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Identification of the state-space dynamics of oil flames through computer vision and modal techniques

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ABSTRACT

In industrial oil furnaces, unstable flames can lead to potentially dangerous conditions. For this reason, elaborate control systems are used to monitor the various parameters of the process that could become the source of such problems. A current trend in research is the one that seeks to apply artificial intelligence techniques to efficiently identify *a priory* anomalous behavior of the flames, so as to help improving the time response of the automatic control. In system dynamics theory, it is common sense that an accurate modeling of the process under study directly affects the performance of the controlling apparatus. Unfortunately, due to the complexity of the process, physical models of flame propagation are still not as much faithful as they should to be used for control purposes. On the other hand, could the complex dynamics of flame propagation be described in terms of an identified assumed model, one would come up with a tool for the improvement of the control strategy. In this work, a new approach based on Operational Modal Analysis (OMA) tools is used to identify four degree-of-freedom second order state-space models of oil flame dynamics in a prototype furnace. Grabbed images of a CCD camera, after being processed through a computer vision method, provide sets of characteristic vectors which, then, serve as input data to an identification OMA algorithm based on the Ibrahim Time Domain Method. Models of unstable and stable flames are built and validated through spectral analysis of the reconstructed time-domain characteristic vectors. The truthfulness of the validation scheme was then confirmed by a quantitative modal assurance criterion modified to suit the current application. On the grounds of the results obtained, it is possible to assert that the proposed approach for the description of flame dynamics can likely predict the occurrence of unstable conditions, thus becoming another tool that might be used in an automated control system.

1. Introduction

The monitoring of oil-flame conditions in industrial petrochemical plants is of capital importance in terms of economy, environment-friendly operation, and safety. Currently, a wide array of sensors performs the task of measuring and informing the plant staff who, ultimately, judges the necessity of intervening to alter control parameters. This process has two drawbacks: firstly, sensors like thermocouples, flow meters, opacity meters, pressure sensor or even air–fuel ratio gauges are normally expensive and require frequent maintenance interventions; secondly, the judging ability of distinct operators is not the same, which might lead to below-standard functioning condition, including potentially dangerous ones. The first drawback pointed above should be tackled by replacing the specialized sensors by a frame-grabber and a set of low-cost CCD video cameras properly inserted in the furnace; those cameras can produce a continuous flow of flame images exhibiting luminance patterns that are well correlated to the physical combustion variables. The second drawback can be handled with computer vision routines able to identify normal or abnormal combustion states through the analysis of the sequence of flame images grabbed by the cameras. However, such an aim cannot be successfully achieved unless the decision-making be supported by reliable inferences on the image processed data. That is why the computer vision based systems for combustion processes monitoring usually apply a heterogeneous set of statistical and artificial

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intelligence techniques, especially multivariate statistics, artificial neural networks and fuzzy logics.

Expert systems with these attributes are getting more and more importance for the oil and gas industries in the last years because of the potential impact to clean combustion. Some of the most recent contributions to this new area are presented in the sequence.

Taking into account that proper identification of coal chemical composition is essential to apply an optimization policy for a coal based combustion process, Zhou et al. (2014) implemented a computer vision method that used flame images analysis to perform the coal classification. In order to achieve such an aim, characteristic vectors of grabbed and averaged RGB flame images related to specific coal combustion processes were constructed using spatial and temporal features of the intensity image signals as well as their R and G/B channels. Then, a series of experiments concerning combustion processes based on 4 different chemical compositions of coal gave rise to a total of 384 feature vectors, from which 2/3 were used in the training of a support vector machine classification algorithm. Further validation tests showed that the accuracy of the implemented method surpassed 80% in all tested cases.

Gómez, Hernandez, Coello, Ronquillo, and Trejo (2013) proposed an artificial intelligence based method to identify 4 states of combustion processes – ‘background radiation’, ‘stable flame’, ‘flame with air excess’ and ‘flame with fuel excess’. Using an optical sensor scanning system to record time series for the average levels of luminance of the furnace concerning the four states mentioned above, the authors construct feature vectors encompassing geometrical and statistical parameters extracted from these signals and their respective power spectra. Those feature vectors were further used to implement a supervised learning process based on a 2-layer MLP neural network whose internal weights were adjusted by a genetic algorithm aiming at improving its generalization capability.

Applying a cascade of statistical and image processing methods, Lin and Jorgensen (2011) synthesized a software based sensor to estimate the NOx emission rate of cement kiln processes. The methodology adopted by those authors consisted in constructing a partial least squares regression model that correlates the characteristic vectors extracted from the two most relevant eigen-images of each RGB flame image with the respective outputs of a set of sensors measuring chemical and physical variables of the process.

Sun, Lu, Zhou, and Yan (2011) carried out laboratorial experiments aiming at identifying parameters that could be related to instability in gaseous flames. After grabbing average images of flames due to combustion processes with different fuel/air ratios, encompassing fuel-lean and fuel-rich conditions, the authors examined the power spectra densities (PSDs) of both the visible and the infrared images. The PSD average frequencies versus fuel/air ratio graphs, from under stoichiometric (unstable flames) to upper stoichiometric (stable flames) conditions, exhibit an easily identifiable maximum (the stoichiometric condition) that can be used as a threshold to identify unstable flames.

In the article of Chen, Chang, and Cheng (2013) a new method of controlling the oxygen fuel rate as well its variability is proposed in order to improve the performance of industrial combustion processes. This method uses PCA compacted sequential sets of RGB flame images to generate measurements representing their main visual characteristics. According to the authors, almost 99% of the variance of the images is encompassed by the two most significant eigen-images of the set, two variables – the weights of those eigen-images – are used as observable variables on a two-loop control system developed to maintain a combustion furnace operating at an optimal and stable condition.

A key feature that must be monitored in order to maintain optimal burning conditions of oil flames is the vapor to fuel rate (VFR), which directly affects fuel nebulization and flame quality. Fleury, Trigo, and Martins (2013) proposed a method based on computer vision and Kalman filtering to monitor nebulization quality of oil flames in a prototype refinery furnace. In short, the authors show that CCD-grabbed images of the flames at a priori known nebulization quality can be used to devise characteristic vectors that generate a set of fuzzy classification rules. Then, the components of a characteristic vector obtained from grabbed images of unknown a priori nebulization quality are assumed to be state-variables of a random-walk state-space model which, through a Kalman filter, effectively estimates the state and the nebulization quality when there is a statistically-proven convergence to a state that matches one of the classification rules. The researchers also state that the method could be improved once, instead of a random-walk model for the evolution of the state, a more accurate description of the system dynamics was employed. The difficulty that arises concerns the fact that phenomenological models available in the literature are poorly capable of encompassing both micro and macro scales occurring in flame propagation. As a consequence, a description based on either one would not cover the wide range of phenomena in between limiting conditions, thus resulting in a poor model under the estimation perspective.

Wang and Ren (2014) used a combined gray-level co-occurrence matrix of flame images and generalized learning vector neural network to estimate rotary kiln combustion characteristics. Texture features of images of flames with ideal working conditions comprised a database employed to train the neural network which, further on, was able to identify complete or incomplete combustion on test images.

In order to distinguish the combustion and ignition characteristics of natural gas components, and the effects of mixture blending, Kamada, Nakamura, Tesuka, Hasegawa, and Maruta (2014) studied the weak flame propagation in a reactor with controlled temperature conditions. Flame dynamics were numerically simulated and experimentally validated against the research octane numbers of each component fuel. Images of the weak flame propagation were grabbed at the experimental setup and, along with wall temperature measurements, provided the necessary data to validate the procedure. It must be pointed out that this important contribution does not employ any kind of automated expert system in the classification process; thus, the reference is justified under the perspective of using images to obtain characteristics of complex systems. Image and expert systems are also present in the work by Tomasoni, Saracoglu, and Paniagua (2014), who devised a flow pattern recognition algorithm in high-speed imaging to detect vortex-shedding and shock waves in ultrasonic air flow.

Another important issue for the adequate operation of refinery furnaces is the early detection of flame instability. This phenomenon may cause the extinction of the flame, resulting in an undesirable dangerous condition. Models for combustion instability in the literature (Bouziani, Landau, Bitmead, & Voda-Besançon, 2005) based on coupled van der Pol equations state that unstable conditions can be detected under certain controlled situations; however, perturbations may induce false instability diagnosis near theoretically stable operation setups. Therefore, a description of the dynamics of the system based purely on data from observations of flames under actual operating conditions could possibly enhance the predictability of AI algorithms in general. In dynamics, a technique that suits this purpose is Operational Modal Analysis (OMA) in the time domain.

Overall, OMA seeks to identify parameters of an assumed model of the system dynamics using information from measurements of the system response to known particular inputs, namely, either step or impulse excitations, in real operating environment. The so called Ibrahim Time-Domain Method (ITDM), one of the tools available to perform the task, is widely employed in the identification of frequencies and modes of vibration in structures like stayed