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# PID TUNING TO CONTROL FORCE AND VELOCITY IN A LARGE-SCALE TRIBOMETER USING GENETIC ALGORITHM AND FUZZY LOGIC

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***Abstract.*** *Flexible riser pipes are used in conjunction with stiffeners (bend stiffeners) in offshore oil exploration and production to prevent exaggerated bending caused by marine currents and waves. The relative motion between risers and stiffeners leads to a thickness reduction of the polymeric outer layer, and determines pipe replacement. To investigate this problem, a tribometer with a normal load of up to 1 MN, capable of reproducing longitudinal reciprocating movements was developed. This was accomplished in a submerged medium in order to simulate the full-scale interactions that occur in the field. To keep the experiment parameter load and speed constant during the test, PID controllers were incorporated into the test rig using a programmable logic controller (PLC). Three methods were used to adjust the controller parameters. The first method was the reaction curve of Ziegler & Nichols. The second and third methods arose from the development of a genetic algorithm (GA) which uses fuzzy logic to simultaneously evaluate the integral time absolute error, overshoot and settling time. In the second method the GA made the adjustment using the transfer function obtained by system identification. In the third method, the GA used the real system for tuning PID, i.e., it had an online adjustment with the system in operation. The latter method showed the best performance in PID tuning of the system, fulfilling all the performance requirements.*

***Keywords:*** *Large-scale tribometer, Risers, Genetic algorithms, Fuzzy logic, Tuning of PID controllers.*

## 1. INTRODUCTION

Flexible riser pipes, composed of layers of polymers and cold-formed plain carbon steel strips, are widely used in offshore oil exploration and production. They transfer the oil from the wellheads to the platforms or from one platform to another. They are also used to inject water into the well and to conduct the electric and control cables to the wellhead.

These pipes are exposed to dynamic loads arising from waves and water currents below sea level that set the platform in movement. To avoid large curvature of the riser pipes near the connector/pipe transition, a bend stiffener is used. It reduces the cyclic bending loads at the transition from the pipe to the connector.

Nevertheless, the bend stiffener does not restrict the riser pipe axial movement and so the riser pipe slides in relation to the bend stiffener, leading to the wear process of the polymeric layer of the outer riser pipe. The exposure of plain carbon cold-formed steel strips to sea water leads to their quick corrosion and then the whole system has to be replaced.

So, to reproduce field conditions that are observed in contact between flexible riser pipes and bend stiffeners, a new test rig was conceived, designed and constructed in the Laboratory for Friction and Wear Technology at the Federal University of Uberlandia.

The apparatus is able to test pipes with an internal diameter ranging from four (101.6 mm) to nine inches (228.6 mm), with normal loads of up to 1 MN. The maximum sliding velocity is 10 mm/s and the maximum stroke is 200 mm. Figure 1 schematically presents the large-scale tribometer.

In order to keep the test parameters, force and speed, constant during the process, PID controllers were incorporated into the control and drive system using a programmable logic controller (PLC).

In this apparatus, force and velocity function independently but they can cause a disturbance in the oscillation loop and vice versa. This happens because the action of one of these parameters restricts the other. Thus, the closed loop control system must work correctly and effectively in order to achieve the best performance of the tribometer. So, the PID controller parameters have to be adjusted accordingly.

In this context, the simple objective method of reaction curve of Ziegler and Nichols (Nicula, 2010) for tuning PID controllers can be considered. Emphasis should also be given to the genetic algorithm (GA) which is one of the effective methods for PID tuning (Nahapetian *et al*., 2008).

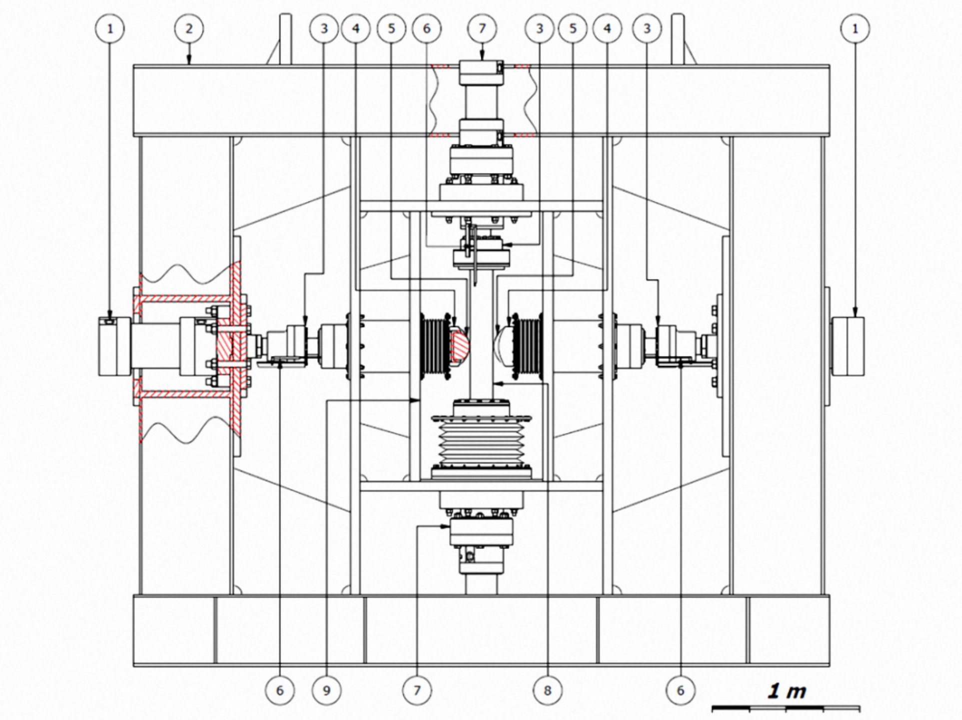

Figure 1. Schematic representation of the large-scale tribometer. (1) horizontal hydraulic cylinder, (2) steel structure, (3) normal load cell, (4) sample holder, (5), bend stiffener specimen, (6) LVDT (linear variable differential transformer), (7) vertical hydraulic cylinder, (8) flexible riser pipe sample and (9) water reservoir.

When using genetic algorithms (GAs), a function to be maximized or minimized has to be chosen. This is known as the evaluation function. In the case of the PID tuning, this function indicates combinations of constants for the controller. To evaluate the fitness of a set of PID constants it is common to use the integral time absolute error - ITAE. However, if this function is chosen, other important performance parameters such as overshoot and settling time are disregarded. Thus, for an optimized fit of PID parameters, the integral time absolute error, the overshoot and the settling time must be taken into account. In order to evaluate all these parameters simultaneously, fuzzy logic was used in the evaluation function.

To accomplish the PID tuning, it is common to identify the system transfer function, because working with a theoretical model brings lots of advantages regarding the processing speed and allowing an application of several methods of tuning in a more simplified and rapid manner (Ljung, 1999).

However, the identification of the transfer function of a system is not easy and requires skilled and experienced personnel. Moreover, a linear model does not always describe perfectly the characteristics of a system (Ljung, 1999).

In order to evaluate the best way to adjust the PID for the systems proposed in this work, two approaches are used, tuning with and without system identification.

## 2. LARGE-SCALE TRIBOMETER

The riser pipe sample is put in reciprocating vertical movement by two hydraulic cylinders, while two identical samples of the bend stiffener material are pressed against the pipe by two other horizontal hydraulic cylinders.

The velocity and direction of oscillation of the vertical cylinder are controlled by a proportional directional valve, while the normal force that is applied by the horizontal hydraulic cylinders is controlled by a pressure control valve. These two valves are controlled by the PLC.

The horizontal force is measured by two load cells (Figure 1). The sliding velocity is measured using a linear variable differential transformer (LVDT). The data acquisition is carried out using a Spider8® signal conditioner module configured by the software Catman®.

A supervisory system that acquires the test data and controls the whole system was developed using the software Labview®. The force and sliding velocity data are transmitted to the supervisory system by the Catman® using ActiveX controls.

All PLC variables are available via the Ethernet communication in an OPC server (OLE for Process Control) that was generated using a software from Smart Software Solutions, named CoDeSys Gateway Server. Thus, the PLC variables can be read and changed by Labview®.

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Using OPC communication and Catman® ActiveX controls, the supervisory system can then get all the measurement data and send them to the PID controllers of the PLC, as well as choose the constant values and the setpoint of these controllers.

# 3. METODOLOGY

## 3.1 Development of Genetic Algorithms (GAs)

In this work, the GAs development was accomplished using the software Matlab®. Two GAs were developed. The first one, GA1, is applied to the identified transfer function and the second GA2 is intended for use in the plant. The following are the characteristics of the developed GAs.

### 3.1.1 Evaluation Function of GA1

The first step in constructing a GA is to define its evaluation function. The population of individuals to be evaluated is that of the input for the evaluation function and is composed of a matrix in which each row corresponds to an individual. Each individual has the three controller constants Kp, Ki and Kd.

Through fuzzy logic it is intended to create an evaluation function that simultaneously analyzes the integral time absolute error, the overshoot and the settling time, so that the lower the value of these parameters, the greater the "rank" that the individual will receive.

In order to obtain the system response, a test function is built using the Simulink® of Matlab®, where this function, Fig. 2, receives as input data the reference values (setpoint "C") and the PID controller constants, the system transfer function ("G"), the maximum and minimum values for saturation of the control signal and the test time in seconds (time for obtaining the system response). The response is returned in the variable "Out1".

Note that besides the individuals and the transfer function, other parameters are needed such as the maximum and the minimum control signals, the setpoint and the test time. These parameters are part of the input data of the evaluation function. They are entered using the main function of GA1.

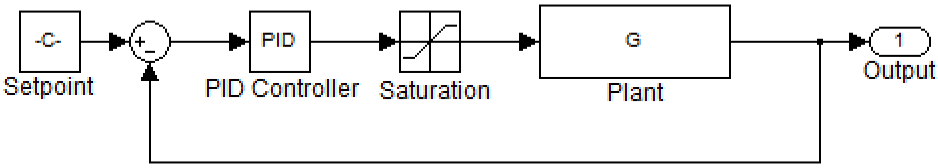


Figure 2. Test function of GA1 for obtaining the system response for each individual.

The criterion to calculate the settling time (2% or 5%, for example) is also established by the main function of GA1. Afterwards, it is necessary to define, for each variable, the corresponding fuzzy terms and the membership functions, so that the variables can be evaluated using fuzzy logic strategy (Kohagura, 2007). For each variable, three fuzzy sets are assigned as follows: “low”, “medium” and “high”. The membership functions of the three fuzzy sets of variables overshoot and settling time follow the principle of the fuzzy sets of integral time absolute error, Fig. 3. In this figure $ITAE_{min}$ represents the minimum value of integral time absolute error found between all tested individuals, $ITAE_{avg}$ represents the average value, and $ITAE_{max}$ represents the maximum value.

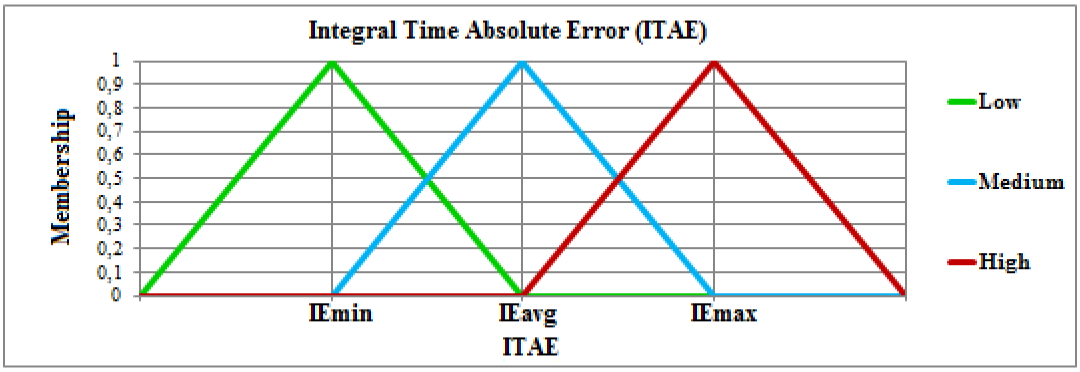


Figure 3. Membership functions of integral time absolute error.

Due to its calculation facility, triangular membership functions are defined for the fuzzy sets. Thereafter, the fuzzy sets for the output variable “rank” have to be defined with their respective membership functions, Fig. 4.

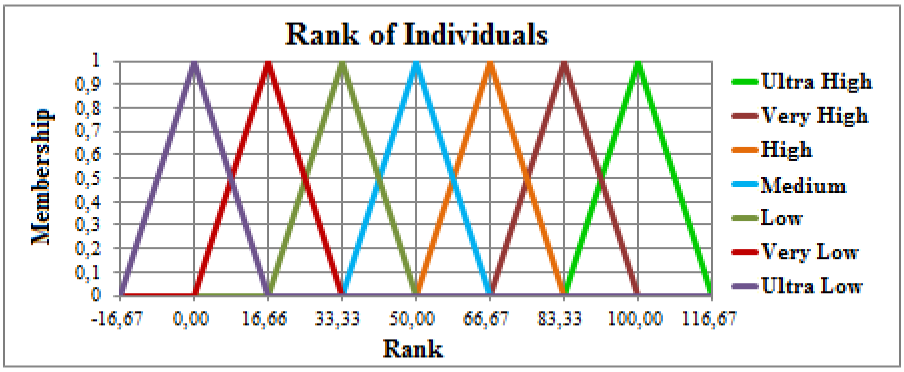


Figure 4. Membership functions of rank.

To perform the inference, only rules with “AND” operators are used. Table 1 shows the rules used in the fuzzy ranking system. “UH” is for "Ultra High", “VH” is for "Very High", “H” is for "High", “M” is for "Medium", “L” is for "Low", “VL” is for "Very Low" and “UL” is "Ultra Low".

Table 1. Fuzzy rules (used operator: “AND”).

| Rules | ITAE | Overshoot | Settling time | Rank |
|---|---|---|---|---|
| 1 | L | L | L | UH |
| 2 | L | L | M | VH |
| 3 | L | L | H | H |
| 4 | L | M | L | VH |
| 5 | L | M | M | H |
| 6 | L | M | H | M |
| 7 | L | H | L | H |
| 8 | L | H | M | M |
| 9 | L | H | H | L |
| 10 | M | L | L | VH |
| 11 | M | L | M | H |
| 12 | M | L | H | M |
| 13 | M | M | L | H |
| 14 | M | M | M | M |
| 15 | M | M | H | L |
| 16 | M | H | L | M |
| 17 | M | H | M | L |
| 18 | M | H | H | VL |
| 19 | H | L | L | H |
| 20 | H | L | M | M |
| 21 | H | L | H | L |
| 22 | H | M | L | M |
| 23 | H | M | M | L |
| 24 | H | M | H | VL |
| 25 | H | H | L | L |
| 26 | H | H | M | VL |
| 27 | H | H | H | UL |

Because of its simplicity, the center of the sum method (COS) is used in defuzzification. At the end of the defuzzification process, the individuals are ordered according to the obtained score in a matrix in decreasing order. The individual with the highest rank is placed in the first line of this matrix. The values of Kp, Ki, Kd, integral time absolute error), overshoot, settling time and corresponding rank are found in each line. Figure 5 shows an overview of the procedure performed by the evaluation function GA1.

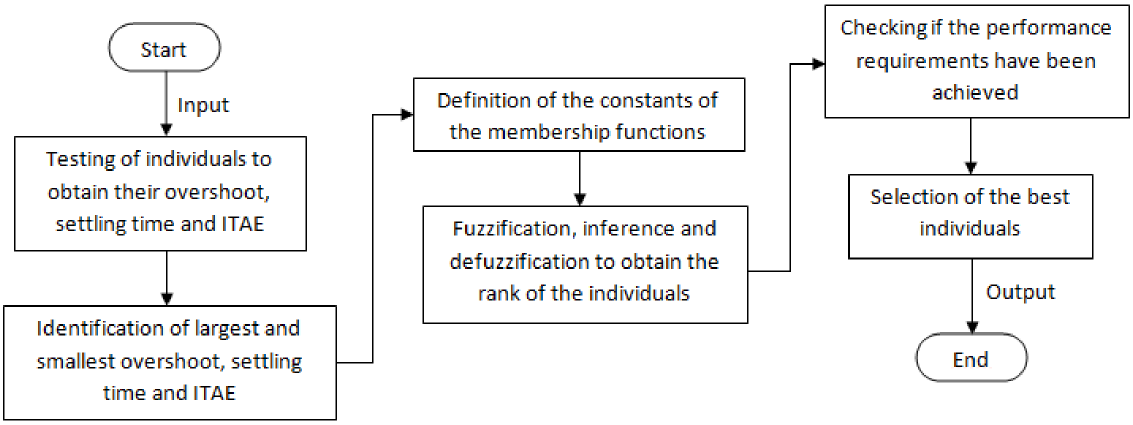


Figure 5. Procedure performed by the evaluation function of GA1.

### 3.1.2 Evaluation Function of GA2

The difference between the evaluation functions GA1 and GA2 is in the test function. Instead of using the Simulink® of Matlab®, as in the GA1 evaluation function, a test function that was created in Labview® is used for obtain the response of the real plant.

After the input data has been received, to test an individual in the plant, the evaluation function of GA2 creates four text files (extension ".txt") in the same folder, as shown in Fig. 6a. The first file comprises the setpoint; the second has the constants: Kp, Ki e Kd of an individual; the third file contains the test time and the fourth file has the value of a variable called token.

At the same time, the test program is running and reading the value in the token variable, as shown in Fig. 6b. When the value of token becomes one, the test program executes a test in the plant using the parameters read in the files created by the evaluation function. At this time, the evaluation function is reading the token value.

Then, at the end of the test, the test program creates two text files, one contains the obtained time vector and the other comprises the corresponding output, and changes the token. When the token becomes zero, the evaluation function evaluates the tested individual using the system response that is in the files created by the test program. At the same time, the test program waits for a request of a new test by evaluation function, according to the procedure presented in Fig. 6. This figure shows an overview of how the evaluation function works and it also shows the GA2 test program. Figure 7 shows the system data flow.

Having defined the evaluation functions, other parameters of GAs such as the size of the initial population, the selection method for crossover, the method and rate of crossover, the method and rate of mutation and the method and rate of individual reinsertion were defined.

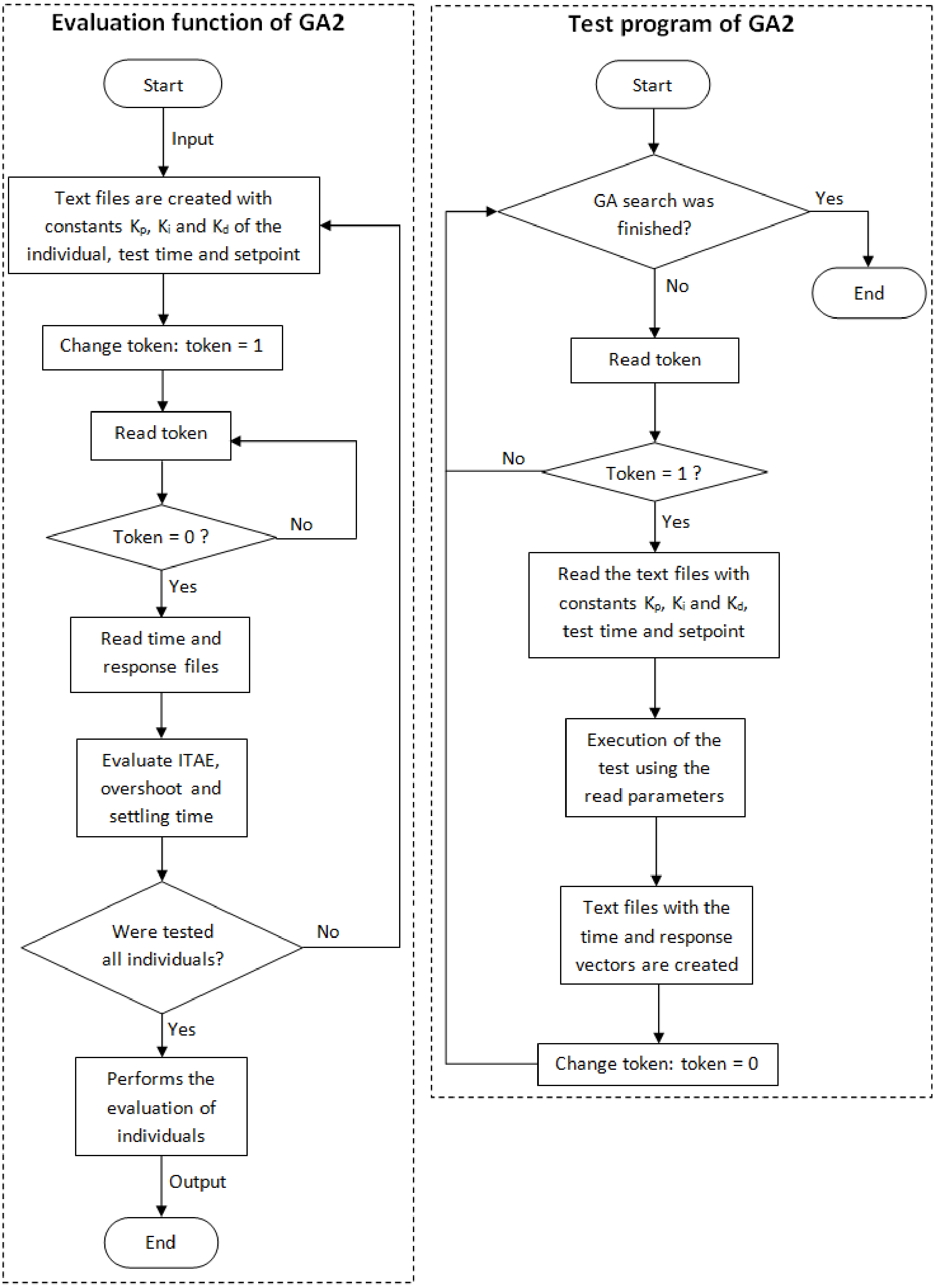
Two types of mutation were used in GAs. One was called "higher mutation" in which one individual of the offspring is randomly selected. Then one of the constants Kp, Ki or Kd is arbitrarily selected and multiplied by a number between 0 and 2 that is also randomly selected. In the other type of mutation, called "lower mutation", the constant is multiplied by a random number between 0.9 and 1.1. This mutation is responsible for the fine tuning of the controller parameters.

It is important to note that when using "higher mutation", even if the best Kp, Kd and Ki are outside the intervals where the initial population was generated, the GA can find these parameters.

Using different test configurations, it was observed that the best performance of GA1 for an initial population of 50 individuals could be obtained with the configuration presented in Tab. 2. This configuration was also applied to GA2.

Table 2. Final configuration of GAs.

| | |
|---|---|
| **Type of reinsertion** | fitness-based (parents and offspring) |
| **Number of reinserted individuals** | 10 |
| **Selection method for crossover** | Linear Ranking |
| **Type of crossover** | Intermediate recombination |
| **Number of offspring per generation** | 40 |
| **Number of "higher mutation"** | 75% of offspring |
| **Number of "lower mutation"** | 12,5% of offspring |



a) b)

Figure 6. Overview of the a) evaluation function and of the b) test program of GA2 that have in common the variable token.

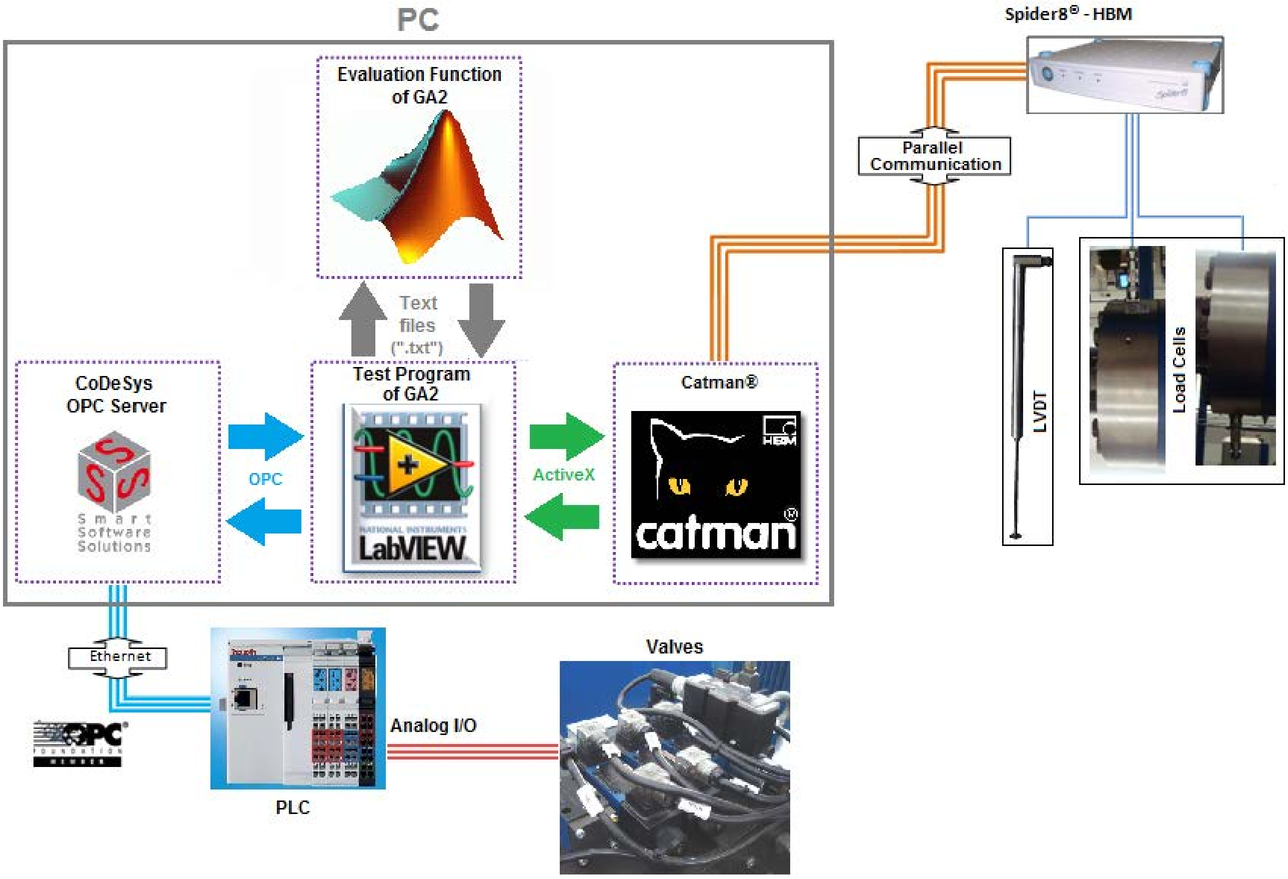


Figure 7. Data flow diagram of the control system for adjusting the controller parameters by GA2.

## 3.2 Implementation of the PID Tuning Methods

In the large-scale tribometer, forces of about 60 kN are required to simulate the contact between the four and six inch flexible riser pipes. The sliding velocity is about 4 mm/s and the reciprocating sliding stroke is about 30 mm. These values were used as setpoints in the PID tuning.

Figure 8 shows the procedure for tuning the parameters of the PID controllers for the sliding velocity and the normal force.

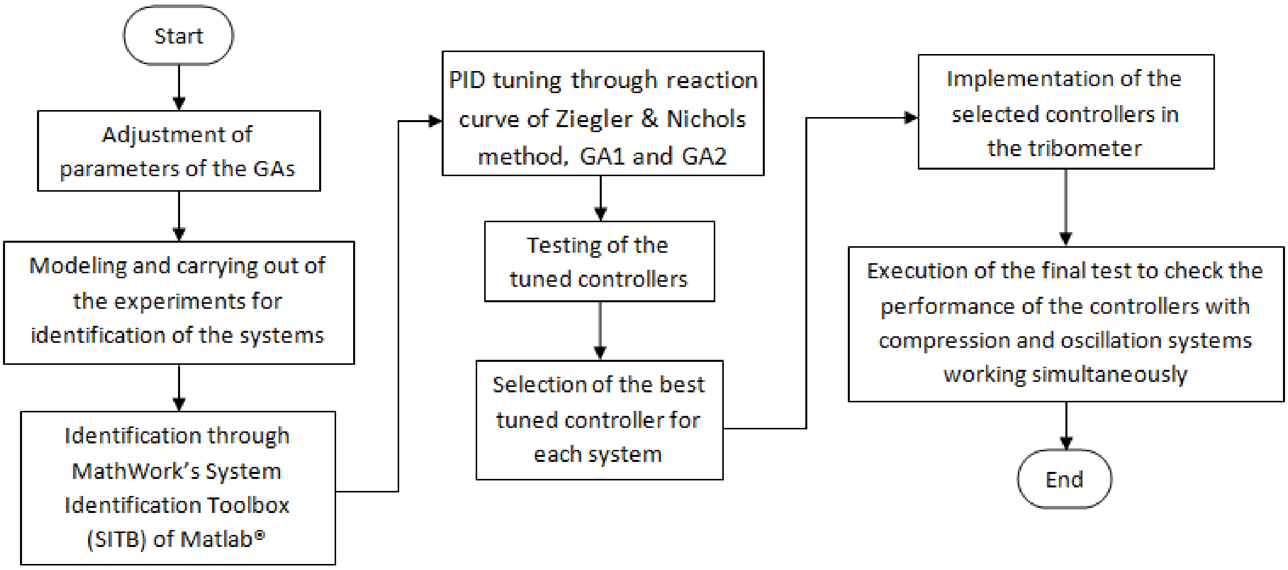


Figure 8. Overview of the procedure for adjusting the parameters of PID controllers.

## 4. RESULTS AND DISCUSSION

Figure 9 shows the results obtained during the large-scale tribometer PID tuning for a setpoint of 60 kN. The graphic described by the mathematical model represents the results obtained using the transfer function obtained by system identification presented in the reference (de Freitas, 2011). The other graphics describe the return when using the real plant.

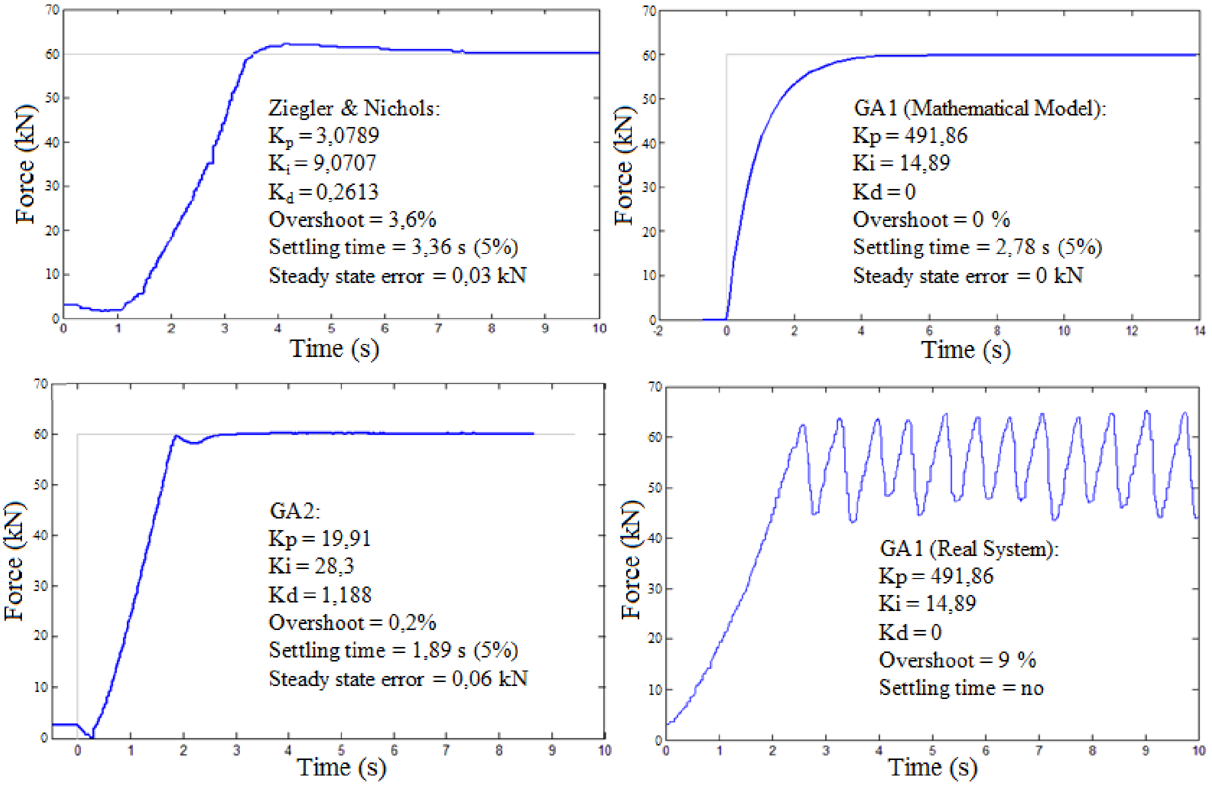


Figure 9. Results obtained during the PID tuning for a compression load of 60 kN.

Figures 10 and 11 show the results obtained when adjusting the PID parameters for the sliding velocity of 4 mm/s with the system moving upwards and downwards. Concerning the overshoot, the settling time and the steady state error for each method of PID tuning, it was observed that the Ziegler & Nichols method was successful in controlling only the force.

The developed genetic algorithm GA1 for PID tuning using the identified transfer function led to very good results for the mathematical model. However, when implementing the obtained controllers by this method in the real system, a satisfactory performance was obtained only for the oscillation system. This shows the difficulties in system identification, i.e., it is very difficult to find a mathematical model capable of representing a real system satisfactorily.

The use of a genetic algorithm for PID tuning using the real plant (GA2) showed a better performance, both for the compression system and for the reciprocating system. This shows the advantages of using this method, since the GA tries to improve the output of the real plant, avoiding errors and deviations that may be made in the identification of systems.

The great advantage of the designed genetic algorithm to adjust the PID parameters using the identified transfer function rather than the actual plant is that it may be performed for a very large number of generations of GA, and thus a much greater refinement can be achieved. But to have a satisfactory result, it is necessary to successfully identify system.

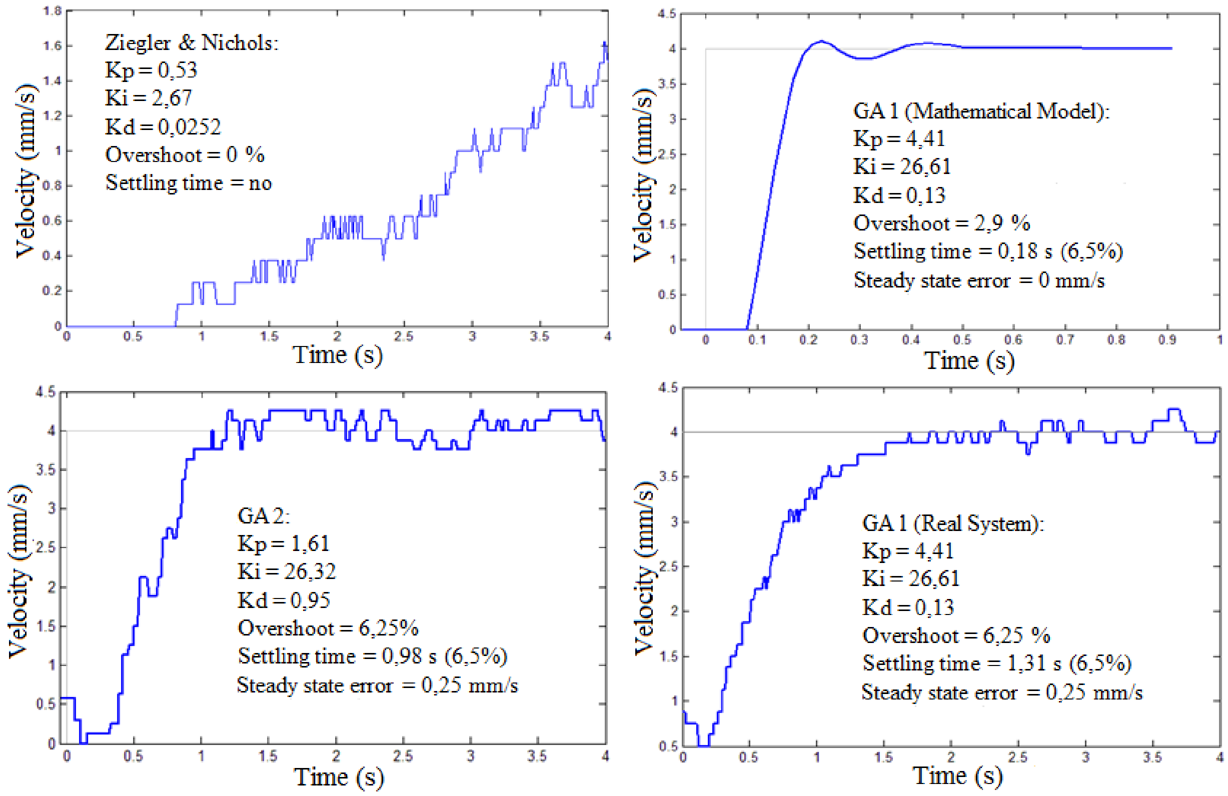


Figure 10. Results obtained during the PID tuning for an upwards sliding movement with a velocity of 4 mm/s.

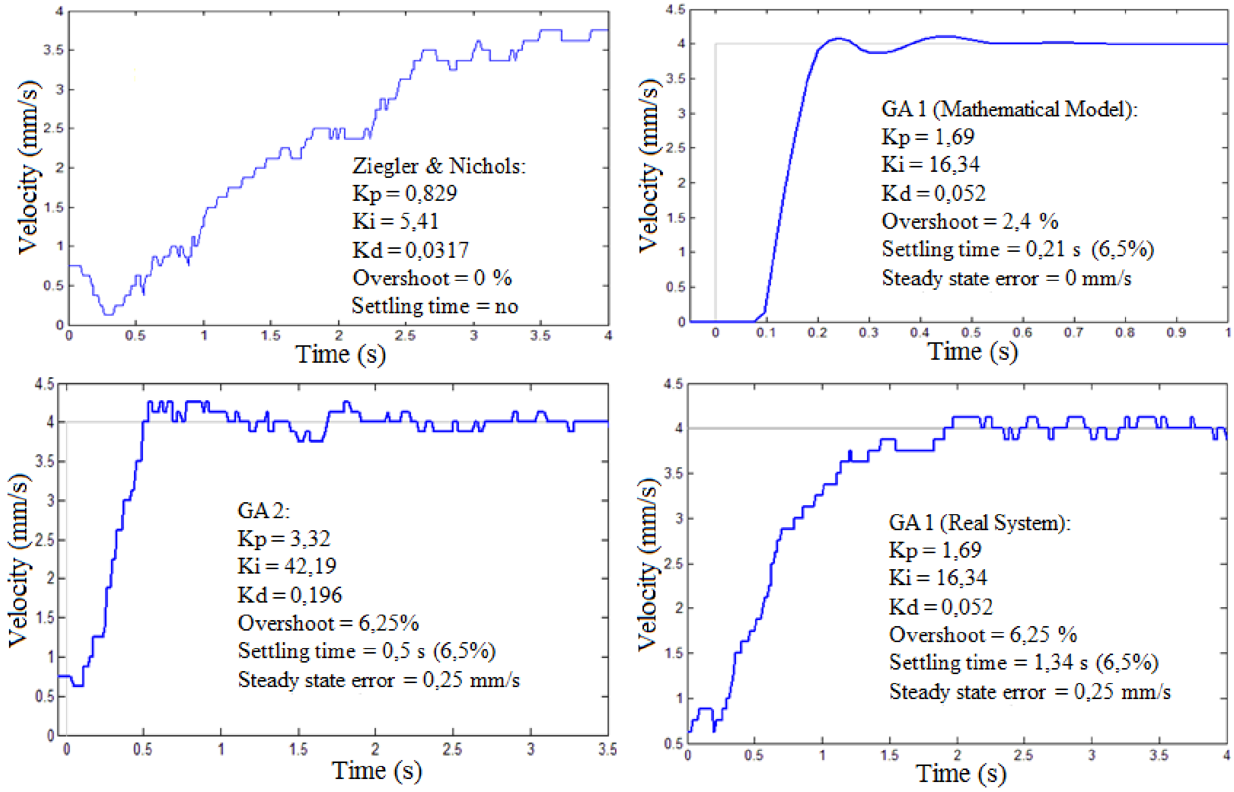


Figure 11. Results obtained during the PID tuning for a downwards sliding movement with a velocity of 4 mm/s.

After performing the PID tuning, the performance of controllers with both systems operating at the same time was evaluated, for the reason that the compression system causes a disturbance in the oscillation system and vice versa. The controllers adjusted by GA2 were used, because they showed a better performance when operating separately.

Figure 12 shows the performance of the sliding velocity system before and after the implementation of the controller adjusted by GA2 for a setpoint of 4 mm/s. The values close to zero correspond to the reversion during the oscillatory movement.

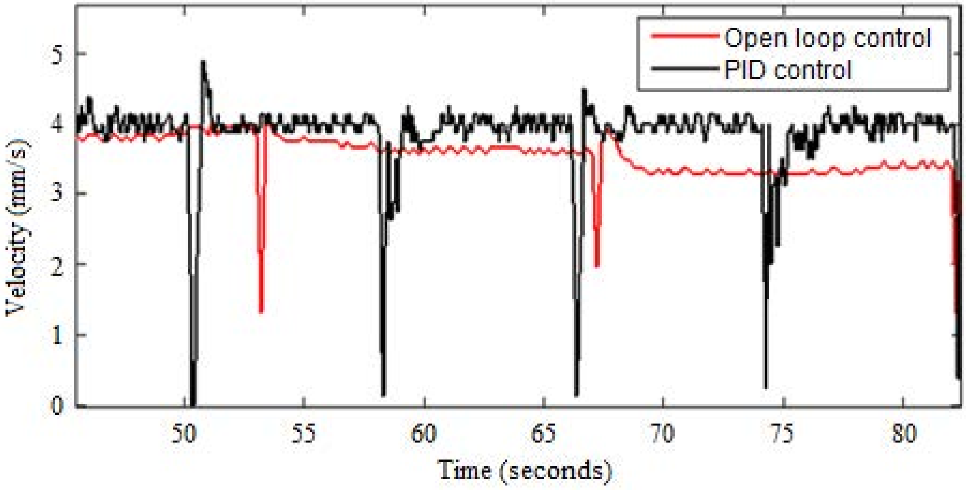


Figure 12. Sliding velocity behavior before and after the implementation of the PID controllers.

Figure 13 shows the performance of the force system before and after the implementation of the controller, adjusted by GA2 for a setpoint of 55.6 kN.

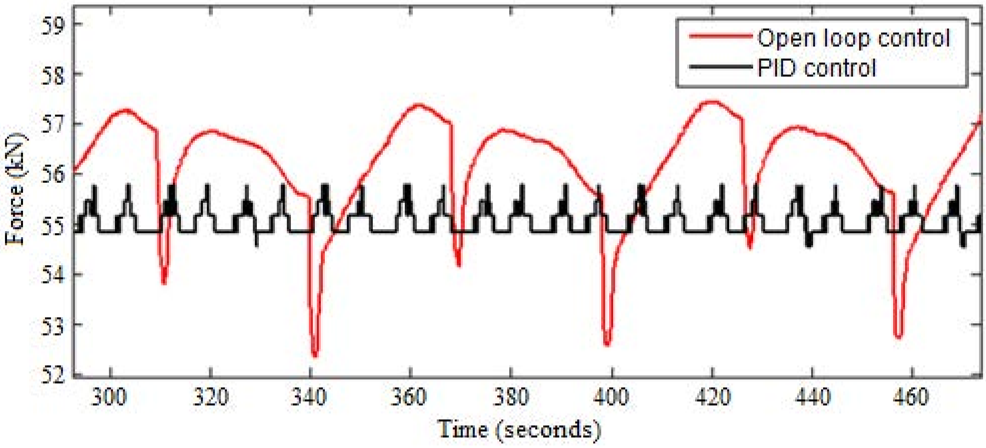


Figure 13. Compression force behavior before and after the implementation of the PID controllers.

In the oscillation system, before the implementation of the PID controller, it was observed that the sliding velocity was at the beginning close to 4 mm/s but during the test it was constantly changing. This was caused by changes in the system due to heating of the hydraulic oil, to changes in the coefficient of friction between the riser pipe and the stiffener, among other factors. The important thing is that with the implementation of the PID controllers, this did not happen anymore and the sliding velocity remained close to 4 mm/s.

The non-controlled compression system had an oscillation of about ± 3 kN while the controlled system showed an oscillation of about ± 0.5 kN. Thus, the controlled system maintains a more constant compression force, bringing greater reliability for the tests. In the system uncontrolled, it was also observed that, during the test, the compressive force had a tendency to decline due to temperature changes of the hydraulic oil. These effects occurred on a smaller scale compared to the velocity variations. But with implementation of the PID controller, these effects disappeared.

## 5. CONCLUSIONS

The fuzzy logic proved to be a powerful tool when applied to the evaluation function of the genetic algorithms in PID tuning. It was able to evaluate simultaneously integral time absolute error, overshoot and settling time for each PID controller, helping the GAs to make the best choices taking into account these three parameters.

The tuning of PID controllers for the compression and oscillation system in a large-scale tribometer was carried out successfully, so that the performance requirements for each system have been met. The implementation of PID controllers in the supervisory program made it possible to achieve the goal of maintaining the compression force and the sliding velocity constant, and so helping to increase the repeatability of the wear tests as well as their reliability.

## 6. ACKNOWLEDGEMENTS

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