variety of applications is indicated.

Keywords: combustion instability, pulsation, flame visualization, phase locking

(Some figures in this article are in colour only in the electronic version)

Introduction

The study of thermo-acoustic pulsations has become an important step in the development of lean premix burners. Lean flames are prone to exhibit combustion instabilities; therefore special care has to be taken in the combustor design to avoid and mitigate these pulsations. Since the time–space correlation between heat release and the acoustic field is of crucial importance in this process, phase resolved visualization techniques are typically used in experimental analysis of thermo-acoustic instabilities. Such studies yield crucial information for the design and development of commercial combustors such as in gas turbines. For example by analysing phase-correlated images, different burner variants can be compared, selected and design guidelines for new variants can be deduced as part of the development process.

Phase resolved visualization is an imaging technique in which images are averaged that correspond to a certain phase angle of a trigger signal. Typically an acoustic signal is used as a trigger (e.g., a forcing signal from a loudspeaker or a signal of a microphone that captures the acoustic field). In industrial combustion applications, the local turbulent fluctuations are generally larger than the acoustic amplitudes. Therefore, efficient phase averaging methods are needed in order to visualize acoustic fluctuations by averaging out turbulent contributions.

In this paper, a novel method for phase resolved visualization is presented. This method makes use of Hilbert transforms to extract instantaneous phase angles of the pulsation data. The method is applied in post-processing which has the advantage that several frequency ranges of interest can be analysed from one set of experimental data and no complicated online trigger schemes and delay lines have to be applied. Thus, both the frequency ranges of interest and the phase resolution can be specified in post-processing. An additional advantage of signal treatment in post-processing is that non-causal band-pass filters can be used which avoids any phase distortion. This technique increases the flexibility of the method and simplifies the experiment greatly.

The method has been used in applications such as imaging of chemiluminescence of flames and laser diagnostic methods such as laser induced fluorescence (LIF) and particle imaging velocimetry (PIV). It has even been applied successfully to analyse video images from standard video cameras. It proves especially useful for noisy data signals with multiple dominant spectral components. The method can be applied without the need of forcing a pulsation on the airflow as is often [1–6] done. For the proof of principle, a very simple imaging
method has been chosen. In the present paper, a combustion instability in a test facility has been visualized using OH*-chemiluminescence (CL) as a qualitative measure for heat release. The described effects are sufficiently characterized by the OH*-CL method. Naturally the use of this highly efficient and flexible processing method for more sophisticated methods is recommended and has been applied as well. Results will be presented elsewhere.

This instability was characterized by a superposition of two frequencies: one that corresponds to the first axial mode of the test facility (the 1/4 lambda mode) and one that correspond to the first tangential mode of the circular combustion chamber.

Experimental setup

The tests have been performed in the atmospheric single burner combustion test rig on a full-scale industrial burner as described earlier [6, 7]. Combustor air is electrically preheated, fed into a plenum chamber and flows from there through the (swirl-inducing) burner and the combustion chamber. Natural gas is used as fuel. The thermal power in the experiment was between 400 and 800 kW. The combustion chamber is cylindrical in shape and air-cooled. This setup is not chosen to resemble the gas turbine but rather to produce a fluctuating stagnation point in the flow field. The details of the burner are not essential to the effect described here since the focus is a methodological one. The burner swirl is clockwise in the flow direction. The conditions of the burner are that of a heavy duty gas turbine, which requires a high mass flow (burner velocity) and relatively lean condition (low air-to-fuel ratio). The operating point discussed here however deviates from normal operating conditions by running at slightly higher power.

The normalized spectrum is shown in figure 1. The frequency axis is scaled as a Strouhal number (Sr = frequency (f) × burner diameter (D)/u_{burner}. Since such high amplitudes could damage the test rig, the measurement was limited to less than 1 min. This was enough to produce the results discussed here.

Figure 1. Fourier transformed FFT spectrum of pressure signal. Intensity is plotted as a function of frequency expressed as the Strouhal number. The two most intense peaks refer to Strouhal 0.16 and 1.83. The side wings of the peaks arise from the combination of the two.

Flame images were recorded through the exhaust tube of the rig (figure 2) with an intensified camera operated at 10 Hz. In a 90° elbow piece, the hot gas was separated by a quartz window in front of the camera and a UV filter (DUG11x, Schott) was installed to ensure that only radiation from the OH*-chemiluminescence (~CL indicating heat release from the flame) is detected. The DUG11x filter is advantageous due to its high transparency in the UV. At least for natural gas measurements, it has been shown to exhibit almost identical scaling behaviour to heat release as a narrow band-pass filter around the OH* band at 308 nm, encouraging the interpretation of light intensity (through the DUG11x filter) being related to heat released by the flame. For each measurement point only about 300 images were recorded in less than 1 min, which enabled the experiment to be conducted even at amplitudes which would be destructive to the rig if applied for longer times.

No triggering or delay lines were necessary since the correlation was purely done in post-processing. Any erroneous data or trigger events could therefore be prevented from affecting the quality of the average images. The visualization of two different frequencies from the same raw data just by sorting them into different order ensures absolutely identical conditions for both.

The view angle is chosen in the counter flow direction to investigate nodal planes of the combustor as is shown in figure 3. CL images are actually the projection of a 3D flame onto the 2D image of the camera indicating heat release from the regions where the OH* radical is formed by chemical energy converted into heat and radiation. The heat release is indicated by the OH* emission collected in the UV. At least for the lean regime of a premix flame, the OH*-CL intensity rises monotonically with heat release and therefore resembles heat release at least qualitatively as has been discussed and utilized by many groups [8–13].

It has been pointed out that OH*-CL does not generally measure the heat release [14] but tests under varying conditions have shown that in the range of operating parameters of the burner this relation is given. For our purpose, such qualitative statements are sufficient (although they can also be analysed quantitatively) since we are mostly interested in the time structure of the signal.

The images therefore resemble the heat release integrated along the line of sight in the 2D projection, since the view direction and the mean flow direction are parallel transversal movements which are not directly observable with this setup. Axial movements should however be well observable.
Two water-cooled microphones (one upstream and the other downstream of the burner) have been used to record the acoustic pulsation levels in the combustor. The microphone signals \( p \) are digitized and recorded on a PC with a data acquisition board. Simultaneously, the trigger signals from the camera were recorded. Sample-and-hold hardware and a sufficiently high sampling rate ensured that all signals could be recorded with a high phase accuracy.

**Post-processing**

**Data processing method for off-line phase locking**

The interactions between heat release and the acoustic field have been visualized using the phase resolved imaging technique. More conventional methods of phase locking typically use a band-pass filter, pulse generator and a delay line. The band-pass filter is set to a frequency range that contains some dominant pulsation peak of interest. The filtered microphone signal then triggers a pulse from the pulse generator. The delay line can be adjusted to achieve the desired phase shift of the pulse, which is then sent to the camera or laser. In this way the images have a fixed phase with respect to the microphone signal (or other reference signal), averaging a sequence of images which yields a phase-locked image. Repeating this for a range of phase angles yields a phase-locked sequence that gives a visual representation of the periodic motion at the specific frequency. This method yields good results and has been reported in numerous papers [1]. However, because the phase-locking procedure is performed on-line, only pulsations in one frequency range can be analysed for one experiment. Moreover, the online band-pass filtering operation will inevitably introduce a phase distortion in the pass band, which impairs the quality of the averaging procedure.

The newly developed method makes use of the recorded and stored time traces of the acoustic signal and the camera (or laser) trigger signal. To do so, a band-passed Hilbert transform of the microphone signal is calculated. The phase of this complex-valued time trace represents the instantaneous phase of the acoustic signal within the frequency band of interest. Because the filtering procedure is done off-line, zero-phase distortion can be achieved for the band-pass filtering operation. The time instants at which each image is recorded are known because the trigger signal of the camera has been recorded; thus since the instantaneous phase is also known as a function of time, each image can be assigned an instantaneous phase for one (or more) frequency bands. Then the range of phases is divided into a number of equally spaced intervals; all images corresponding to a certain range of phase angles are then averaged. Finally, the sequence of averaged images for each phase interval yields the phase-locked recording.

**Assignments of phase angles by use of the Hilbert transform**

\[ t_p = \{0, \, dt, \, 2dt, \ldots, \, (N - 1) \, dt\} \]
\[ p(t_p) = \{p_1, \, p_2, \ldots, \, p_N\} \]
\[ t_i = \{t_1, \, t_2, \ldots, \, t_K\} \]
\[ z(t_p) = \{z_1, \, z_2, \ldots, \, z_N\} \]
\[ I(t_i) = \{I_1, \, I_2, \ldots, \, I_K\}. \]

The reference signal \( p(t) \) is sampled at a fixed frequency \( 1/dt \). The sampling frequency should be chosen such that it is larger than twice the highest frequency component in \( p(t) \). In our application, the reference signal is taken from a wall-mounted microphone in the combustion chamber. The recorded intensity images, \( I_k \), do not necessarily have to be sampled at a fixed frequency; neither do they have to be recorded at a minimal sampling frequency. However, the exposure time of the image should be smaller than one divided by the maximum frequency of interest. In practical applications, the number of recorded images \( K \) is much smaller than the length of the acquired pressure trace \( N \). This is because the recording speed of the camera limits the time interval between two successive images and is thus much larger than the sampling period of the reference signal \( dt \).

The trigger signal is recorded simultaneously with the reference (microphone signal). This signal has the logic value 1 at the time instants where an image is taken, and is otherwise zero. Note that the time instants in \( t_i \) are not necessarily integer multiples of the sampling period \( dt \). However \( dt \) is chosen sufficiently small so that by approximation \( z = 1 \) if \( t_p(n) = t_i(k) \).

The pressure signal typically consists of one or more dominant frequency components plus a background noise (figure 5). The intensity images of the flame are assumed to have similar underlying dynamics. The aim of the analysis presented here is to extract motion and intensity variation of the flame corresponding to one (or more) of the dominant frequency components. The idea is to apply a conditional averaging of the images: the average of images that corresponds to a certain phase-angle range is taken (figure 4).

This procedure is repeated for a number of phase ranges and possibly for more frequencies. A sequence of these phase-averaged images can then be interpreted as a ‘movie’ of the flame corresponding to the motion at the specified frequency.

The most crucial step in the analysis is to determine to what phase of the periodic motion the image corresponds. For
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**Figure 4.** Upper graph: pressure amplitudes plotted in red against phase angle from the Hilbert transform for the pulsation at Strouhal $= 1.8$. The black trace indicates amplitudes of the filtered signal. A clear sinusoidal distribution is visible. Lower graph: number of images of each of the 12 groups of phase angles for which the averaging has taken place. Averages over the 12 bins are plotted and coincide with the filtered trace. The deviation of the red unfiltered pressure traces from the pure sine wave indicates turbulent noise but also fluctuations to other frequencies such as $S_r = 0.16$.

**Figure 5.** Real time signal (blue) and signal filtered for the occurring frequencies in multiples of the highest frequency at $S_r = 1.8$. The coloured traces are filtered signals referring to $S_r = 0.16$ (red), $S_r = 0.42$ (green) and $S_r = 1.8$ (black).

For a given frequency band, the phase at every instant of time will be determined from the reference signal (the pressure trace) by using a method similar to the Hilbert transform.

The Hilbert transform of a signal is a time-varying complex quantity of which the real part is equal to the original signal, and the imaginary part is a $90^\circ$ phase shifted version of the original signal. The Hilbert transform has an interpretation (for quasi-monochrome signals) of instantaneous amplitude, phase and frequency if respectively the modulus, argument or the time derivative of the argument of the complex quantity is taken. The instantaneous phase is of specific interest in the context presented here: once the phase of the reference signal is known for the instant of time where an image was taken, then all images corresponding to a specific phase (range) can be averaged to obtain the phase averaged pictures.

The Hilbert transform can be computed by taking the Fourier transform, setting all frequency components with
frequencies larger than the Nyquist frequency $f_{QN} = \frac{1}{2T}$ to zero, and then applying the inverse Fourier transform:

$$C(t_p) = F^{-1}\{F\{p(t_p)\}H(f_{QN} - f)\},$$

(2)

where $F$ represents the Fourier transform operation and $H$ is the Heaviside function: it is zero for values smaller than zero and one for values larger than zero.

The instantaneous phase only has a meaningful physical interpretation if only one dominant frequency component is present in the signal. However, a typical pressure signal will consist of multiple dominant frequencies. Therefore a band-pass filtering operation is applied to the reference signal that filters out all frequencies except a small frequency range of interest. When applying a band-pass filter, care has to be taken for phase distortion. A perfect band-pass filter without phase distortion can only be realized off-line in post-processing. One way of doing this is by taking the Fourier transform of the signal, then setting all frequencies outside the frequency band of interest to zero, and then taking the inverse Fourier transform.

Note that these methods of band-pass filtering both involve the same steps: taking the Fourier transform, setting a range of frequency components to zero and applying an inverse Fourier transform.

The filtering operation and Hilbert transform can therefore be combined into one operation. Defining the frequency that is to be analysed as $f_{Q}$ and using a bandwidth of $df$, the complex valued, band limited Hilbert transform of the signal is given as

$$C(t_p) = F^{-1}\{F\{p(t_p)\}H(f_q - f_{Q} + df)H(f_q + df - f_{Q})\},$$

(3)

**Phase averaging**

The argument of this quantity is the instantaneous phase of the components of the signal within the selected frequency band. So, in this way, each image corresponds to a certain phase $\phi = \omega t$. Dividing the range of phases into $M$ intervals of width $\pi M$, all images that correspond to a specific phase interval will be selected and averaged:

$$\bar{I}_m = \langle I \rangle_{\langle \omega t \rangle M - \pi/2 < \omega t < \pi/2}/M$$

(4)

where $\bar{I}_m$ is the $m$th phase-averaged image and $\langle \cdot \rangle$ denotes the conditional averaging operator (the arithmetic mean is used here), in which the condition is that the phase should satisfy the specified phase range. Now all $M$ phase averaged images are displayed as a sequence, which represents the flame motion at the specified frequency. The averaging operation can easily be extended to include a condition on, e.g. the amplitude of oscillations (the absolute value of $C$).

**Visualization of acoustic sources**

The source of acoustic intensity is (for low Mach number flow) given by the divergence of its flux: $F = \nabla \cdot (p' u')$, which can be written for small gradients of pressure fluctuations as $F = p' \nabla \cdot (u')$. In the case of combustion, the strongest source of volume expansion is the heat release; hence the acoustic flux is proportional to the product of pressure and heat release $p' Q'$. The heat release–pressure correlation integral—often called the Rayleigh integral—is frequently used in analysis of thermo-acoustic systems [15–17] because it is a measure of the spatial–temporal correlation between pressure and heat release.

If the chemiluminescence’s intensity can be considered as being proportional to the heat release, then a graphical representation of the energy source can be obtained by phase-averaging the product of the pressure fluctuation and the intensity fluctuations:

$$R(x, y) = \langle p'(\phi) I'(\phi, x, y) \rangle.$$  

(5)

It has to be noted that the two-dimensional image is actually a projection of a three-dimensional property on the camera image.

$$R(x, y) = \int R(x, y, z) \, dz$$

$$= \int \langle p'(\phi, x, y, z) I'(\phi, x, y, z) \rangle \, dz.$$  

(6)

The three-dimensional pressure field is difficult to obtain and can in this example only be deduced from the single measurement located in the combustor liner. For the low frequency pulsation, the mode shape is very uniform and well described by the single microphone measurement. For the high frequency mode ($Sr = 1.8$) however the mode shape of the acoustic mode has several nodal planes with varying sign and intensities.

Note that such a presentation is closely related to the Rayleigh criterion for combustion instability [18, 19] because it visualizes where heat release and pressure are in phase, and hence drives the instability. The presentation of the heat release–pressure correlation plot as the Rayleigh plot for the high frequency mode is however not straightforward.

Once the phase relation for each image has been obtained, such quantities are readily obtained in several ways as is shown in figures 9–11 where this quantity is plotted. The red colour represents regions where the instability is enhanced while the blue colour refers to regions where damping occurs. Note that an average through the combustor in the axial direction is observed and regions of different signs might cancel along the line of sight.

The heat release–pressure correlation plot can be obtained in several ways. In the standard procedure [17], each heat release measurement (pixel intensity) is multiplied with each unfiltered pressure signal including all frequencies and noise sources. However, the filtered microphone signal can also be used to obtain the phase relation referring to a selected frequency band allowing one plot to be obtained for each frequency band. A plot similar to the latter is also obtained by multiplying the phase angle with the averaged images (figures 6 and 7) for each frequency.

The Rayleigh index (indicating damping or driving an instability) can be defined for each point in space from the fluctuations of heat release distribution and the pressure distribution. For low frequencies and long wavelengths (like $Sr 0.16$ in this example), the pressure distribution can be assumed to be uniform over the whole image, while for high frequencies the pressure distribution is expected to be more complex (exhibiting nodal planes, for example). This has to be considered in the interpretation of the heat release–pressure correlation plots.
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Figure 6. Phase averaged images locked to frequency $Sr = 0.16$. The intensities are not shown but rather the fluctuations with respect to the average image over all images (phases). Blue stands for the negative deviation from the mean and red for the positive deviation. White represents similar values.

Figure 7. Phase averaged images locked to the frequency $Sr = 1.8$.

Results

The data shown here were recorded in about 1 min, while using the current technology would have taken more than 20–40 min for each frequency. Since the level of amplitude was too high to be maintained longer in the rig, this method proved the only way to visualize the modes.

In figures 6 and 7, the phase-averaged images are shown as a sequence as a function of phase angle. Figure 6 was obtained by choosing a frequency band for phase-locking that corresponds to the first dominant peak at about $Sr = 0.15–0.2$ in the pulsation spectrum shown in figure 1. Figure 7 corresponds to the second peak at about $Sr = 1.8$. The amplitude of the heat release fluctuation is up to 20% of the mean (figure 8).

Both images show clear phase dependence. The spatial pattern for the two images is very different. The first mode shows very little dependence on the azimuthal angle, whereas the intensity of the second image shows a rotation in time around the axis. This observation corresponds to acoustic characterization of the test facility in previous work: the lowest frequency corresponds to the first longitudinal acoustic mode and the second is close to the first tangential mode. The longitudinal mode is a quarter-wave mode with a pressure antinode close to the flame location and a pressure node close to the (open) exit. The tangential mode consists of a superposition of two half-wave modes: one with vertical motion and the other with horizontal motion.

The intensity in figure 6 evolves with phase as a series of concentric rings. This indicates that the axial location of maximum fluctuating heat release oscillates periodically in the axial direction. Since the shape of the flame is roughly conical, this axial motion is seen as a series of concentric rings that increase and decrease in diameter.

The Rayleigh plots in figures 10 (left) and 11 (left) indicate that the flame being central contributes most to the driving mechanism of this pulsation. Note that this plot could not have been produced with the conventional technique [15, 17] as shown in figure 9.

The pattern of heat release in figure 7 corresponds to the first tangential acoustic mode. Because of the symmetry two modes exist for the same frequency. The two modes have a similar pattern, but one is rotated 90° with respect to the other. In [20] it was demonstrated that if such a mode is unstable, the...
two degenerate modes will couple due to nonlinearities, and will inevitably cause a rotating mode shape. The speed of such a rotation is predicted to be equal to the speed of sound (or an integer multiple of it). This corresponds to one revolution per period and that matches with the results shown in figure 7.

The change of sign in the plot on the heat release–pressure correlation plot on the right-hand side of figures 10 and 11 (for high Sr) refers not to change in the actual Rayleigh criterion for this region but rather to a change of sign in the pressure distribution for the corresponding mode. The observed nodal plane originates from the node in the pressure field, which is recorded only at one point near the left side of the image where the correlation is positive. This behaviour seems to dominate over the correlation with the low Sr as is seen by comparison with the unfiltered Rayleigh plot in figure 9. The heat release maximum rotates clockwise in the flow direction and therefore in the same direction as the mean swirl.

Conclusions

A method to correlate flame images in a post-processing step has been developed by Alstom and its use has been demonstrated for OH*–chemiluminescence images in a swirl combustor. The novelty of the method is that it uses the pulsation signal time trace before and after a trigger event and makes use of properties of the Hilbert transform to avoid phase distortion. It was possible to resolve two different thermo-acoustic pulsation modes (an axial and a transversal) from the same data set (recorded at low repetition rate in less than one minute). The transversal mode is actually a combination of two degenerate transversal modes rotating in the swirl direction. From the phase correlated data, heat release–pressure correlation plots for the two frequencies could be obtained. To increase the data quality for cases where more than one mode is active, a weight can be assigned from the frequency analysis to focus on the predominant mode at that instant. The experimental results shown in this paper are an example of an application of the newly developed method. The method has been applied to a wide variety of other applications including simple video images and particle imaging velocimetry (PIV). These results will be the topic of subsequent publications.

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References

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Figure 10. Rayleigh plot from filtered pressure function locked to frequency Sr = 0.16 (left) and Sr = 1.8 (right).

Figure 11. Rayleigh plot from phase averaged images locked to the frequency Sr = 0.16 (left) and Sr = 1.8 (right) using an idealized cosine function for the pressure.