Diagnostics of Combustion Instabilities through Frequency Analysis of High-Speed-LIF Image Sequences

by

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ABSTRACT

Pressure oscillations, so called humming, induced by thermoacoustic combustion instabilities, occurring in connection with swirl stabilized lean premixed burners, are one of the main limiting factors for the maximum power and the lifetime of gas turbines. In worst case, humming can lead to instantaneous destroyment of the engine through combustion chamber wall destruction and subsequent deblading of the turbine.

In order to get basic information about the chain of reasons for those instabilities a method was searched to visualize both, the spatially and timely resolved flame structure as well as its time dependent displacements. As the PLIF method is able to visualize the first item, its application with high pulse and frame repetition rates enables to deliver the wanted information about the resonant flame front oscillations.

This technique was in-situ applied to a 260MW stationary gas-turbine at the Seabank Power Station in Bristol (UK).

However, applied in an environment of a high pressure combustor, the high speed PLIF technique has its constraints regarding the obviousness of information. Therefore the experimental output (image sequences) were subsequently processed using tools of digital signal processing. It has been found that spatially resolved Fourier Transformation in the time domain is a useful tool in extracting the wanted information from the PLIF “movies”, that is the frequency dependent flame front motions.

INTRODUCTION

Humming in turbomachinery is easy to detect and measure by sampling a timely resolved pressure signal. It is far more difficult to obtain experimental evidence and data of the combustion instabilities held responsible for the formation of humming and its resonant amplification. See [6] for a detailed model of a closed loop interaction between equivalence ratio and pressure, respectively flame heat release, as oscillation driving mechanism.

Pressure oscillations don't take place in current numerical simulation of gas turbine combustion. Therefore experimental data on timely and spatially resolved flame structure is needed to improve numerical simulation and to gain a better understanding of the processes involved. The overall aim is to identify the ultimate causes of those instabilities in order to avoid them as much as possible. Since this is highly specific to the type and construction of the combustor and combustion chamber, transferability of results from the lab [7] is very restricted. Thus the effort of direct flame visualization inside a stationary gas turbine was made.

The task is to extract information on flame structure from a high pressure and high temperature burning chamber of a stationary gas turbine with a thermal power of almost 700MW. The first step towards this goal was the development of the experimental setup for high speed PLIF and its application in the gas turbine environment. This setup includes, among other things, an excimer laser, a high speed image intensified camera and optical components, none of which was ever intended to operate in a power station environment. A trigger regime had to be established to synchronize frame taking with the pressure oscillations. Many modifications on the gas turbine had to be made to gain optical access to the burning chamber and to protect the technical components from the heat. The detailed description of the experimental work is beyond the scope of this paper.

This paper focusses on the following step, the evaluation of the experimental raw data, which do not abandon the wanted information at first sight. However, if the image data are of the digital type, the information can be extracted by applying digital signal processing tools. The experimental output comprised a huge quantity of data. Therefore a parallel mainframe was needed for doing the DSP computations.

EXPERIMENTAL SETUP

The in-situ application of PLIF in a stationary gas turbine requires a great deal of technical effort to be made. PLIF is a technique in which narrow banded laser light is used to excite energy transitions highly specific to certain species of atoms or molecules. For a detailed description of the field of LIF-diagnostics on premixed hydrocarbon flames see [1], [2]. With a wavelength of 248nm excitation of OH-radicals and O_2-molecules takes place. See [3], [4] for a detailed description of the transitions involved. The corresponding re-transitions to the electrical ground state emits light of certain discrete wavelength and can therefore be detected to visualize the concentration of OH and O_2 in the area of interest.

Diagnostic setup consists of three major components. The first one is the optical excitation system with a KrF excimer laser operating a 248nm wavelength. The laser light is formed into a lightsheet, for the purpose of spatially resolved LIF data [5], and guided to the area of interest inside the combustion chamber by several optical components. There is a water cooled laser probe included in the optical path. This provides the access to the burning chamber. The probe also contains the feeding for the CO_2-cooling of the laser exit window. The whole system, which is illustrated in fig.1, is triggered externally and operates at repetition rates up to 200Hz.

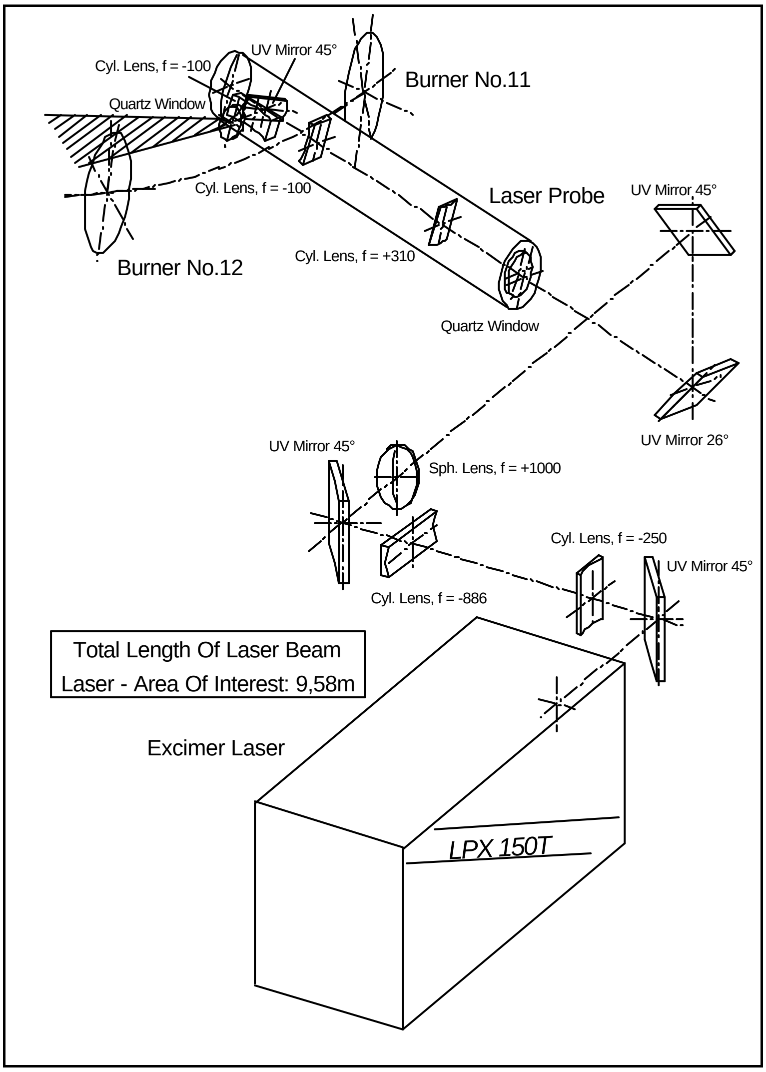


Fig.1: Optical Setup of Excitation Laser Beam

The second major component is the detection system for the induced fluorescence. It consists mainly of a high speed, image intensified CCD camera, a frame grabbing computer and optical filters. Beyond that many modifications on the turbine had to be made to establish a camera viewfield with a direction to the area of interest, that is, as much as possible, orthogonal to the laser lightsheet. Intensive cooling is a must in order to protect optical components from destruction and to gain a reasonable signal-noise ratio in the image data. Details on the point and field of view of the camera are given in fig.2. In the upper part of fig.2 the burner is shown from its back view, that is the opposite direction as viewing it from inside the combustion chamber. The laser probe is indicated at its position where it protrudes through the wall of the combustion chamber. The laser lightsheet is tilted 13 degrees against the connection from the center of the burner and the laser probe. The camera is viewing the lightsheet from below, 20 degrees off from the perpendicular viewing direction. In the lower part the configuration is shown in its vertical section from the cameras point of view below the burner. The laser probe is tilted 6 degrees against the burners middle axis. The lightsheet was slightly divergent in its direction of thickness, but inside the imaged area the thickness was at maximum 3mm. This can be neglected because the camera is performing a line of sight integration in that direction. The focal line of the lightsheet is indicated in fig.2.

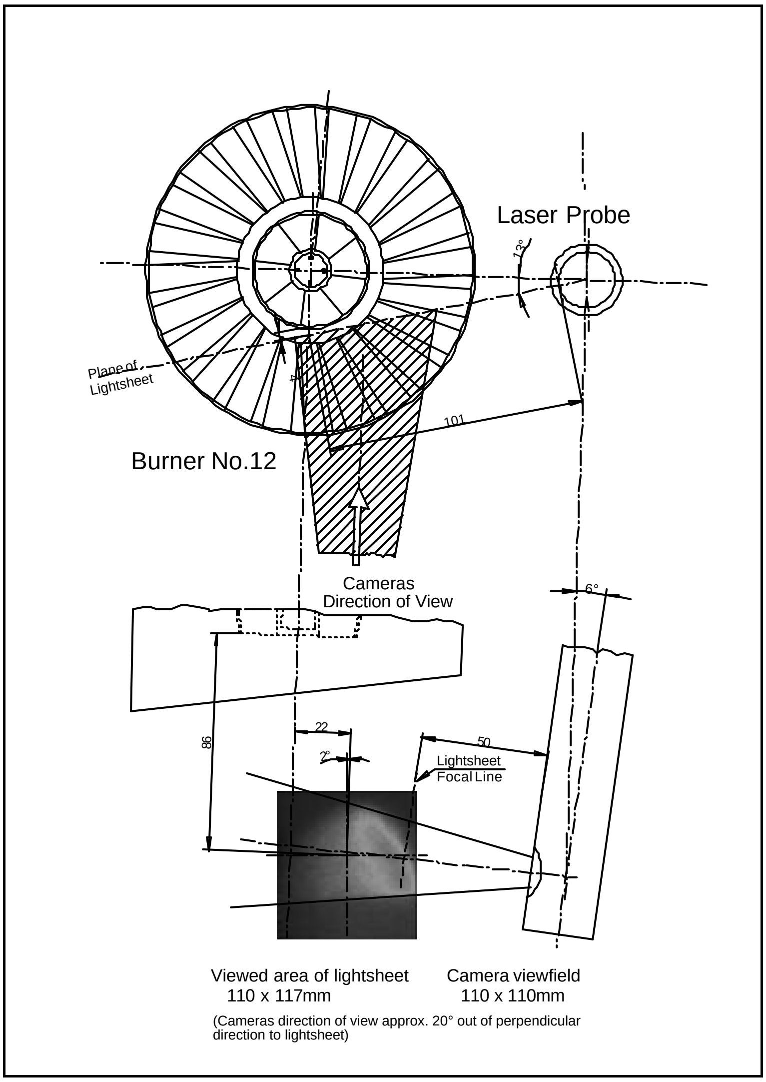


Fig.2: Position of lightsheet and cameras field and direction of view inside the combustion chamber of the gas turbine

The whole configuration was set up to visualize a part of the diffusion flame area on the left hand side of the video images and a part of the premixed zone on the right hand side. The triggering of this image acquisition system is tuned to the excimer laser.

The third component is the trigger regime. It uses data from the humming detection system to synchronize the image acquisition to the frequency of the resonant combustion instability. The turbine provides pressure sensors close to the burning chamber. The analog signal was captured at a sampling rate of 10kHz and the main humming frequency was detected using online FFT. This frequency, with an additional offset of a few percent, was used to trigger the PLIF system. Off-tuning the trigger frequency with respect to the main humming frequency results in the effect of a stroboscopic visualization of the LIF signal structure. Therefore in the resulting video the flame instabilities, which are assumed to be periodical with the frequency of humming, occur at the beat of frame rate and humming, that is the given offset.

This mode of operation is possible, because the gate time of the camera is very short in comparison to 1/framerate, and it is necessary, because the frequency of humming and the maximum repetition rate of the PLIF system are of the same order of magnitude. With 200Hz image acquisition rate one can only see periodic processes up to 100Hz directly in the resulting video and the resolution in time would be very poor. By adapting the frame rate to the frequency of humming one can avoid this disadvantages, paying the price of loosing the original frequency of humming in the video.

DIGITAL SIGNAL PROCESSING

Viewing the obtained data one can hardly recognize the periodic processes that have been expected. This has several causes. Due to the turbulent flow in the area of interest a part of the observed LIF signal comes from a wild mix of density distributions which are completely stochastical in time and place. Another part of the observed signal comes from periodic processes which run on scales of length beyond the dimensions of the lightsheet, since the sheet and the field of view cover only a fraction of the burners flame cross section. Furthermore LIF signal intensity depends not only on the local concentrations of OH respectively O_2, but also on laser intensity, which can also vary. The obtained LIF videos show the overall superposition of these effects and therefore the flame instabilities, which are frequency linked to the humming, are not very prominent in the unprocessed video.

Applying statistical analysis techniques, such as averaging or forming standard deviations, one gets only static information on the flame behavior in time. In order to get dynamic information one has to think of methods to suppress the unwanted parts from the signal so that the effects corresponding to the humming outcrop more clearly.

It was found that the Fourier-Analysis is a suitable method for the analysis of videos that are assumed to contain periodic processes. The basic technique used in this method is to extract the discrete pixel intensity function of each pixel from the video. This is done by transposing a matrix given by pixel and frame number. The resulting set of data contains n functions with m discrete values, where n is the number of pixel in one frame and m is the number of frames in a video. Each of these functions can be transformed to the frequency domain by applying a Fast Fourier Transformation. Assuming the oscillations to be stable in frequency during each measurement one can get a high resolution in frequency by using only few statistical degrees of freedom. Some attempts to use Wavelet-techniques on the data have also been made. At first sight there were no new results, but this is subject to future work.

In a first step one can view the envelope spectrum of all pixel spectra. This envelope spectrum shows any oscillation in intensity independent of its localization and size, as long as it has a significant magnitude with respect to the background noise.

In a second step one can compute frequency selective images, that is the amplitude of a prominent oscillation from the envelope spectrum plotted as density plot. The images are of the same size as the original video and they show the spatially resolved magnitude of oscillation at a given frequency, or, to be more precise, the mean magnitude within a given frequency band.

The third approach in analysis of the data is to apply a digital band pass filter on a video for the purpose of extracting the spatial dynamics of the given oscillations. This is a very suitable method for overcoming the problems described at the beginning of this chapter.

RESULTS AND DISCUSSION

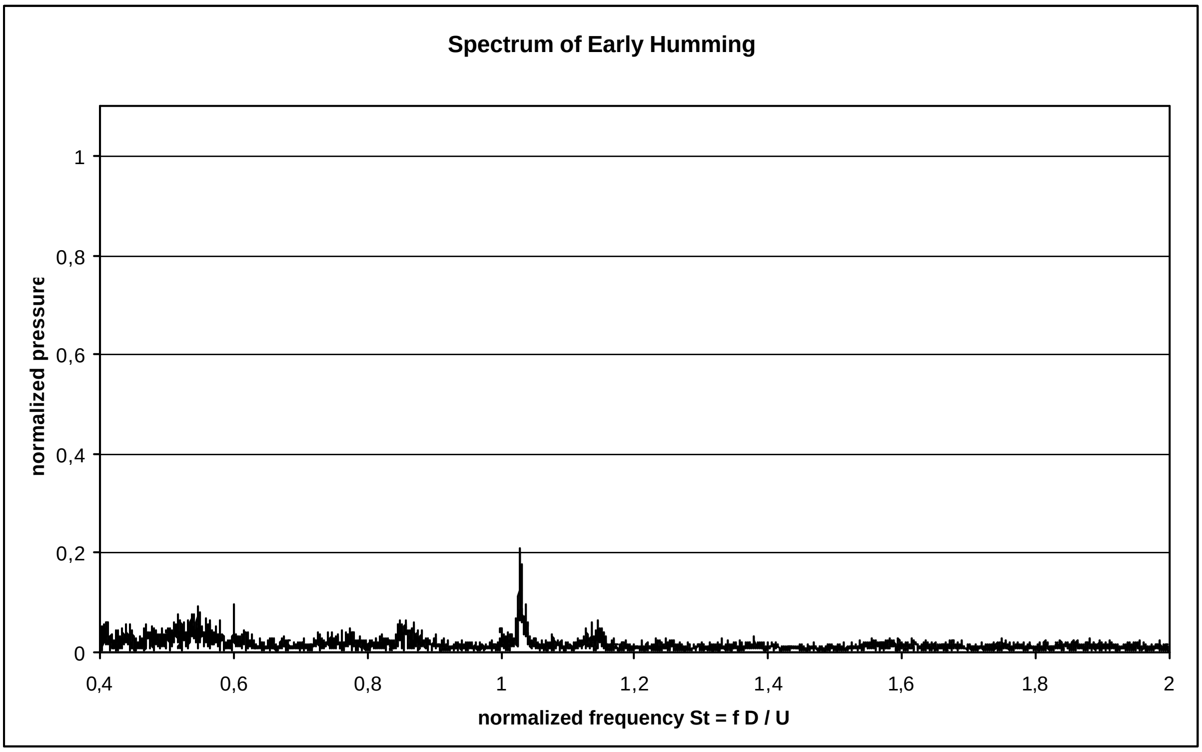


Fig.3a: FFT-Spectrum of a digitally sampled pressure signal. Humming is just originating at St ~ 1,03. Samplerate was 10kHz.

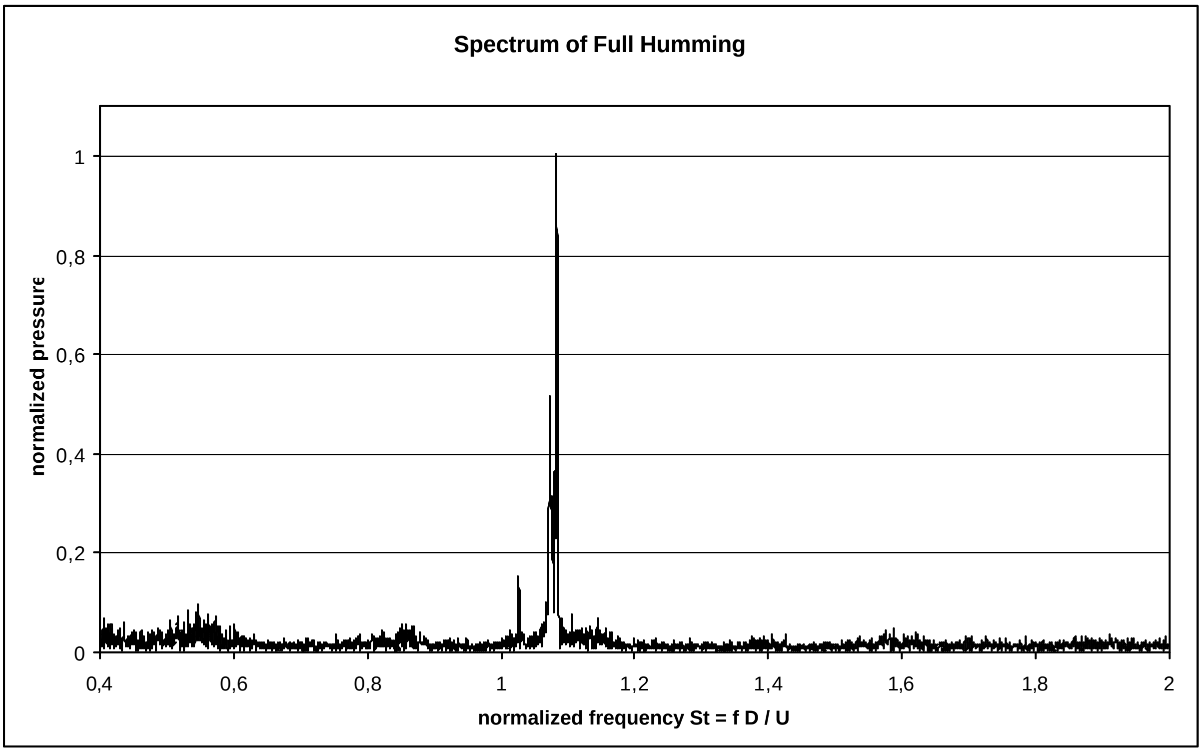


Fig.3b: FFT-Spectrum of a digitally sampled pressure signal. Humming is fully distinct at St ~ 1,08. Samplerate was 10kHz.

Fig.3 shows two spectra of the humming detector pressure signal, taken with a intermission of 142s. The spectra were obtained using FFT on digitally sampled data at a rate of 10kHz. The pressure amplitude is scaled to 1 for the maximum amplitude in fig.3b. The frequency on the x axis is given by means of Strouhal number St = f D/U, where f is the frequency, D is the effective diameter of the burner and U is the flow velocity. The first spectrum shows the humming as it is just about to come into existence, while the second one shows it fully distinct. The mean frequency of the pressure oscillations is shifting with their amplitude, which indicates a closed loop interaction between pressure and flame might be the cause for the formation of the instabilities. Apart from that the early stages in the formation of humming are of a particular interest for the understanding of the mechanism.

As stated above the assumption of a closed loop interaction between pressure and flame can explain the measured frequency shift. Starting with an instability in the flame and thus heat release, an instability in pressure is the cause. One can assume this process to be stochastical in the beginning. Pressure instabilities will be reflected within the burning chamber and travel backwards to the inlet ducts, where they cause fluctuation in stochiometry. These fluctuations on their part cause fluctuations in the heat release of the flame and thus closing the loop. This oscillating system has resonant frequencies, and the shift in frequency in combination with the dramatic rise in amplitude is the typical behavior for a coupled resonant oscillation.

At the time the measurement depicted in fig.3a was taken corresponding flame visualization data is available. Unfortunately video data could not be gathered during the fully distinct humming shown in fig.3b, because the gap between the two measurements was to short. Concerning fig.3a the corresponding video consists of 983 frames. Fig.4 shows the standard statistics of this video.

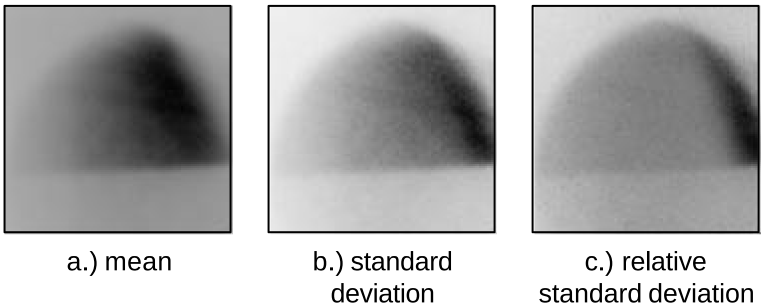


Fig.4: Standard statistics of early humming flame visualization video

The statistic pictures of this video are scaled to maximum 8bit dynamic each. Therefore comparison in magnitude is not possible. What can be seen in this pictures is the general structure of the video regarding the borders of the cameras field of view and the assumed flame structure in the plane of the lightsheet. Fig.5 depicts more detailed information on that topic. The boundaries of the resulting visible area of flame are given by lightsheet borders at the top and the bottom. The pressure housing window limits the visible area on the right hand side while the combustion chamber window is the limit to the left. Both windows are of the same size, but they occur with different diameters in the picture because of their different distance to the cameras lens. Taking the mechanical construction of the optical setup into account there is good reason to assume the left hand side of the visible area to be in the diffusion flame area of the burner, while the right hand side depicts a sectioning of the premixed area. In between there is an intermediate boundary area.

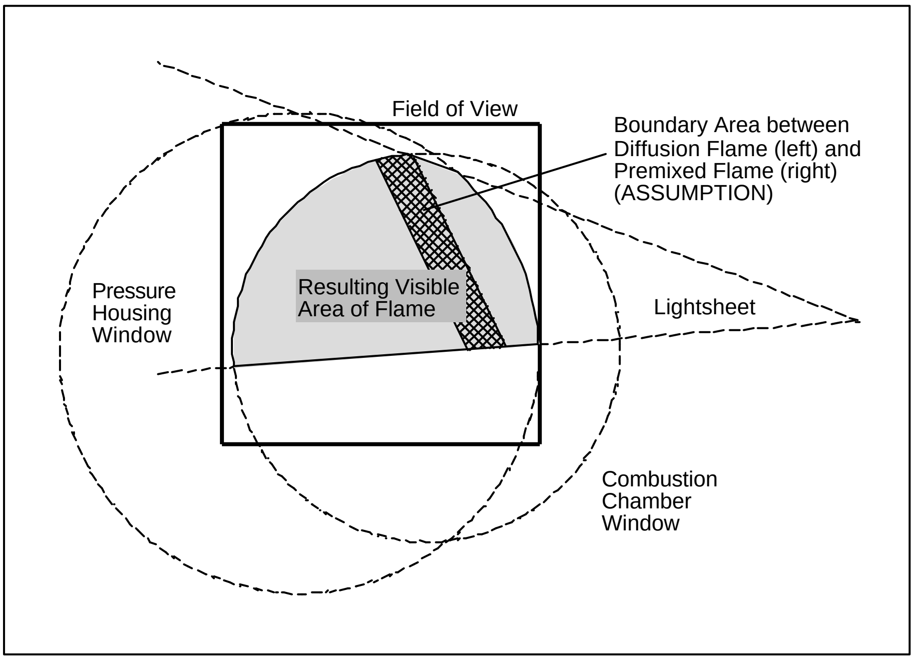


Fig.5: General structure of LIF-videos regarding borders and area of flame

In the unprocessed LIF-videos periodic processes could not be seen. Therefore FFT calculations were applied on the video data. Fig.6 shows the intensity spectra from the video corresponding to the beginning of humming described above. Two plots are given for comparison. The first one a.) shows the spectrum of the mean intensity, while the second one b.) depicts the envelope spectrum. From the difference one can clearly see that there are additional oscillations in the video, which are necessarily localized. Otherwise they would also occur in the mean intensity spectrum a.). There are two additional peaks in the spectra. Both of them can be lead back to power line frequency. Both plots are scaled to 1 for their maximum amplitude, but magnitude comparison is possible by taking the two additional peaks into account.

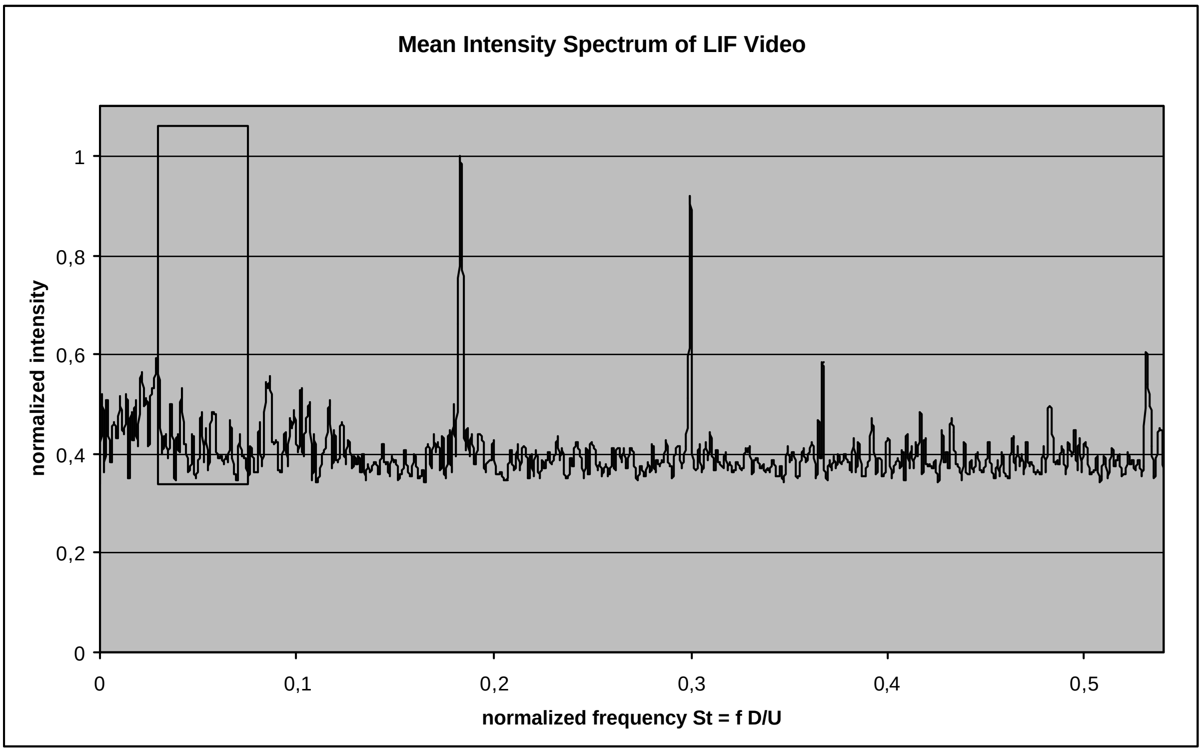


Fig.6a.: Mean intensity spectrum of video data corresponding to the time of originating humming

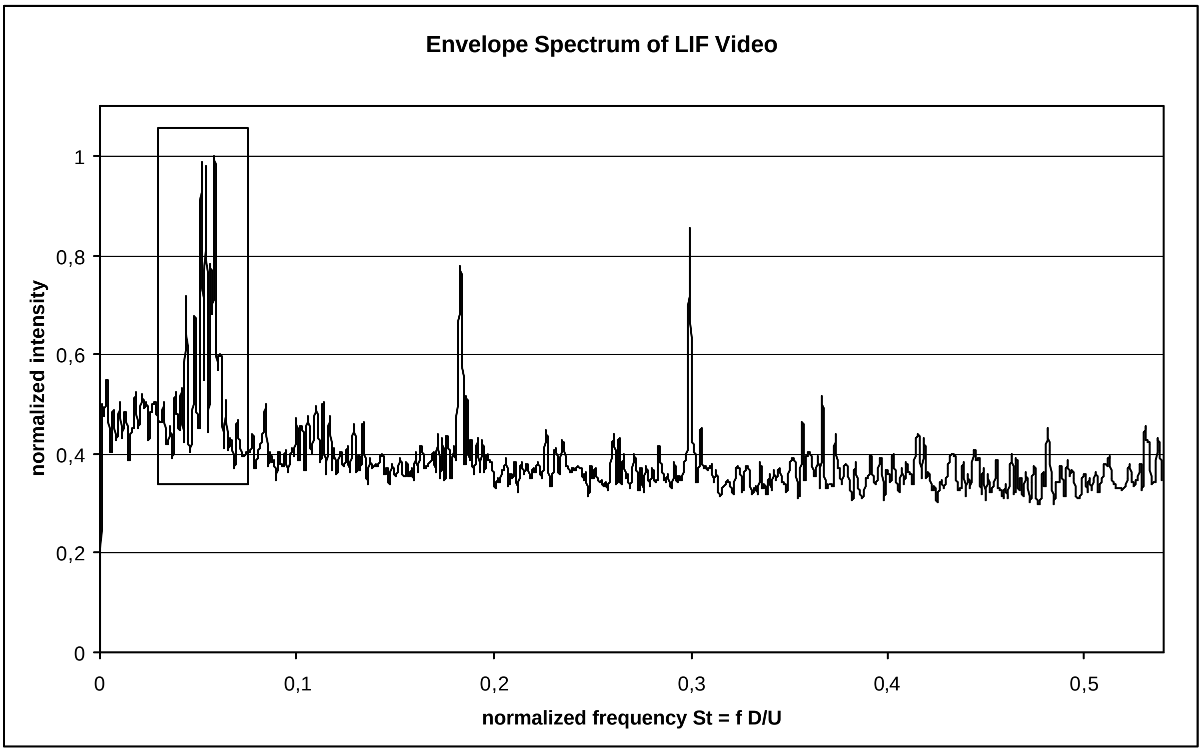
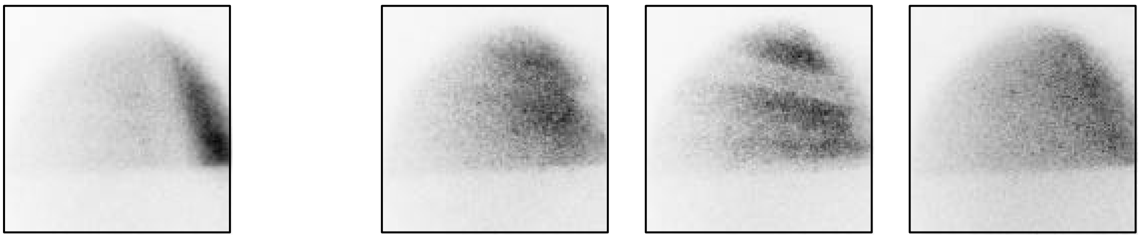


Fig.6b.: Envelope intensity spectrum of video data corresponding to the time of originating humming

The next task is to determine the localization of the periodic processes. For this purpose frequency selective pictures were computed for each of the major peaks in the envelope spectrum. The results are given in fig.7.



St = 0,054 corresponds to frequency of humming

St = 0,18 corresponds to PLF

St = 0,30 corresponds to PLF

St = 0,528

Fig.7: Frequency selective pictures of video data

In the frequency selective plots each pixel shows the magnitude of oscillation at the given frequency. It can be seen clearly that the humming frequency oscillations are localized to the area of premixed flame. Three more plots are given for comparison they correspond to the major frequency peaks in fig.6. The localization of the humming oscillations is very similar to the relative standard deviation in fig.4. Combining this information one can state that the main part of the dynamic processes in the LIF-video relate to the humming. The magnitude of the humming frequency in the envelope spectrum is an additional prove for this statement.

For the purpose of resolving the dynamic behavior of the oscillating area in more detail a digital band pass filtering was applied on the video data. This method consists of the following three steps. First step is to compute a FFT on each pixel of the video. Second is to mask the set of data to eliminate the unwanted parts of the spectrum. The last step is to calculate the inverse FFT on that data to regain the time domain data. This method has no influence on the phase spectrum of the video data. What comes out is a video where the oscillations of a given frequency band are clearly depicted. For presentation in a paper one period of oscillation was extracted from the resulting video. It is shown in fig.8.

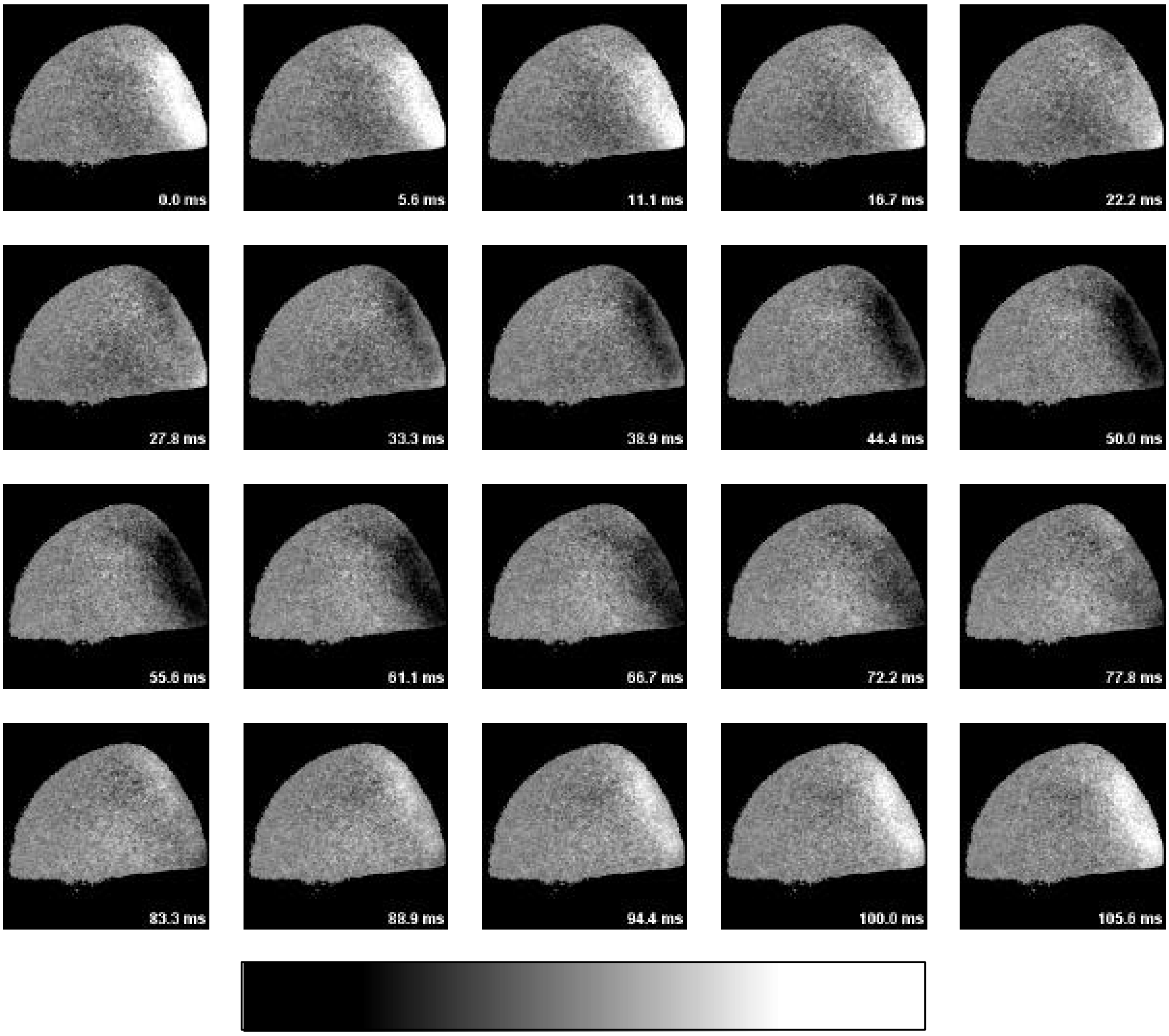


Fig.8: One period of Oscillation from the band pass filtered video

It can be seen that the oscillating area is not completely in phase. The flame indicating signal is travelling downwards the premixed flame area. Loosely spoken the flame extinguishes and is blown out in downstream direction. After that the flame reignites and also travels downstream until the cycle starts again. Maybe the flame does not really extinguish but the heat release of the flame shows this non stationary behavior. The movement in downstream direction indicates a flame blowout and thus fluctuations in stochiometry. These fluctuations may result from pressure oscillations acting on the inlet ducts, and therefore support the theory of a closed loop interaction. For a theoretical treatment of the mentioned closed loop circuit as driving mechanism for combustion instabilities in gas turbines see [6].

To clarify phasing throughout the oscillating area, calculations were done in which the phase shift of the humming oscillation in the video were extracted for each pixel. Fig.9 shows the results.

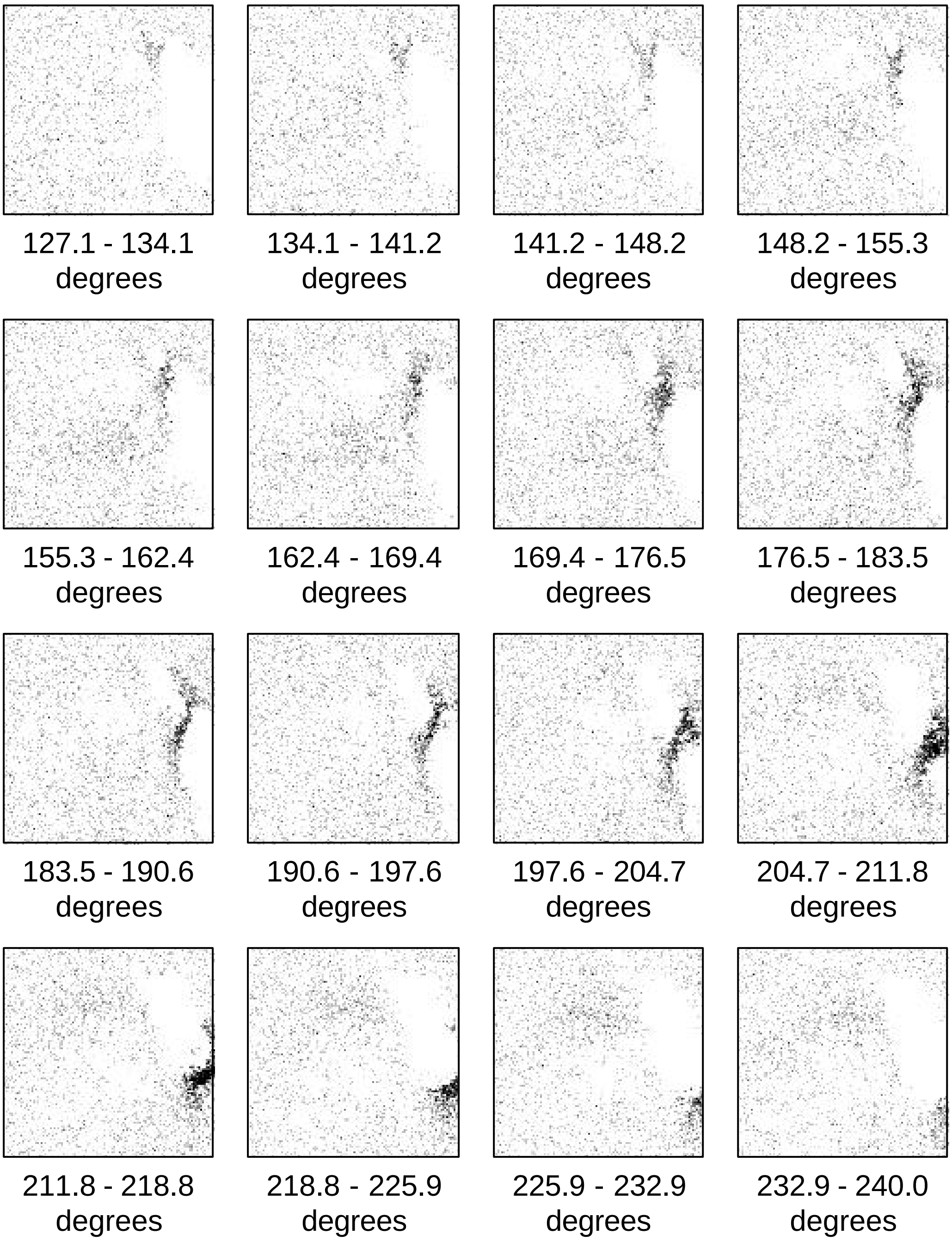


Fig.9: Phase localization throughout the video data on early humming

This phase calculation shows that the impression of a downstream travelling flame signal, one gets from the band pass filtered video, is correct. The areas, which are in phase are much better localized than the moving flame signal from the band pass filtered video. This makes it possible to extract the distance the flame has covered and a corresponding difference in phase. From this information one can easily calculate the velocity of the moving flame by

$$V_{flame} = \frac{2p\ f\ s}{\Delta p},$$

where f is the humming frequency, s is the measured distance and Δp is the phase difference. The burners exit velocity can be calculated from the mass flow and the density of air and combustible. These two velocities are equal within the error in quantity of $s/\Delta p$. Everything is pointing to a non stable flame in the vortex area. Instead the flame performs flashbacks and is subsequently blown out.

ACKNOWLEDGEMENTS

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