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The impact of biofuel properties on emissions and performances of a micro gas turbine using combustion vibrations detection

C. Allouis[b,*], A. Amoresano[a], R. Capasso[a], G. Langella[a], V. Niola[a], G. Quaremba[a]

[a] Dipartimento di Ingegneria Industriale – Università degli Studi di Napoli Federico II, via Claudio 21, 80125 Naples, Italy
[b] Istituto di Ricerche sulla Combustione - CNR, via Claudio 21, 81025 Naples, Italy

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ABSTRACT

The use of pure vegetable oils in Micro Gas Turbine can damage the injection system or the combustion chamber causing undesired vibrations. An ideal solution would consist in having an available tool able to forecast and/or follow in real time the vibrational state of the combustion device. The present paper describes tests performed on a low emission Micro Gas Turbine for power generation, fueled with different liquid fuels, including commercial diesel oil and its blends with pure rapeseed oil. A particular attention was paid both on the emissions and on the measurements of the micro vibrational distributions and their correlation under the different fueling conditions using a new signal processing based on a nonlinear method and chaos analysis. We observed that the overall behavior of the MGT fueled with the blends was good, and the emission concentrations of CO, NOx and Total Particle Matter were comparable to the pure diesel oil ones. Moreover, the chaos analysis and the proposed methodology came out as a possible tool for the real-time characterization of the combustion process of the MGT and to individuation of the fuel supplied.

1. Introduction

There is a growing concern that the use of fossil fuels and the associated carbon dioxide emissions are contributing to global warming. The Energy Information Administration estimates that world carbon dioxide emissions from energy production will increase by 51% by 2030, namely from 28.1 billion metric tons in 2005 to 42.3 billion metric tons in 2030 [1]. As energy use grows, concerns over global warming may lead to imposing limits on greenhouse gas emissions from fossil fuel plants. This has stimulated extensive research on the subject of carbon capture and sequestration and an increase of renewable sources. Even though, the future renewable fuels of 3rd generation are not available yet, the use of 1st generation biofuel, pure vegetable oils, is still of interest as an alternative fuel [2, 3], and is commonly used both for transportation and energy production. Many studies are available about fuel preparation and emission characterization of systems fully or partially fueled with pure vegetable oils [4–8]. The use of pure vegetable oils can damage the injection system or the combustion device [4] causing undesired vibrations. The ideal solution would consist in having an available tool able to forecast and/or follow in real time the vibrational state of the combustion device. This objective could be partially solved applying recent mathematical algorithms based on chaos theory [9]. The purpose of this work is to describe an application of recent nonlinear signal processing method to detect and to distinguish the regularity of micro-vibration shown by micro gas turbine (for short, MGT) due to mixed fuels at fixed speed of rotation. The reason of such an approach is because the turbine is a dynamical system extremely balanced, so the vibrational morphodynamics due to the use of very similar fuels, are difficult to determine with the usual linear methods (*e.g.*, the spectral analysis). This creates then a challenge in applied dynamical systems. The signal processing is usually performed by means of classic approach [10] (*e.g.*, spectral analysis) or by applying the most advanced methods based on the wavelet transform or thermography [11–14]. Most of the techniques that have been developed for the analysis of both linear and nonlinear systems are observations of a stationary random process. The difficulty, of course, is identifying when it is appropriate to treat the data as stationary. As a working definition, we may therefore term stationary process to be one in which the measure of interest associated (*e.g.*, pdfs) with collections of observations is not changing in time [15]. However, signal processing performed by spectral analysis or by means of the classic approach based on wavelet transform is not effective. Several testing methods have been proposed for measuring the chaos including the maximal Lyapunov exponent (λ_{max}), the phase space reconstruction and the direct method. Recently, a new test approach for distinguishing regular from chaotic dynamics in deterministic dynamical systems was

* Corresponding author at: IRC-CNR, P.le V. Tecchio 80, 80125 Napoli, Italy.
E-mail address: allouis@irc.cnr.it (C. Allouis).

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proposed [16, 17]. The present paper describes tests performed on a low emission MGT for power generation, providing electrical power up to 30 kWe. Different liquid fuels, including commercial diesel oil, blends of diesel oil with pure rapeseed oil, were tested under fixed load. Primarily attention has been focused on the measures of the micro vibrational distributions and their correlation with gas turbine fueling.

2. Experimental set-up and methods

2.1. Experimental set-up

The Micro Turbine Capstone C30 is a turbine of last generation system with a maximum power output of 30 kWe with 26% electrical efficiency and up to 90% combined heat power efficiency. It is widely used in the aeronautical field; in particular, as energy provider for the aircrafts on parking. It can be also operated with different liquid fuels. The fuel supply system is composed of three nozzles (one main and two auxiliaries). In this paper, diesel as fuel and its blend with rapeseed oil at 1%v/v (for short, Diesel 1%), at 2%v/v (for short, Diesel 2%), at 3% v/v (for short, Diesel 3%), and at 4%v/v (for short, Diesel 4%). were used. The choice of the rapeseed oil as an additive present in a small percentage is to verify an eventual difference between fuels in terms of machine performance. The turbine rotation was set at 85,000 rpm close to maximum speed (*i.e.*, 90,000 rpm) for all the fuels. All parameters of the turbine (*i.e.*, rotational speed of the turbine, power output, exhaust gas temperature, *etc.*) were continuously acquired every 2 s by means of a PC and analyzed at the end of test. The vibrational signals were acquired by means of two unidirectional micro accelerometers, model PCB 352 C22. The acquired data through the accelerometers have been synchronized with each other and were stored in the computer. Synchronization here means that the accelerometer signals were acquired in parallel and aligned on a time basis through a LMS SCADAS data acquisition system. Hence, no electromechanical synchronization system was used for each accelerometer signal (*e.g.*, tachometer signal). Front and side views of the turbine and the location of the accelerometers are shown in Fig. 1 (left and right respectively).

2.2. Methods

The proposed method for distinguishing regular from chaotic dynamics is successful if the noise-level is sufficiently small but also because the balanced dynamics of turbine are essentially stationary and deterministic. Many methods desensitize the test performed on noisy signals but damps the ability to detect slow growth of the features as well as the signature for time series data of moderate length. For such a reason each accelerometric signal was sampled at 102400 Hz for 10 s, for a total of 1,025,024 sampled points. The calculations were performed by using the MATLAB® R2015b software.

The nonlinear method introduced in this work consists primarily in the decomposition of the accelerometric signal into two mutually orthogonal components [18] for projecting them on a plane other than phase space [16, 17, 19]. This plane can be obtained by using the following equations

$$\chi_\omega(m) = \sum_{j=1}^{m} x_j \cos(j\omega) \tag{1}$$

$$\zeta_\omega(m) = \sum_{j=1}^{m} x_j \sin(j\omega) \tag{2}$$

where x_j, $j = 1,2,..,N$ is a time series (*e.g.*, accelerometric signal), $\omega \epsilon (0,\pi]$ and $m = 1,2, \ldots,N$, N length of time series. The functions Eqs. (1) and (2) are two orthogonal projectors and are useful to determine the "signature" of the vibration. For instance, a qualitative information on the regularity or not of the time series may be acquired by observing the development of $\chi_\omega vs\ \zeta_\omega$. It can help to distinguish regular (*i.e.*, according to the Lyapunov exponent, $\lambda < 0$) from chaotic sequences ($\lambda > 0$) [20]. If the sequence of the time series is regular, the expected development of the map will be as illustrated in Fig. 2 (left). *Vice versa*, a chaotic development is as in Fig. 2 (right).

A better characterization of the numerical sequence can be made by means of the mean square displacement $M_\omega(m)$. Sequences that exhibit stable average distances from the time evolution of the numerical series can be classified as stable, regular or stationary. Conversely, if the mean squared distances tend to decrease, the series is then uniformly convergent toward its fixed point. Distances that, on quadratic average, tend to increase in a more or less regular way with respect to the time evolution of the series, define dynamically unstable systems [17]. Let define $M_\omega(m)$ as follows:

$$M_\omega(m) = \lim_{N\to\infty} \frac{1}{N-m} \sum_{j=1}^{N-m} \{[\chi_\omega(j+m) - \chi_\omega(j)]^2 + [\zeta_\omega(j+m) - \zeta_\omega(j)]^2\}$$

$$M_\omega(m) = \lim_{N\to\infty} \frac{1}{N-m} \sum_{j=1}^{N-m} \{[e^{ij\omega} x_j]^2\} \tag{3}$$

where $m = 1,2, \ldots,m^*$ and $m^* << N$ (typically $m^* = N/10$). The Fig. 3 shows the $M_\omega(m)$ diagram of regular (oscillating solid line) and chaotic dynamical system (oscillating dotted line). Finally, by comparing the r.s.f. of Eq. (3) with the power spectrum [17].

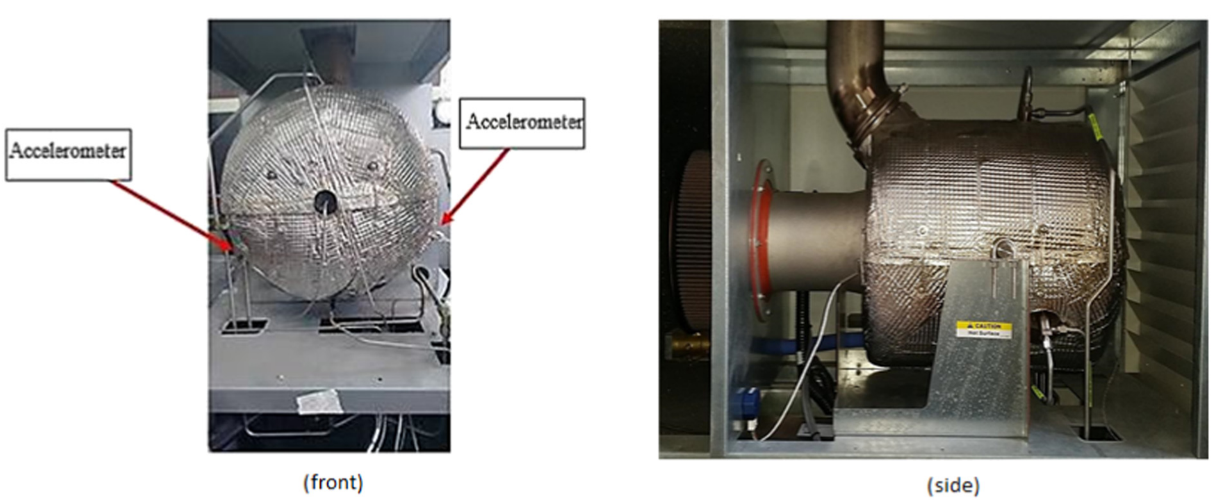

Fig. 1. Turbine with location of accelerometers: front and side view.