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STABILITY ASSESSMENT OF THE RESONANT LINEAR PERMANENT MAGNETIC GENERATORS POWERED BY FREE PISTON ENGINES

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Abstract. *A sustainable development is essential for the future of the planet. Therefore, the technology must satisfy current needs without compromising the ability of future generations to meet their own needs. Hence, this work assesses the stability conditions of a free piston engine powering a linear permanent magnetic generator. This kind of machine use of renewable fuels and has greater energy efficiency. The numerical model used to do it englobe three physical domains: electromagnetism, dynamics, and thermodynamics. The proposed machine works in its resonance frequency. Therefore, a sensitivity analysis is played out, interpreting how the three variables influences on the engine cycle stability: the inlet pressure, air to fuel ratio and the associated mechanical spring stiffness. It is show that working in resonance the machine is more robust and less influenced by the thermodynamics conditions.*

Keywords: *Resonance, Free Piston Engines, Permanent Electric Linear Generators, Stability*

1. INTRODUCTION

A sustainable development is essential for the future of the planet. Therefore, the technology must satisfy current needs without compromising the ability of future generations to meet their own needs. In this way, fossil fuels in power generation are clearly an unsustainable source of energy. According to "Report of the World Commission on Environment and Development", edited in far 1987, the use of renewable fuels and greater energy efficiency are imperatives (Secretary-General, 1987). The free piston engine (FPE) was widely applied, in the mid-20th century until the 1960s, in hydraulic or pneumatic compression operations, including gases directed to generate electrical energy in industrial plants (Achten, 1994 e Mikalsen and Roskilly, 2007). New power electronics, sensors and actuators technologies, bring greater interest in these types of engines, due to their thermomechanical efficiency, almost 56% of thermal efficiency (Van Blarigan, Paradiso et al., 1998) for some projects and between 40 to 50% in the majority of other ones (Jia, Smallbone et al., 2016).

A crucial step in design and optimization of these machines is to calculate the electromagnetic field distribution in their interior. Several techniques exist in the literature to cover these demands. For a design and optimization stage, commonly the sub-domain method is chosen due to its small computation effort, even if that leads to less accurate results (Rodrigues, Santos et al., 2019). Therefore, parametric analysis is a powerful tool which can lead to a wider comprehension of the system, and thus give us sufficient knowledge basis with which is possible to trace the better strategical ways to obtain the best performance and design of a certain equipment. It can also provide information with which control strategy would be designed. A parametric analysis of a numerical model built for design and optimization purposes was developed for a free piston engine (FPE) used to power the linear permanent magnetic generator (LPMG). Using this analysis were observed how the electromechanical efficiency of the generator is affected by the variation of the electrical and mechanical parameters of the system (Rodrigues, Santos et al., 2019). A LPMG powered by a FPE (FPE-LPMG) with a 10 kWe was optimized. A parametric model which includes dynamic, thermodynamic, and electrical principles was used to simulate the machine functioning dynamics. The thermodynamic model includes the scavenging process of the cylinder chamber. The results shown a net efficiency of 49%, it is greater than the most efficient diesel generator produced by General Electric (Rigobello, Santos et al., 2021).

The main goal of this work is to explore the robustness of a free piston engine coupled to a specified linear generator, such that it can achieve maximum efficiency while drive an electrical generator of 10 kW. Based on the optimized parameters values obtained using a genetic algorithm, presented by Rigobello et al. (2021), this paper aims to assess the system robustness using a sensitivity analysis, in other words, evaluate the ability of the system to operate correctly in various thermodynamic conditions and fuel/air ratio around their optimum values, and mapping the failure regions in due an unexpected situation.

2. PHYSICAL MODEL

The multidomain model applied includes thermodynamic, dynamic of solid and flexible bodies and electromagnetism concepts (Rodrigues, Santos et al., 2019). The integration between each domain is represented by the FPE-LPMG model diagram in Fig. 1.
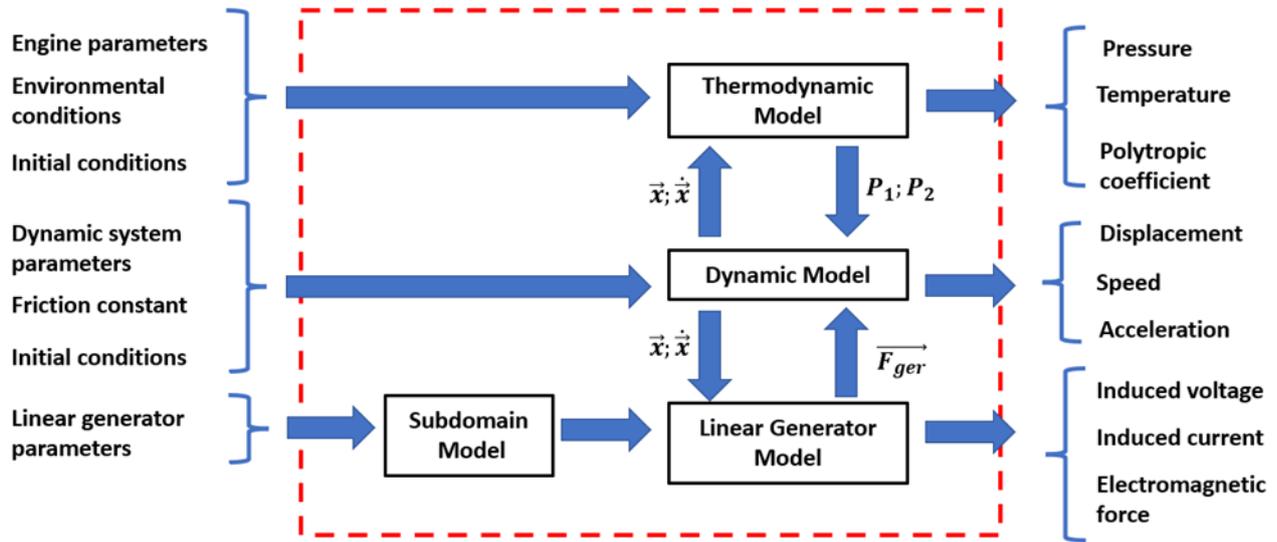

Figure 1. Free piston electric generator model schematic diagram.

The engine is a dual opposed cylinder and, it's physical dynamic model is depicted in Fig. 2 and mathematic model of the system is defined by Eq. (1). The 1 DOF system is excited by the successive expansions of the burned gases in each one of the opposite cylinders, the additional elastic element is associated in series with the gas which is pressurized in the cylinder opposed to one which has just burned and is expanding. Finally, the load imposed by the electrical generator over the motor is represented by its physical model or by an equivalent viscous damping.

Figure 2. Mass, spring and damper dynamic system

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = \underbrace{A_P(P_L(t) - P_R(t))}_{F_{ex}} \tag{1}$$

The excitation force F_ex is due the pressure inside the left cylinder ($P_L(t)$) and the right cylinder ($P_R(t)$), in a way that opposed cylinders produce a periodic excitation which fundamental frequency can be adjusted to be equal the natural frequency of the vibratory system, as are shown in Fig. 3. The last concept is responsible to improve the energy transfer from its thermos-chemical state to the mechanical one (kinetic plus potential energy), thereforehence, improve improving the electrical energy generation.
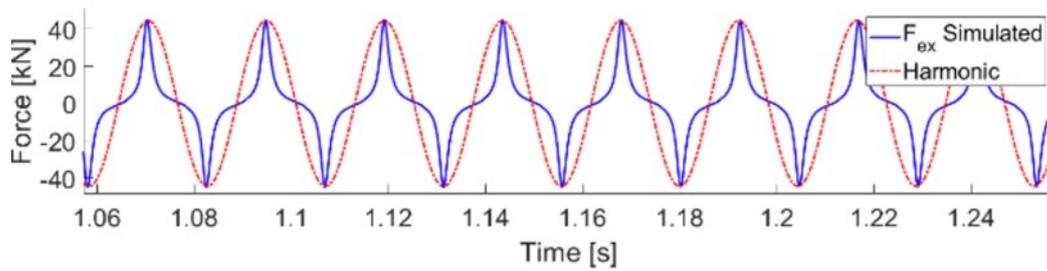
Figure 3. Simulated excitation force and harmonic force

The viscous damping is $c = c_{eq} + c_{loss}$, in which c_{eq} is an equivalent damping due the electric generator and c_{loss} means the internal losses in the machine, overestimated values of these lossesthese losses are around 2%, once that, 2% is the estimated value for friction losses in traditional ICE motors. This simplification. Simplify of the generator as a viscous damper is acceptable, since according to Lenz's Law, the generated voltage is proportional to the speed, consequently, for resistive circuits also the current. In this way, there is a proportionality between the force to move the generator and x˙. Lorentz theorem also assure that magnetic force is proportional to the speed of magnetic field variation, as well as viscous damping (Rigobello, Santos et al., 2021). Starting with thermodynamic model developed in Rodrigues, Santos et al. (2019) the scavenging process, namely uniflow, was added to the model. So that, the thermodynamic model used in this paper is a null dimensional model with homogeneous properties over the control volume, the heat release due combustion is obtained using Wiebe function, the convective heat transfer to the cylinder walls has been considered fixing the wall temperature and the first thermodynamic law applied over an ideal gas was used to obtain the temperature, pressure and polytropic coefficients. Finally, the inner cylinder mass balance has been divided in two stages: valves closed and intake/exhaust stages. In the first stage the mass inside the control volume didn't change and in the second stage the flows through the intake and exhaust valves had been considered in the control volume mass calculation by means of scavenging model (Rigobello, Santos et al., 2021). The dynamic system depicted in the Fig. 1 and represented in Eq. (1) was solved using Runge-Kutta of fourth order method.

3. RESULTS AND DISCUSSION

To study the robustness of the proposed FPE-LPMG a sensitivity analysis method was carried out, to measure the model response to change in three input variables that could lead to an unstable condition, i.e ., the Air Fuel Ratio (AFR), the Intake Pressure and the associated mechanical spring stiffness (k). These parameters vary in the simulation from 11 up to 29, from 100 up to 250 (kPa) and from 0.78 up to 270.79 (kN/m) , respectively. This analysis is useful because it improves the prediction of the model stability. Additionally, the sensitivity analysis is employed to quantify the variation limits of each of the model's parameters around their optimum values, and their importance in the behavior of the system. The other parameters present in the Eq. (1) and used in the simulation are shown in Tab. 1 (Rigobello et al., 2021).

Table 1. FPE-LPMG optimized parameters and main simulation inputs.

Parameter	Value
Operation frequency (Hz)	41.5
Compression Ratio	11.95
Half maximum piston stroke (mm)	32.71
System mass (kg)	10
Cylinder bore (mm)	106.83
Equivalent damping due the electric generator (Ns/m)	272.36
Viscous damping (Ns/m)	51.07
Methane fuel lower heat value (kJ/kg)	48500
Combustion efficiency (%)	10

The Figure 4 depicts three stability maps where two of the chosen three variables are changed simultaneously while the third one remains in its optimal value.
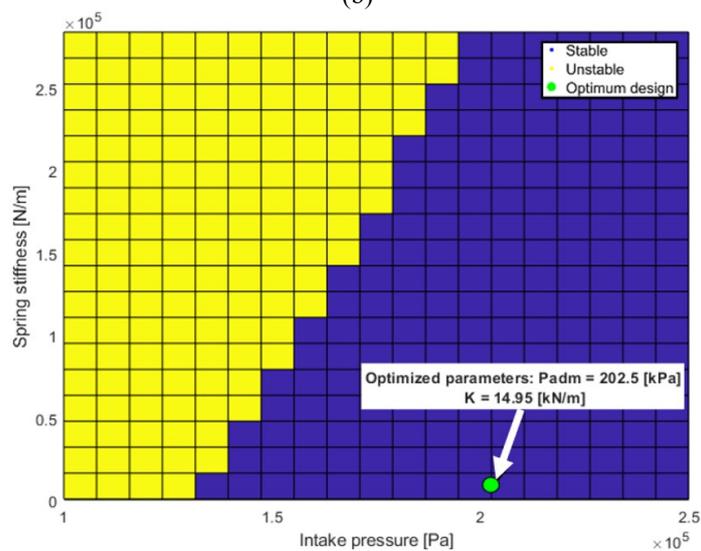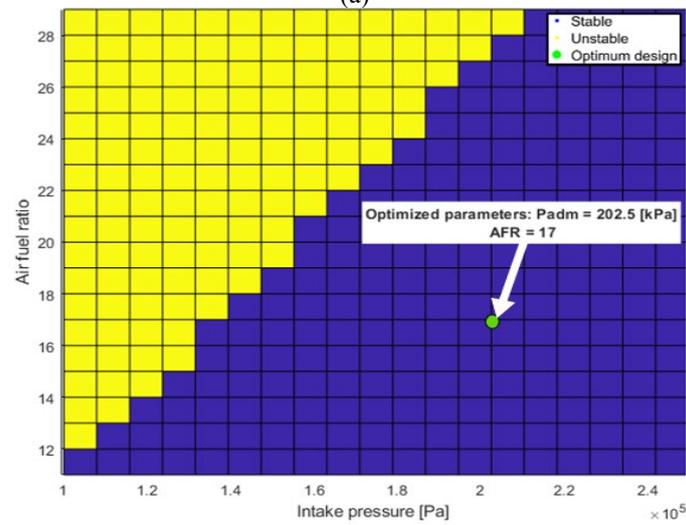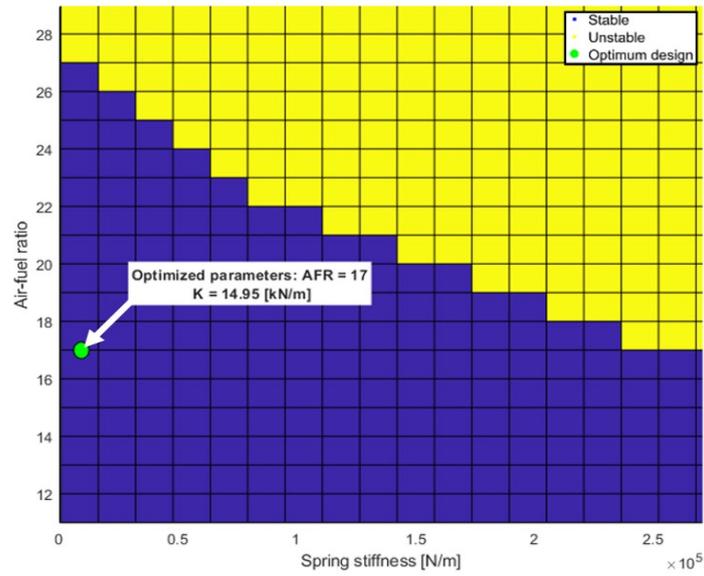
(a)

(b)

(c)

Figure 4. Stability maps: (a) Air fuel ratio x Spring stiffness (N/m); (b) Air fuel ratio x Intake pressure (Pa); (c) Intake pressure (Pa) x Spring stiffness (N/m).

The amount of the energy produced during the combustion of air-fuel mixture is lower for low values of inlet pressure and for high values of AFR. So, it is possible to verify that the amount of energy generated during mixture combustion plays a great influence in the functioning stability. As higher is the energy generated in the combustion, more stable is the machine. There are two extremes in AFR, lean mixtures and rich mixtures, in these extremes the energy free to produce work over the piston is low due the small amount of fuel and due the small amount of oxygen to burn the fuel, respectively. Blair (1996) add that between the lean mixture misfire and the stoichiometric ratio there is a AFR for the maximum power release. At this point, which is around 0.86 of stoichiometric AFR, the excess of fuel increases the combustion speed. Even though this is observed in real motors, here it happens because the Wiebe function, used to model the combustion process, depends on the total amount of fuel injected in the chamber, i.e., more fuel means higher rates of fuel heat release. Besides, optimum design gives robustness to the machine, once that, this design admits a large variation in the studied parameters without occurrence of misfire.
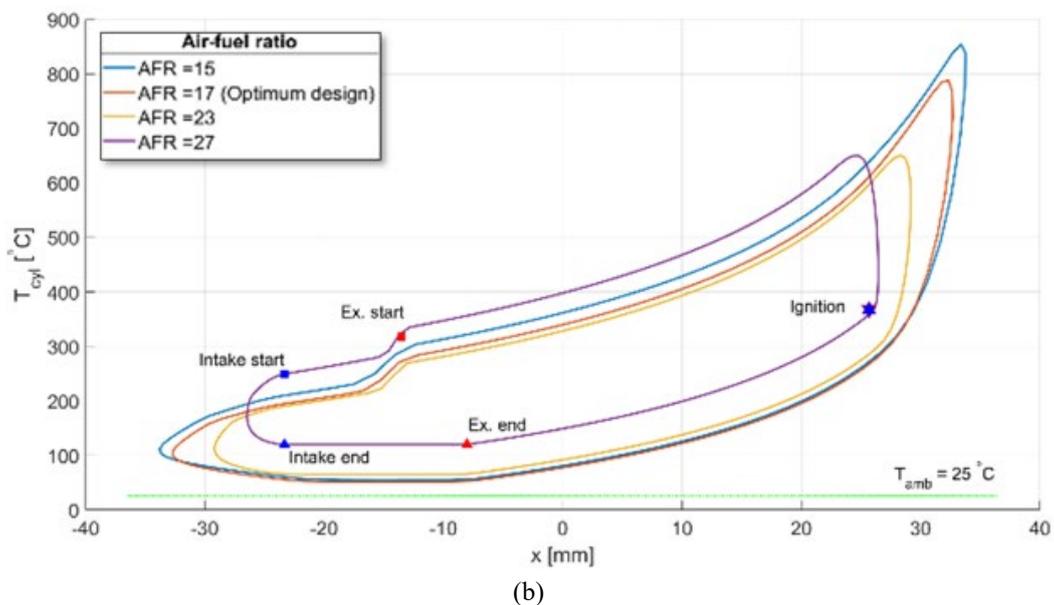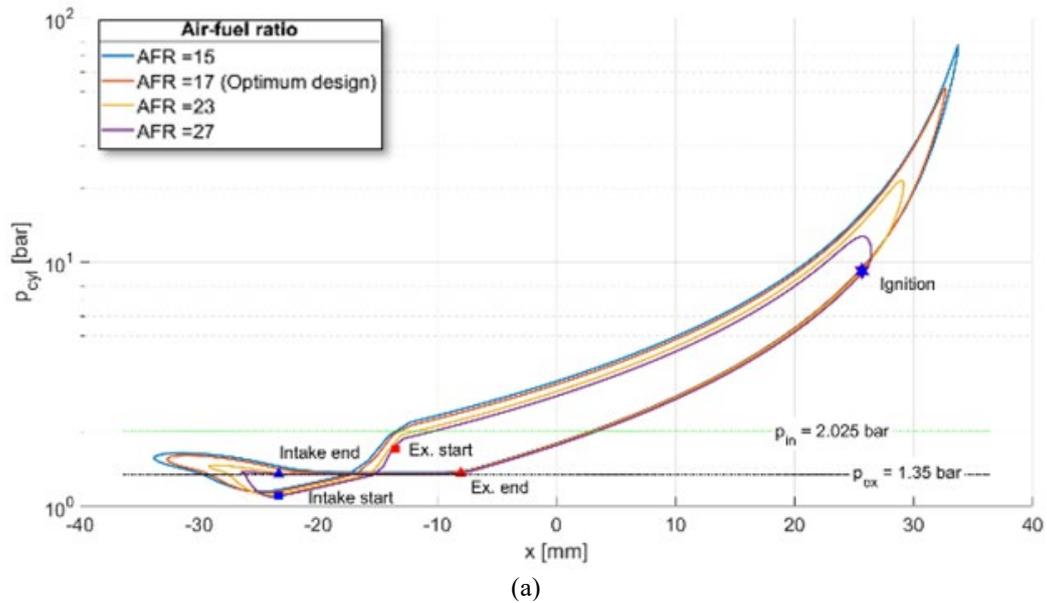

(a)

(b)

Figure 5. Pressure (a) and temperature (b) as a function of piston displacement, considering the associated mechanical spring stiffness of 14.95 (kN/m).

Figure 5 depicts the pressure and temperature variation with piston displacement. It is clear the maximum cycle pressure lowering as the AFR increases. The maximum pressure for AFR=28 is too low to produce the compression of the gas inside the opposite chamber and of the associated spring, so that, it is possible to verify that this configuration is an unstable one as shown in Fig. 4 (a). Additionally, the area inside pressureXdisplacement curve decreases as AFR increases, which means less energy generated by combustion. The maximum temperature increases as AFR decreases; this phenomenon is also related to the application of the Wiebe function. The overlap between exhaust and intake process,

an important characteristic of the Uniflow scavenging process, is also represented. This overlap means that the scavenging starts with the piston pushing out the burned gas, is augmented by the intake port open, which insert fresh mixture in the chamber, and finish with the piston movement.
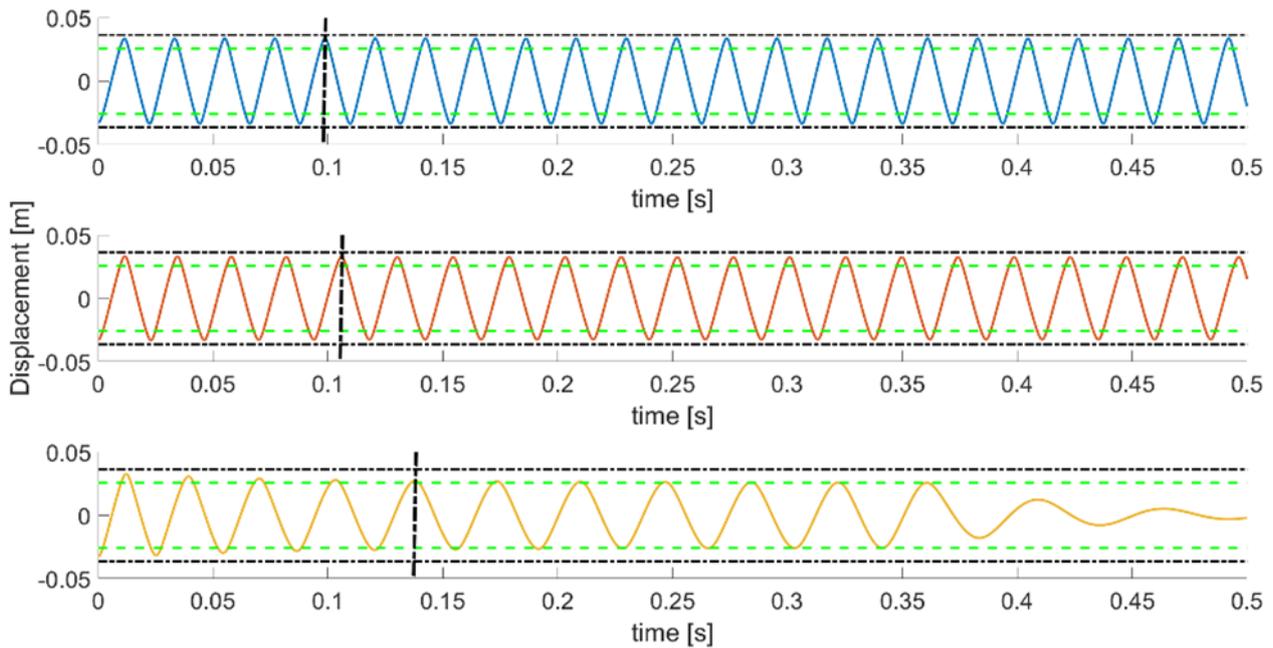

Figure 6. Piston displacement as a function of time. Blue line (AFR=15), Red line (AFR=17), Yellow line (AFR=28). Auxiliary lines: Dash green (Ignition point), Horizontal black dash-dot (Stroke limits), Vertical black dash-dot (Fifth period).

Figure 6 depicts the pistons displacements in three different conditions of AFR. It is possible to see that in the unstable condition (AFR=28 AFR=28) the pistons reach a lower peak after each combustion. This happens due the low amount of energy produced in these successive combustions and the energy decrease as the pressurization decreases until the piston do not pass anymore the ignition point. After this point the pistons are deaccelerated more quickly. It is possible to verify that the displacement reaches a steady state for stable conditions. It should also be pointed out that the working frequency increases as the energy produced by the combustion increases, this is due to a speed enhancement which result in a short period to the piston runs over the stroke.

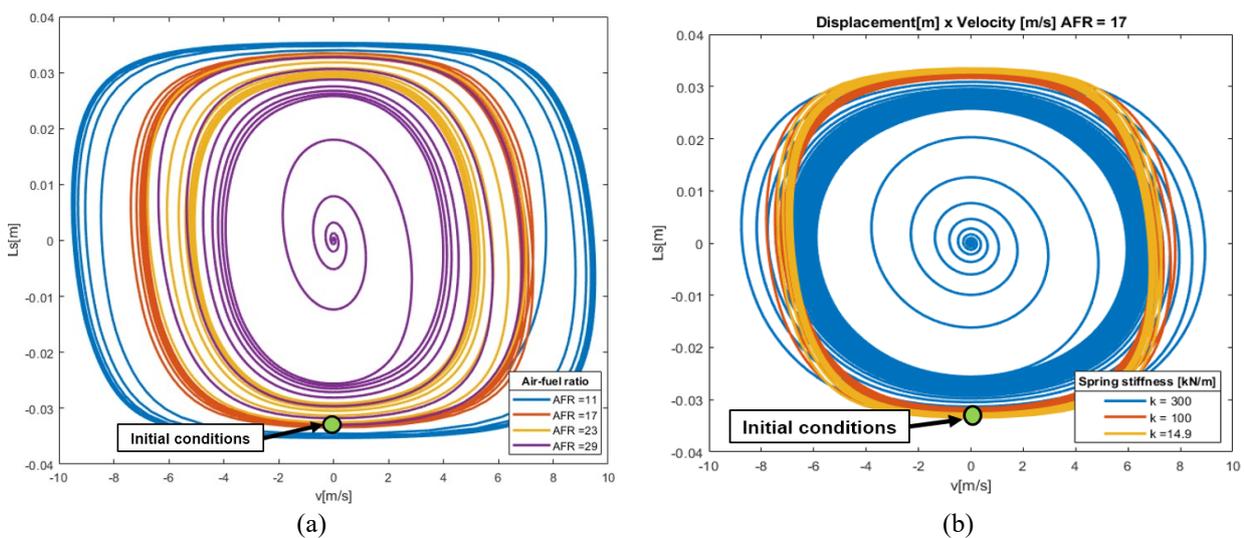(a)   (b)

Figure 7. Piston displacement as a function of piston velocity.

Figure 7 show the simulated piston velocity in function of piston displacement for different air-fuel ratios Fig. 7 (a) and spring stiffness Fig. 7 (b). It is possible to see that the operation cycle with AFR optimum value of 17 is more stable and reaches a steady state more rapidly, oncequickly, once that, the lines for each cycle do not diverge significantly. On the other hand, for the other configurations it is observed a delay in the time taken to reach the steady state, represented

by the spread of the lines. Moreover, as observed in Fig. 6 the Fig. 7 also depicts the instability conditions (AFR=29 AFR = 29 and k=300 kN/m k = 300 kN/m) where the piston slow down until the operation stops.

NextFollowing, we perform an optimizationhad been done a maximum power-seeking optimization, which is a technique to extract the maximum power of the power take-off resistive coefficient or the equivalent damping due the electricfrom the generator even when the motor had variation in its working conditions. The results are showndepict in Fig. 8 for two input variables Air Fuel Ratio (AFR) and Intake Pressure. Based on the results obtained it is possible to verify that the FPE-LPMG produce more power when it is running a slightly rich mixture, and consequently it is observed a higher value for the optimal resistive coefficient (Copt = 196 Ns/m). The lean mixture, when there's a higher concentration of air to fuel, enable the engine to be more efficient but less energy is available to be absorbed by the generator. Thus, a lower value for the optimal resistive coefficient is obtained (C Copt = 115.15 Ns/m), as shown in Fig. 8(a).
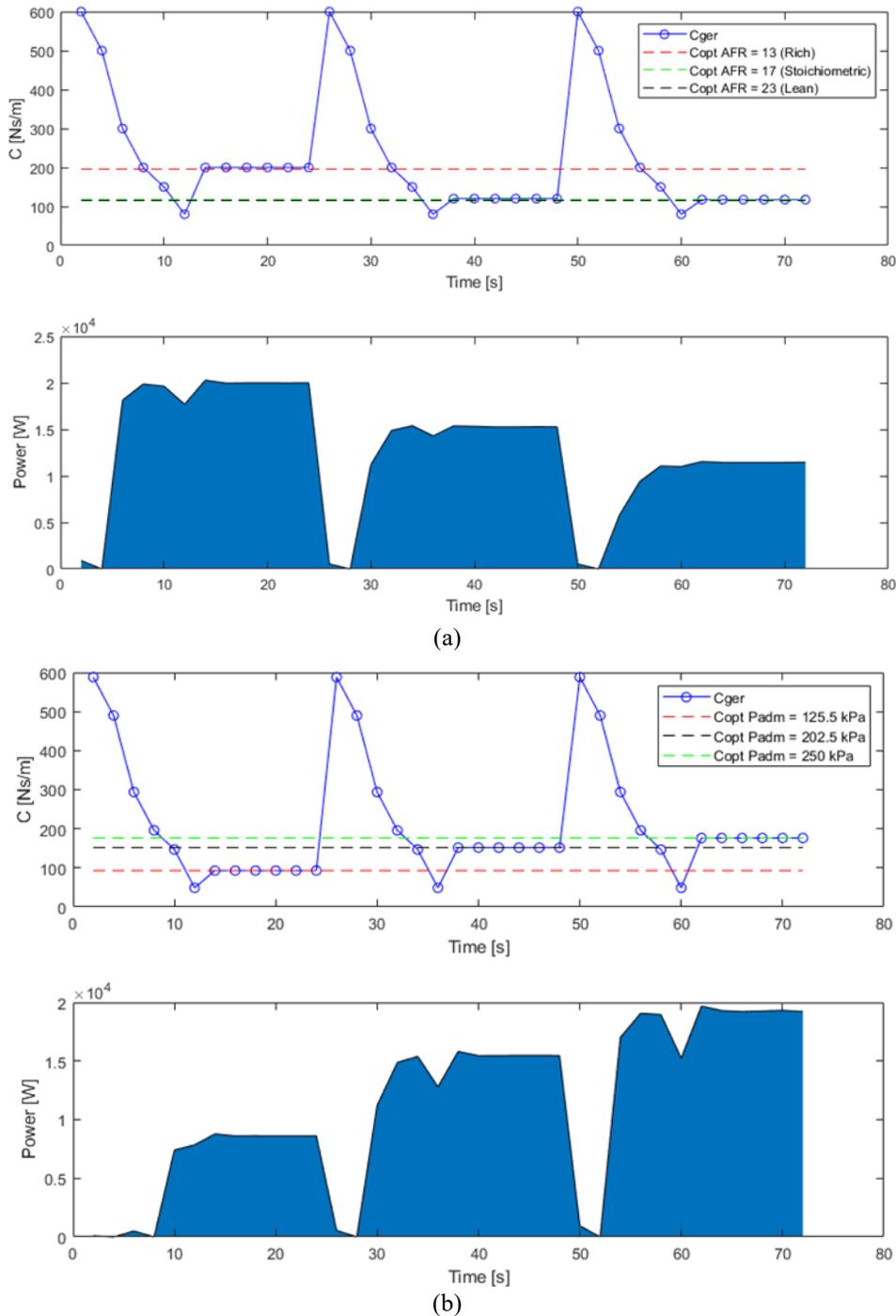

(a)

(b)

Figure 8. Optimization of resistive coefficient C, for the FPE-LPMG subject to changing in input variables, (a) Air Fuel Ratio (AFR) and (b) Intake Pressure (Padm). The resistive power take-off coefficient Copt to optimize the system performance for varying external disturbances are indicated by dashed lines in the plots.

Figure 8(b) depicts the impact of the Intake Pressure variation over the Copt value, and it is possible to see that the pressure is directly proportional to the absorbed power and the optimal resistive coefficient. The reason is that when the intake pressure is higher more air reaches the cylinders, as a result, more fuel can be burned, and the generator can absorb more power. The operation characteristics studied in this paper will be used as a reference for a future optimization work, investigating the feasibility of different extremum-seeking (ES) control schemes to improve the conversion efficiency of a free piston engine used to power the linear permanent magnetic generator.

4. CONCLUSION

This work presented an assessment of the FPE-LPMG working stability. The evaluation was based in the simulation results obtained through a sensitivity analysis, interpreting how the model input variables influences on the engine cycle stability. Hence, the objective to evaluate the ability of the system to operate correctly in various thermodynamic conditions and provide information with which a control model would be designed has been reached.

The study shown the importance of energy produced during the combustion has in the stability of moto generator working. It was demonstrated when it works in the resonance frequency, the FPE-LPMG has more robustness and tolerates more variations in the thermodynamic conditions. The numeric model proposed in previous works was useful to assess the stability and to represent the phenomena which were described in the literature for internal combustion motors when the intake pressure and AFR varies.

It was highlighted the importance of set the charge over the generator as the input conditions varies in the linear motor. This is the most important rule played by the control strategy, i.e., the control strategies as demonstrated should be able to adjust in its optimal value the amount of energy generated by the machine assuring its working stability.

5. ACKNOWLEDGEMENTS

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