Analysis of the impact of sticking forces on the ethanol high-pressure direct injection nozzle

Beatriz Arcêncio
Clayton Zabeu
Fernando Malvezzi
IMT - Instituto Mauá de Tecnologia

ABSTRACT

Given the importance of Brazilian ethanol in reducing CO_2 emissions within the transportation sector and the presence a sticking force in high-pressure direct ethanol injection system caused by some deposits, this study presents an analytical model to simulate the operation of a direct injector and comprehend the influence of these sticking forces on injector dynamic behavior and injection timing.

The results of needle displacement obtained from the analytical model were compared with those derived from a model built using commercial software. The results obtained by both models demonstrated good agreement.

In order to evaluate the effect of sticking force on injector closing time, an experimental test was carried out on an engine. This test aimed to obtain the change in electrical voltage measured at the injector solenoid terminals over time. This variation allows inferring the moment when the needle reaches its seat. It was noted that significant formation of adhesive substance occurred after 9 hours of testing, resulting in a delay of approximately 0.45 ms in closing time when the deposits generated extra sticking force. The analytical model successfully predicted this delay.

INTRODUCTION

The environmental consequences caused by the accumulation of greenhouse gases (GHG) on the planet have been discussed in the political and economic fields, especially after the Kyoto Protocol in 1997, which encouraged the search for energy alternatives to mitigate these pollutants by reducing the use of fossil fuels.

Biofuels are highlighted as an energy alternative for the transportation sector due to the various advantages offered by renewable sources, such as decreased dependence on fossil fuels, a neutral CO_2 emissions balance, low-cost input, and the possibility of reusing waste [4,11,12,14]. The Brazilian ethanol is a protagonist in the country's climate policy to reduce emissions, having a vital role in the energy transition. In the 2020/2021 sugarcane harvest, Brazil produced over 32 billion liters of ethanol used mostly for internal consumption [9]. Moreover, it is important to underscore the superior biomass yield of sugarcane compared to other crops [10].

Recently, high-pressure gasoline direct injection (GDI) technology has been spread from Europe to the global market [1,2,3,5,8]. This system provides the several advantages: (1) Improvement in the efficiency of the process and combustion speed due to smaller droplet sizes provided by the direct high-pressure injection system; (2) formation of stratified mixture regions, with the intent of providing differentiated conditions for ignition or the manifestation of a flame front; (3) improvement in the dosage of the amount of fuel that is admitted into the engine cylinders at each cycle; and (4) the possibility of using multiple fuel injection events within a single cycle, allowing greater control over mixture formation (stratification). In high-pressure systems, controlling the duration of the injection is essential. Deviation from the established standard can lead to a lack of control over the injected mass into the engine, impacting performance, pollutant emissions, and fuel consumption.

In a high-pressure fuel injector, the needle moves axially, allowing pressurized fluid to pass into the combustion chamber. During the opening movement of the injector, electromagnetic force overcomes the opposing forces of the spring and fuel pressure, moving the rod connected to the needle. For closing, the electromagnetic force is interrupted, and the return spring ensures the movement of the needle [13].

Due to its origin in markets where gasoline is the primary fuel, there are only a few published researches about the use of ethanol in high-pressure DI systems. As will be discussed later, there is a possibility of the formation of some deposits in high injection pressure systems, deposits that cause a sticking force between the armature and the electromagnet contrary to the return movement of the needle. This can result in an excess of injected fuel mass due to prolonged opening times.

Considering the significance of Brazilian ethanol for reducing CO2 emissions in the transportation sector and the presence of this sticking force in direct high-pressure ethanol injection systems, this study presents a mathematical model that simulates the operation of a DI. This model aims to facilitate an understanding of the impact of these sticking forces on the dynamic behavior of the injector needle and their interference with injection timing. The final objective of this study is to provide an indication of sticking force impact on the injector closing delay.

METHODOLOGY

As mentioned before, this study aims to comprehend the impact of sticking forces on the dynamic behavior of the injector needle and their interference on injection timing.

The injector closing delay was identified through a steady-state engine dynamometer test to evaluate the effect of the sticking force on the injector's dynamic behavior. The test was conducted under the following conditions:

- Engine: 3-cylinders in line configuration with bore x stroke 75 x 90.5 mm. Compression ratio 10.5:1. Maximum torque 230 Nm @ 1750 rpm and Maximum power 96 kW @ 5500 rpm. Central direct injection at 200 bar, dual VVT, and an aluminum cylinder block.

- Fuel: Several samples of commercial ethanol (sourced from Brazilian distributors) and standard anhydrous ethanol for emissions were tested. All of these samples were compliant with ANP[1] specifications. No fuel additives were employed in this test campaign.

The temporal evolution of electrical voltage across the injector solenoid terminals was monitored to track the needle's seating process. Fig. 1 illustrates the electrical voltage measured at the injector solenoid terminals over time prior to the formation of adhesive substance (at the beginning of the test).

Fig. 2 provides the experimental injector supply voltage values plotted against time subsequent to the formation of the adherent substance. The presence of this substance was noted after 9 hours of testing, resulting in a delay of approximately 0.45 ms in the closing time. The consequence of this delay was an inability to maintain precise control over the injected fuel quantity per cycle.

To reach the goals of this research, a dynamic analytical model of the needle was elaborated. The solution obtained by this model was compared with that derived from Euler's numerical method, which was implemented using MatLab software.

[1] ANP is the Brazilian National Agency for Petroleum, Natural Gas and Biofuels

In some studies, the injector dynamic analysis has been developed using Amesim software [6, 15] or by applying finite element method to simulate multiple physical aspects of the injector [7]. Regarding dynamic modeling of mechanical systems, the approaches typically applied include Newton-Euler equations, the principle of virtual work, Lagrange's equations, Maggi's equation and Kane's formalism [16-20].

For this study, the methodology employed to obtain the equation of motion for the needle, aimed at assessing the impact of sticking force on the injector closing delay, was grounded in Newton's second law.

In order to evaluate the needle displacement results obtained from the analytical model, a comparison was made with those generated by another model, built with the *GT-Suite / Gamma Technologies* software.

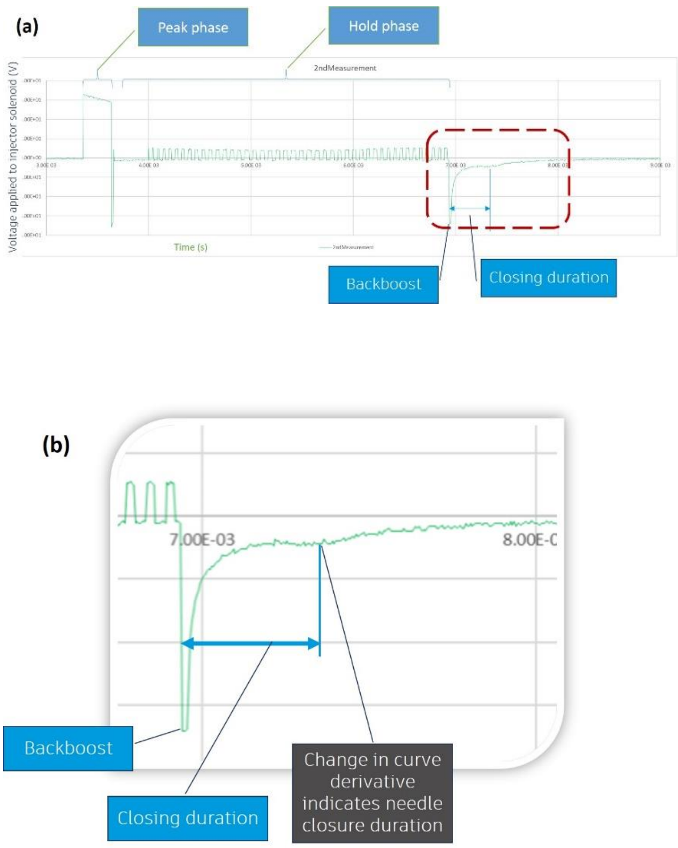

Figure 1. a) Electrical voltage at the injector solenoid before adhesive substance formation; b) Enlarged view of the region highlighted by the dashed line in Fig. 1a

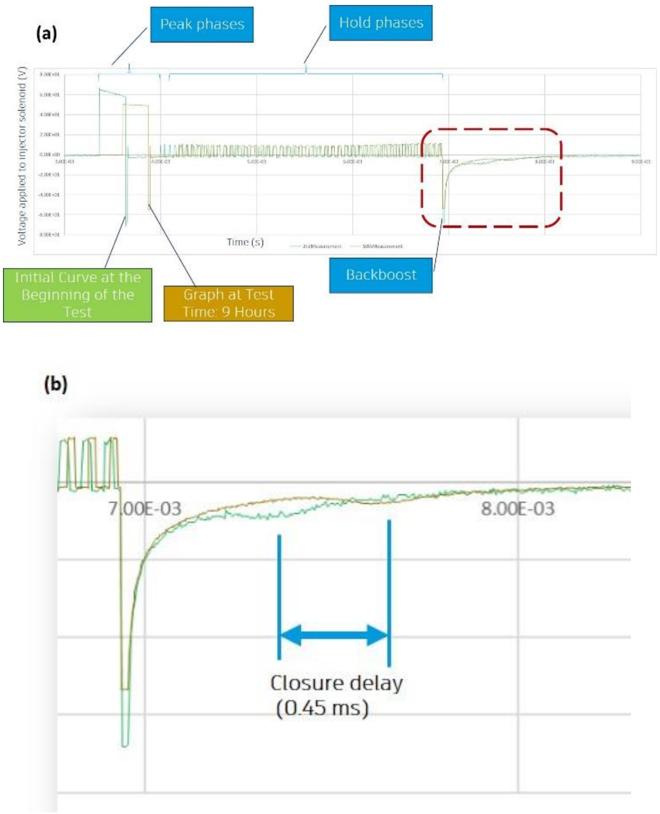

Figure 2. a) Electrical voltage at the injector solenoid after adhesive substance formation; b) Enlarged view of the region highlighted by the dashed line in Fig. 2a

ANALYSES OF INJECTION NOZZLE

Table 1. Parameters and symbols employed in the simulations.

Symbols	*Description*	*Values*	*Units*
F_{em}	Electromagnetic opening force	--	N
g	Acceleration of gravity	9.81	m/s²
m	Mass of needle	0.0041	kg
k	Spring constant	250000	N/m
F_0	Spring preload	30	N
d	Maximum needle stroke	$8 \cdot 10^{-5}$	m
t	Time	--	s
s	Space	--	m
F_{el}	Spring force	--	N

Table 1 shows the parameters employed in the analyses of this study.

The structure of an injector nozzle (Figure 3) was simplified through the dynamic model shown in Figure 4.

As mentioned before, the differential equation of motion for the injector needle was derived using Newton's second law (Eq. 1). The solution was obtained using both analytical method and Euler's numerical method, which were implemented in *MatLab* software.

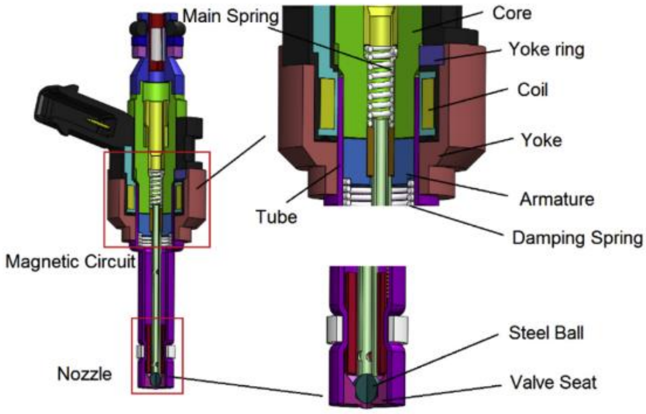

Figure 3. Injector structure [13]

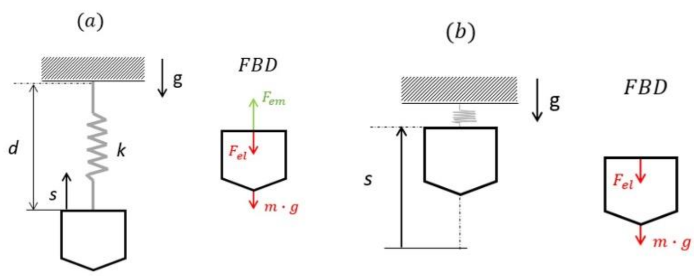

Figure 4. Simplified model in
(a) initial upward movement (b) downward movement

$$\ddot{s} = \frac{F_{em} - m \cdot g - k \cdot s - F_0}{m} \quad (1)$$

The electromagnetic force varies in the time domain, as shown in Figure 5, with a maximum value of 90N. This value was defined based on a similar injector employed in this study and available within the *GT-Suite* software.

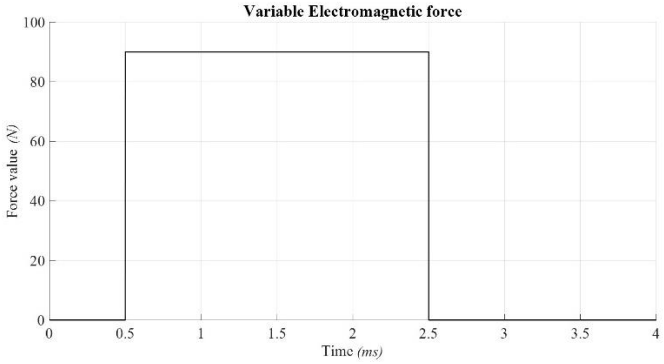

Figure 5. Variable Electromagnetic force

To assess the analytical model of Eq. (1), an equivalent model of the injector was built using the *GT-Suite* software, as presented in Figure 6.

The needle displacement results obtained from both models were compared. For comparison purposes, neither model incorporated fluid-structure interaction.

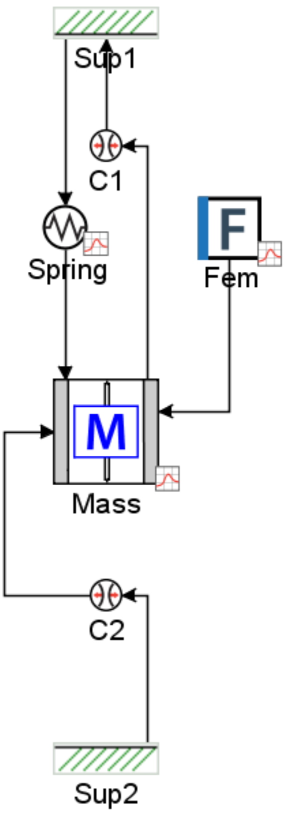

Figure 6. Simplified injector model built in the *GT-Suite* software

In order to evaluate the effect of the adhesive substance on the injector's dynamic behavior, a sticking force (F_A) was defined as a generic force resulting from the concentrated adhesive substance at the upper support of the injector (Figure 7). This force acts counter to the needle's downward movement. It is assumed that the magnitude of this force is inversely proportional to the distance between the needle and the top of the upper support, with its maximum effect limited to 80% of the distance *d*. In its dimensioning, the behavior of the electromagnetic force in any DI injector was replicated over time, and the force reduction was modeled using an exponential function (Eq. 2). The choice of this function was based on the force reduction outcomes obtained in the simplified injector model built within the GT-Suite software, as shown in Fig. 11.

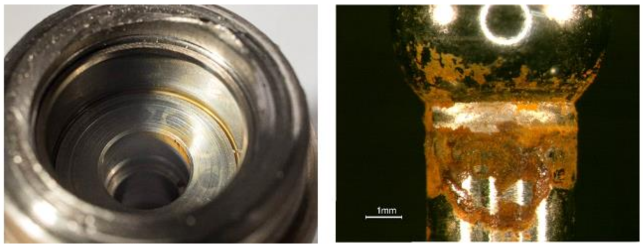

Figure 7. Adhesive substance in the injector

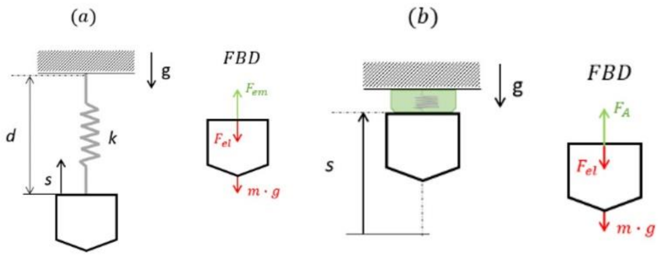

Figure 8. Model with sticking force

$$F_A = (b + F_0) \cdot e^{-16.500 \cdot (d-s)} \tag{2}$$

The analytical model considering the action of sticking force (FA) is described in Eq. (3).

$$\ddot{s} = \frac{F_{em} - m \cdot g - k \cdot s - F_0 + F_A}{m} \tag{3}$$

Table 2. Sticking force

% of F_{el}	*Value of* b
25%	$b_{25} = 0.25 \cdot k \cdot d$
50%	$b_{50} = 0.50 \cdot k \cdot d$
100%	$b_{100} = 1.0 \cdot k \cdot d$

The maximum action factor of the sticking force is *b*. The performance of different F_A values was analyzed, based on the maximum elastic force (Table 2).

Figure 9 shows the behavior of different sticking forces in the downward movement of the injector needle.

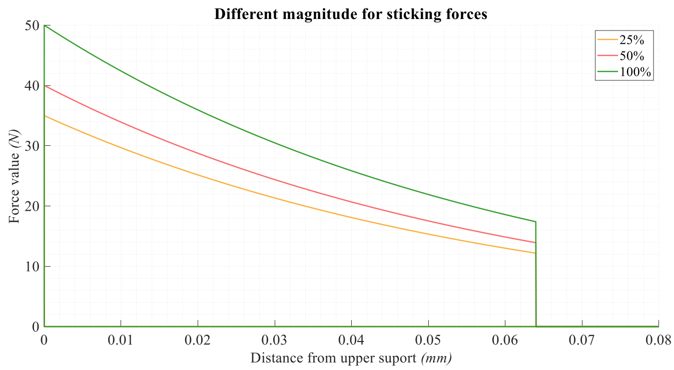

Figure 9. Different magnitudes for sticking force

RESULTS AND DISCUSSION

The results obtained in this study include the following:

a. The displacement of the injector needle during the opening or closing cycle obtained from the analytical model without considering the impact of sticking force.

b. A comparison between the results of item (a) and those generated by the injector model built in GT-Suite.

c. The displacement of the injector needle during an opening/closing cycle obtained from the analytical model considering the effect of the sticking force (Eq. 3).

d. The experimental results of the supply voltage of an injector as a function of time after the formation of the sticking force.

These results are presented below.

Figure 10 shows the displacement of the injector needle during an opening/closing cycle obtained from the analytical model without considering the effect of the sticking force, as described the analytical model (Eq. 1).

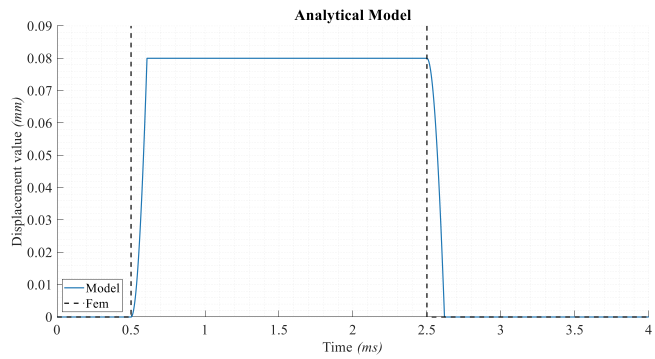

Figure 10. Displacement obtained from simplified analytical model

Fig. 11 presents the comparison between the ODE solution (Eq.1) and the results obtained from the model created using the GT-Suite software, as depicted in Figure 3. It can be noted divergences in the solution obtained with the GT-Suite, attributed to the effects of damping provided by the contact material and the mass penetration within the upper and lower support, both at the end of the opening and closing movements of the injector.

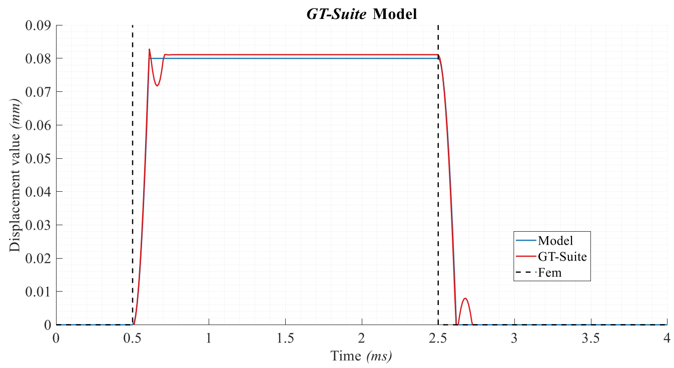

Figure 11. Comparison of simplified needle dynamics models

From the solution of the equation of motion of the injector needle (Eq. 3) using the Euler's numerical method, it is possible to simulate the influence of the sticking force on the downward movement of the needle, as shown in Fig. 12.

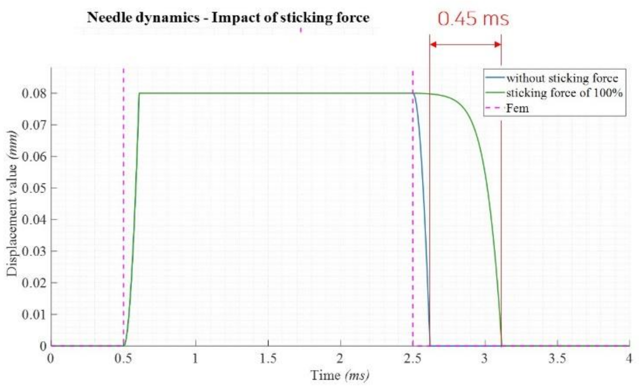

Figure 12. Influence of sticking force on closing time

CONCLUSIONS

This study presents an analytical model to simulate the operation of a DI injector and comprehend the influence of sticking forces on the dynamic behavior of the injector and e injection timing. The generated model enabled the prediction of injector needle closing time delay, considering a force contrary to the spring action (equivalent to the effect of deposits) during the closing movement of the needle.

The generated model demonstrates that an equivalent delay in injector nozzle closing time, observed experimentally, correlates with a calculated sticking force of the same magnitude as the spring force. This value is not negligible and has strong impact on the needle dynamics and fuel injection control.

The continuity of this study expect the inclusion of the fluid flow effect in the analytical model and the performance of experimental tests for direct measurement of the displacement of the injector needle.

ACKNOWLEGEMENT

Authors want to thank Fundação de Desenvolvimento da Pesquisa – Fundep Rota 2030, Project 27192 – Evaluation of high-pressure fuel injection systems working with Brazilian ethanol, for the granted Scientific Initiation scholarship.

REFERENCES

[1] Lee, Z., Park, S. Particulate and gaseous emissions from a direct-injection spark ignition engine fueled with bioethanol and gasoline blends at ultra-high injection pressure, Renewable Energy, Vol. 149, 2020, Pp. 80-90, ISSN 0960-1481.

[2] Baumgarten, C. Mixture formation in internal combustion engines. Berlin: Springer-Verlag Berlin Heidelberg, 2006, ISBN 978-3-540-30836-2.

[3] Merker, G. P.; Schwarz, C.; Teichmann, R. Combustion Engines Development – Mixture Formation, Combustion Emissions and Simulation. Berlin, Heilderberg: Springer, 2009, ISBN 978-3-642-02951-6.

[4] Aleiferis, P.G., Serras-Pereira, J., Romunde, Z. V., Caine, J. Wirth, M. Mechanisms of spray formation and combustion from a multi-hole injector with E85 and gasoline, Combustion and Flame, Vol. 157, Issue 4, 2010, Pp. 735-756, ISSN 0010-2180.

[5] Postrioti, L. Cavicchi, A., Paolino, D., Guido, C., Parotto, M., Gioia, R. D. An experimental and numerical analysis of pressure pulsation effects of a Gasoline Direct Injection system, Fuel, Vol. 173, pp. 8-28, 2016.

[6] Yao, X., Zhang, Z., Kong, X., Yin, C. Dynamic Response Analysis and Structure Optimization of GDI Injector based on Mathematical Model, International Journal of Reliability, Quality and Safety Engineering, Vol. 25, No. 2, 1850008, 2018.

[7] Cheng, Q., Zhang, Z. D., Guo, H., Xie, N. L. Simulation and analysis on electro-magnetic-thermal coupling of solenoid GDI injector, International Journal of Applied Electromagnetics and Mechanics, Vol. 46, Pp. 775-792, 2014.

[8] Kim, D., Shin, J., Son, Y., Park, S. Characteristics of in-cylinder flow and mixture formation in a high-pressure spray-guided gasoline direct-injection optically accessible engine using PIV measurements and CFD, Energy Conversion and Management, Vol. 248, 114819, 2021, ISSN 0196-8904.

[9] UNICA – União da Indústria de Cana-de-Açúcar e Bioenergia. Annual data on sugarcane, ethanol, sugar production and sugarcane cultivated area. Avaliable in: https://observatoriodacana.com.br, Accessed on 13 feb. 2023..

[10] Leite, R. C., Cortez, Barbosa, L. B. O etanol combustível no Brasil, Revista Biocombustíveis no Brasil: Realidades e Perspectivas, Ministério das Relações Exteriores, 2008. *In Portuguese*.

[11] Ajala, E.O., Ighalo, J.O., Ajala, M.A. et al. Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment and economic sustainability. Bioresour. Bioprocess. 8, 87, 2021.

[12] Mariano, A. P., Dias, M. O. S., Junqueira, T. L., Cunha, M. P., Bonomi, A., Maciel Filho, R. Utilization of pentoses from sugarcane biomass: Techno-economics of biogas vs. butanol production, Bioresource Technology, Vol. 142, Pp. 390-399, 2013, ISSN 0960-8524.

[13] Cheng, Q., Zhang, Z., Xie, N. Power losses and dynamic response analysis of ultra-high speed solenoid injector within different drive strategies, Applied Thermal Engineering, Vol. 91, Pp. 611-621, 2015.

[14] Pati, S., De, S., Chowdhury, R. Exploring the hybrid route of bio-ethanol production via biomass co-gasification and syngas fermentation from wheat straw and sugarcane bagasse: Model development and multi-objective optimization, Journal of Cleaner Production, Vol. 395, 136441, 2023, ISSN 0959-6526.

[15] Ferreira, A. M., Kajino, E., Maia, R., Salvio, R., Augusto, V. B. Development of 1D simulation model of fuel injector for PFI application, XXV Simpósio Internacional de Engenharia Automotiva, Blucher Engineering Proceedings, Vol. 4, Pp. 170-179, 2017, ISSN 2357-7592.

[16] Pakzad, S., Akhbari, S. Mahboubkhah, M. Kinematic and dynamic analyses of a novel 4-DOF parallel mechanism, J. Braz. Soc. Mech. Sci. Eng., Vol. 41, Pp. 561, 2019.

[17] Abadi, B. N. R., Mahzoon, M., Farid, M. Singularity-Free Trajectory Planning of a 3-RPRR Planar Kinematically Redundant Parallel Mechanism for Minimum Actuating Effort. Iran J Sci Technol Trans Mech Eng, Vol. 43, Pp. 739–751, 2019

[18] Malvezzi, F., Orsino, R. M. M., Stavropoulos, K. D. Parameter optimization for a vibration attenuation system on ambulance stretchers. In: 51st International JVE Conference, Dublin, 2021.

[19] Horn, A., Malvezzi, F., Orsino, R. M. M.On the use of Maggi's equation in the dynamic modeling of multibody systems. In: 46th International JVE Conference, 2020, St. Petersburg. On the use of Maggi's equation in the dynamic modeling of multibody systems. St. Petersburg, Russia: JVE Journals, Vol. 32, Pp. 166-171, 2020.

[20] Malvezzi, F., Orsino, R. M. M., Coelho, T. A. H. Lagrange's, Maggi's and Kane's Equations Applied to the Dynamic Modelling of Serial Manipulator. Lecture Notes in Mechanical Engineering. 1ed.: Springer International Publishing, Pp. 291-304, 2019, ISBN 978-3-319-91217-2.