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ORIGINAL ARTICLE

Control system to counteract axial displacement during the welding of huge pipes

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Abstract Development research has been carried out in order to solve a practical industrial problem: to counteract axial displacement (axial drift or axial creep) of workpieces during the welding process. Solutions found in the literature generally provide adequate results; however, they are mechanically complex with high purchase and maintenance costs. A mechanically simple and inexpensive solution is proposed in this paper. Axial drift is measured with a low-cost custom-built contact displacement sensor. This sensor can measure axial drift without calibration or set-up operations. It is highly robust in order to function correctly in industrial conditions. A pneumatic cylinder moves the idle turning roll along a rail, modifying the longitudinal position of the idle turning roll in order to counteract axial drift. The position of the idle turning roll is controlled by a control algorithm, which consists of a set of rules. Tests were carried out in order to validate the proposed solution, which can be applied to existing turning rolls thereby significantly reducing costs.

Keywords Axial displacement · Anti-drift · Turning rolls · Circular welding · Welding pipes · Encoder

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1 Introduction

The manufacturing of metal products is now focused on the production of huge weighty pieces for various application areas: wind power, petrochemicals, etc. The construction of this type of product requires welding together cylindrical parts of large dimensions, called pipes. This welding process can be performed automatically or semi-automatically, following different types of welding processes:

- Within the procedures for arc welding, there are many variations depending on various parameters in the welding process, such as the use or non-use of flux and the electrode type. These factors determine the nomenclature of the welding process TIG [1], MIG [2], GMAW [3], SMAW [4], etc.
- Welding processes can also be classified into two different types: longitudinal and circular.

In the circular welding process, pipes are welded along their circumference using a circumferential weld bead. To do this, the entire workpiece must be rotated in order to maintain the welding electrode in a fixed position and to allow the complete circumference of the piece to be placed over the welding head. The welding head is fixed to a welding arm as shown in Fig. 1.

Turning rolls placed at both ends of the piece are usually used to rotate the workpiece. The workpiece is rotated as the friction of the wheels of the turning rolls is transmitted to the surface of the workpiece. There are several suppliers of these systems. A driving/power turning roll is needed to transmit the movement to the workpiece. In most cases, there is no need for a second driving turning roll; since the force generated by the first is able to rotate the piece, a simple turning roll helps support the weight of the workpiece and provides stability to the system. This second type of turning roll is called an idle turning roll.

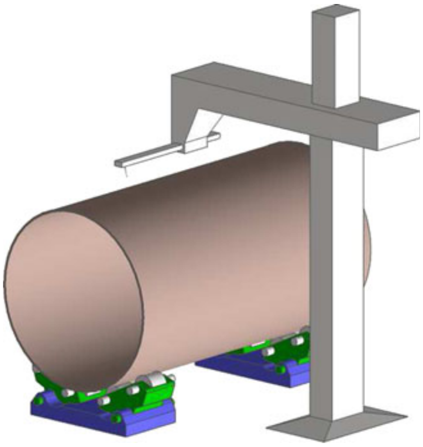

Fig. 1 Circular welding process

An overview of a turning roll can be seen in Fig. 2. The turning roll (in blue and yellow) houses the drive motors of the driving/power turning roll.

Unwanted axial movement is produced when the piece starts spinning due to irregularities in its symmetry and a lack of precision in placing the workpiece on the turning rolls. This axial movement or drift is depicted in Fig. 3.

Because of the narrow longitudinal correction permitted in the welding head, in order to correct this unwanted displacement of the workpiece, the welding process must be stopped and the workpiece re-positioned on the turning rolls. To accomplish this, a crane or other machinery may be needed, with the consequent loss of productivity. Moreover, if the drift is excessive, the turning roll may fall to the ground.

There are two types of commercial solutions designed to mitigate this effect:

- Solutions based on raising and lowering the axes of the idle turning roll
- Solutions based on varying the eccentricity of the axes of the idle turning roll

These solutions share several common features:

- Displacement is measured with a high-precision non-contact sensor, usually laser or ultrasound.

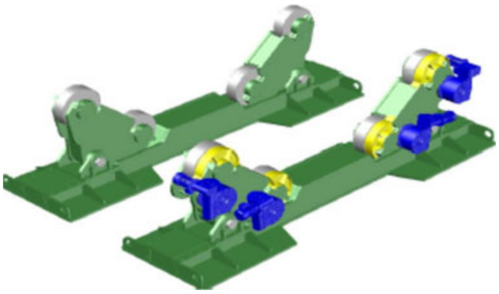

Fig. 2 The turning roll—composed of power turning roll and idle turning roll

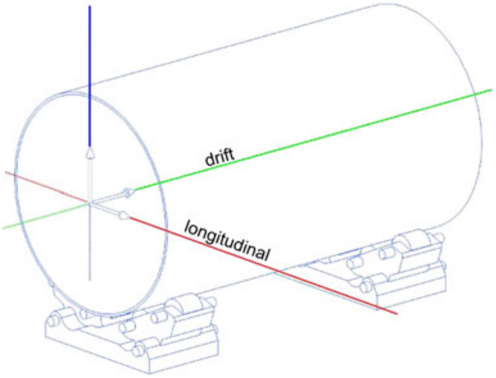

Fig. 3 Representation of longitudinal and axial movement or drift

- The actuators are based on servo-acting on the wheel axes of the turning roll.
- These solutions are specific products offering high accuracy (about 1–2 mm, of longitudinal displacement).

In the context of this work, these solutions have been discarded for two main reasons:

1. The high cost associated with the replacement of the current systems for anti-drift systems. These solutions also have higher operating and maintenance costs: high accuracy sensors that require precise calibrations, specific staff training, long set-up times, etc.
2. The company wants to keep the existing turning rolls, making the fewest possible changes.

Thus, the development and design of devices and control systems for controlling unwanted displacement in the turning rolls is necessary. This research work addresses these issues in the day-to-day cases encountered in the welding processes in the company Ingeniería y Diseño Europeo, S.A. (Gijón, Spain).

The use of robots for the welding process has been the focus of various research works in recent years, for example designing new automatic welding systems [5–8], software applications [9] or the on-line detection of defects using different methods [10, 11].

The causes of axial drifting and control solutions were analysed in [12–14, 18] and patents for mechanically complex anti-drift systems have been published [15–17].

The objective of this research work is to design and test an innovative system to control axial displacement or drift in the pipes during the welding process. The control system was designed to meet the following requirements: simplicity, robustness, low cost, no need to carry out substantial modifications of the turning rolls and no need for complicated adjustments or maintenance. As far as the authors know, this is the first time that an anti-drift control system that fulfils the aforementioned requirements has been designed and tested.

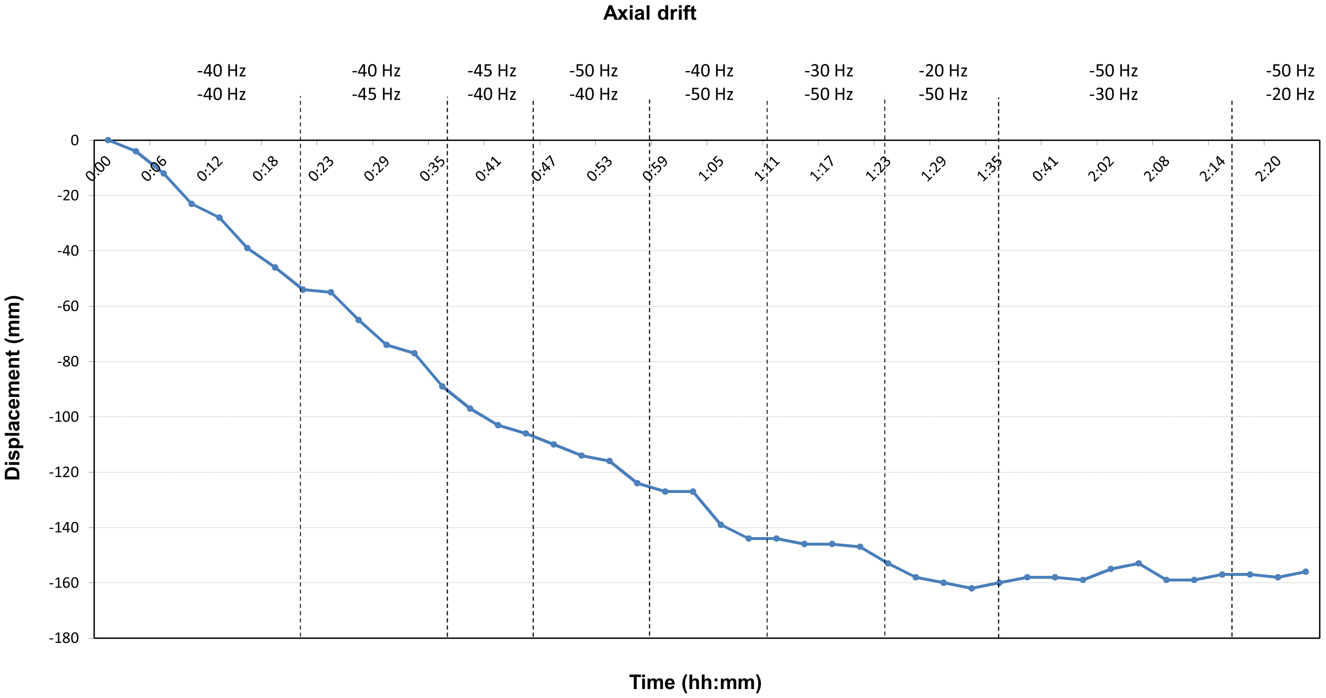

Fig. 4 Test varying the frequency of the supply voltage of the motors in the power turning roll

In the following sections, a study of drift displacement is presented, the design and implementation details of the control system proposed are described and the results obtained in tests are shown.

2 Study of drift displacement

The set of causes influencing axial displacement in the workpieces are varied, but the most significant are:

- Lack of uniformity in the cylindrical form of the workpieces
- Irregularities in the position of the turning rolls: different heights, inclinations or wear after continued use

These factors cause the appearance of forces in the longitudinal axis sufficient to cause unwanted axial displacement.

A study into the factors that could be modified to control axial displacement and its effects was conducted. As the system design must be easily adapted to the equipment currently in use by the company, the set of factors to study was reduced to:

1. Rotation speed of the turning rolls: by changing the frequency of the supply voltage of the motors in the power turning roll
2. Rotation direction in the pipe: by changing the direction or the frequency of the supply voltage of the motors in the power turning roll
3. The position of the turning rolls: by modifying their longitudinal position

Tests were carried out to verify the correlation between the three variables with longitudinal displacement or drift. In the cases of speed of rotation and rotation direction, these variables are governed indirectly by the frequency of the supply voltage of the driving power turning roll.

2.1 Speed of rotation of the power turning roll

The displacement of the workpiece caused by changing the frequency of the supply voltage of the motors in the power turning roll is shown in Fig. 4. All of these frequencies have the same sign, that is, they have the same rotation direction.

For proper operation of the welding process, sudden movements that can cause a discontinuous movement of the workpiece must be avoided. Thus, the difference between the frequencies must not be excessive. The test shows that differences in the speed of the turning rolls cannot be used as a control parameter to counteract drift.

2.2 Rotation direction in the pipe

The influence of rotation direction is shown in Fig. 5. The change of the rotation direction is performed through a reversal of the supply voltage of the motors in the power turning roll.

As can be seen, if the system is running at a rotation speed V and the longitudinal displacement or drift occurs in

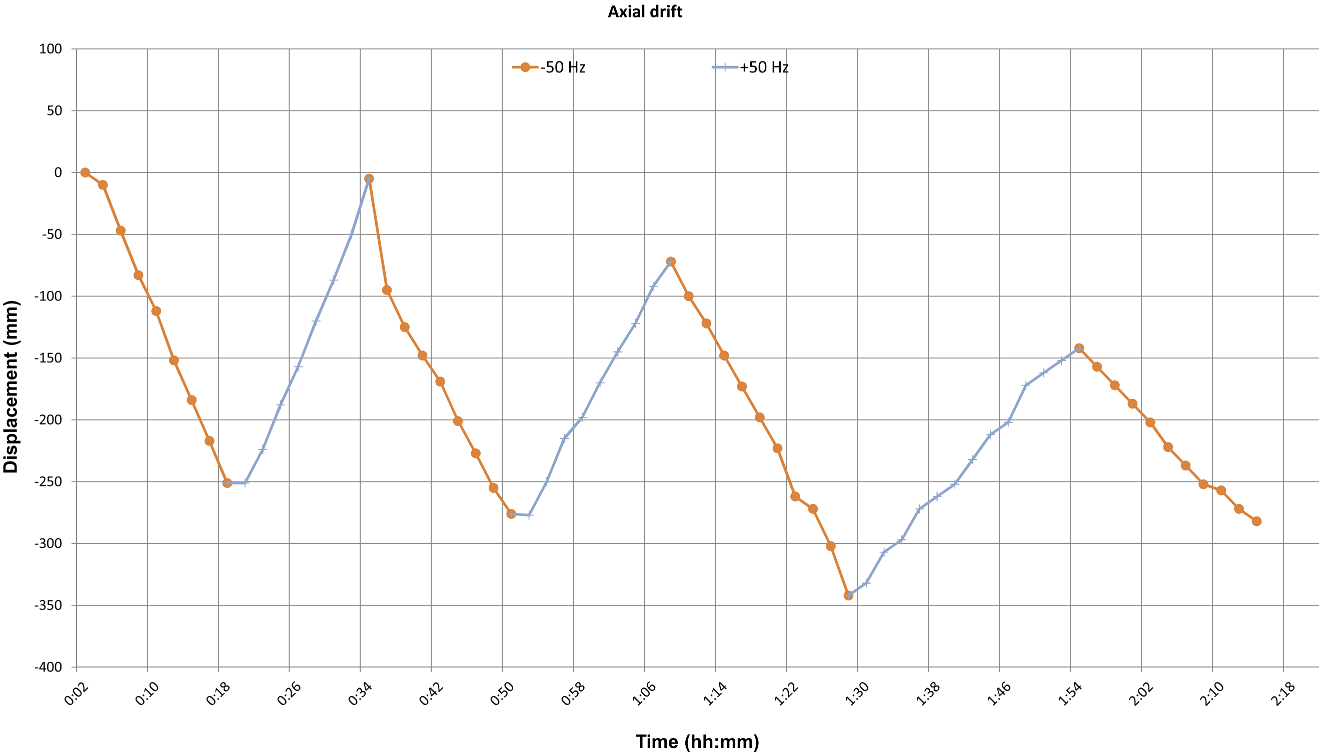

Fig. 5 Test varying the rotation direction

a certain way, by varying the rotation speed to $-V$ (same speed and opposite direction), the longitudinal displacement or drift will be in the opposite direction. Therefore, the direction of rotation determines the direction of the axial displacement. However, this method is only a partial solution since the change of rotation direction of the workpiece involves a stop and start of the longitudinal welding in the opposite direction.

2.3 Position of the turning roll

The following sets of tests were designed to determine the influence of the longitudinal position of the turning rolls on the axial displacement or drift. The results can be seen in Fig. 6. The proposed system for varying the longitudinal position (Fig. 3) of the turning roll can be seen in Fig. 7.

In this test, different longitudinal displacements in the position of the turning roll are performed with different rotation directions. The supply voltage of the motors in the power turning roll was kept constant in order to isolate the effects of the longitudinal displacements on the position of the turning roll. For example, in the second segment, the original position of the turning roll was modified and a lateral displacement of +13.5 cm occurred. The drifting speed also increased. In the third segment, the longitudinal position was changed in the other direction, reversing the direction of the axial displacement.

As a result of this test, it can be concluded that:

- A change in the direction of rotation of the pipe directly affects the direction of the displacement. This conclusion was also reached in previous tests.
- The lateral displacement of the turning rolls influences the axial displacement directly and proportionally. This factor can be used to control drift displacement.

After the conclusions reached in the tests described in the previous section, an automatic system to control axial displacement during welding of cylindrical elements (pipes) was designed and developed.

3 Design and implementation of the control system to counteract axial displacement

3.1 Hardware of the control system

A displacement sensor is needed to perform automated measurement of the displacement or drift, taking into account the following requirements:

- Accuracy: An accurate measurement of the axial movement in the turning roll must be provided. For the tests performed, a resolution of ±5 mm was sufficient.

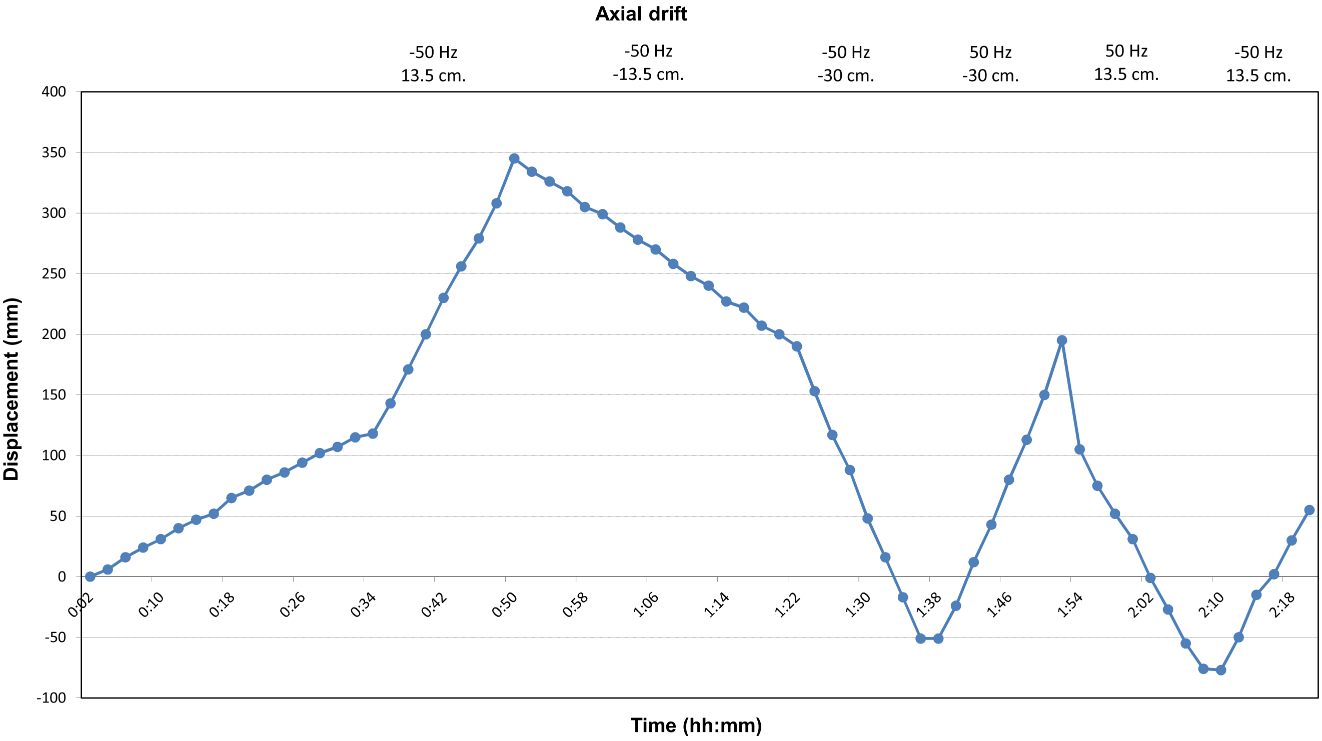

Fig. 6 Test varying the longitudinal position of the turning roll

- Robustness: The system must operate in harsh environments.
- Usability: The system must be easy to use. Complex procedures such as calibration operations may eventually lead to errors in the operation process.

In compliance with these requirements, two alternatives were initially evaluated: non-contact displacement sensors and contact measurement sensors. The non-contact displacement sensors (see Fig. 8) have high precision, but were discarded for the following reasons:

- Because non-contact displacement sensors must be on a horizontal plane aligned with the turning roll, they require accurate initial calibration each time they are used. It is therefore necessary to have qualified staff to operate these sensors.
- The thickness of the walls of the pipes is very fine, making it difficult to measure.
- Any object between the pipes and the sensor can cause errors in the measurement.

Thus, a contact-sensor mechanism is used to perform the measurements. A measurement system based on commercial encoders was designed because of its reliability, accuracy and low cost. Two encoders are used in the measurement system: one for measuring the axial displacement in the pipes and one to provide the direction of rotation of the pipe.

The rotational motion of the workpiece produces friction with the roller which rotates the direction encoder. Thus,

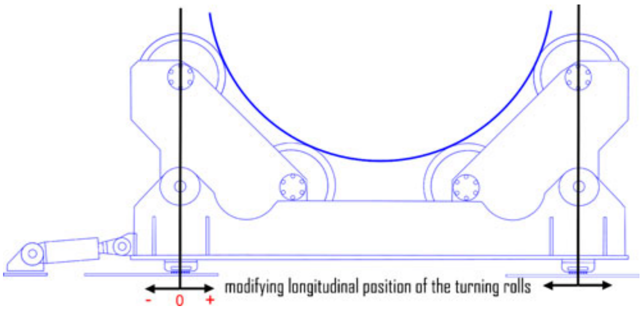

Fig. 7 Proposed system for varying the longitudinal position of the turning roll

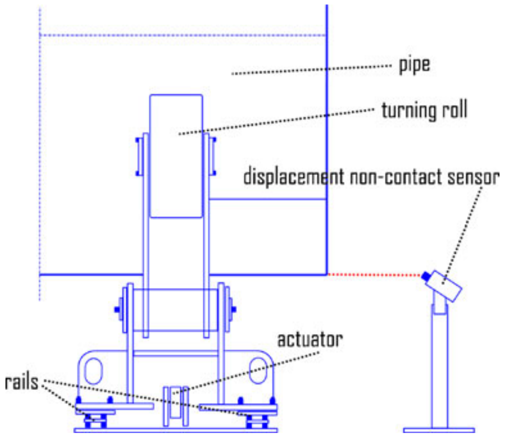

Fig. 8 Non-contact mechanism to perform the measurement

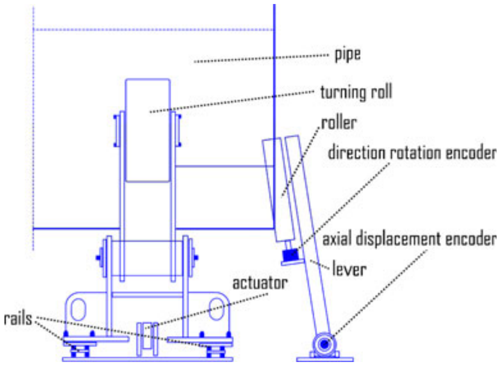

Fig. 9 Sketch of the measurement system using two encoders

depending on whether the pulses in the encoder are negative or positive, the direction of rotation is obtained. When an axial displacement occurs in the workpiece, the lever of the measurement system is moved and produces pulses in the displacement encoder proportional to the axial displacement of the workpiece. A diagram of the measurement system is shown in Fig. 9. A photograph of the system working in the workshops of Ingeniería y Diseño Europeo, S.A., can be seen in Fig. 10.

A system that allows longitudinal movement of the pipe was also designed and developed. This movement is transverse to the symmetrical axis of the pipe, allowing controlled movement of the workpiece on the horizontal plane. This system uses a pneumatic cylinder that moves the idle turning roll over the rails. A diagram of the proposed design for modifying the horizontal position of the turning roll can be seen in Fig. 11. Figure 12 shows the pneumatic cylinder.

Several options were evaluated to implement the control algorithm designed in order to counteract axial displacement. The control algorithm must interact with the developed sensor in order to read the displacement and the direction of rotation and with the actuator in order to allow the longitudinal displacement of the pipe. Among the options considered were:

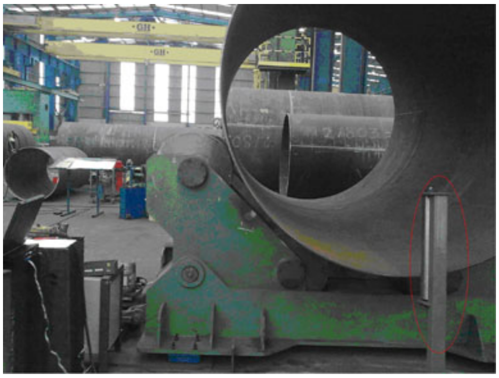

Fig. 10 Measurement system used in tests

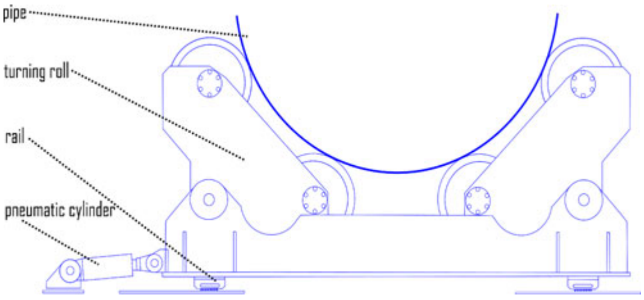

Fig. 11 Proposed design to modify the longitudinal position of the turning roll

- An industrial PC with an I/O card
- A PLC
- Design of a small board which would use a micro-controller to run the control algorithm

The third was selected as being the most economically viable for the construction of the prototype. An RCM 3700 Rabbit micro-controller, which has a development environment (IDE), was chosen. It allows the development of applications using the programming language Dynamic-C and can embed sections to perform multitask operations, operating in real time.

3.2 Software (control algorithm)

An automatic system to control axial displacement during the welding of pipes was designed and developed.

Fig. 12 The pneumatic cylinder

```
ControlLoop()
1. {
2. displacement ← getDisplacement()
3. direction ← getRotationDirection()
4. if(displacement ≥ THRESHOLD){
5.    if(direction == CLOCKWISE){
6.      writeOutPut(EXTENSION)
7.      waitFor(DELAY=INERTIA_TIME)
8.    }
9.    else{
10.     writeOutPut(CONTRACTION)
11.     waitFor(DELAY=INERTIA_TIME)
12.   }
13. }
14. else if(displacement ≤ - THRESHOLD){
15.   if(direction == CLOCKWISE){
16.     writeOutPut(CONTRACTION)
17.     waitFor(DELAY=INERTIA_TIME)
18.   }
19.   else{
20.     writeOutPut(EXTENSION)
21.     waitFor(DELAY=INERTIA_TIME)
22.   }
23. }
24.}
```

Fig. 13 Control algorithm

The proposed algorithm uses the lateral displacement to control the position of the pipe over time. The algorithm uses only four basic rules based on rotation direction and axial displacement. The custom build single-board computer has four digital inputs to receive information about direction and axial displacement provided by the two encoders. The four digital inputs are channels A and B for both encoders.

The instructions of the four rules of the control algorithm can be seen in Fig. 13. First, displacement is obtained (2). Second, the direction of rotation is obtained (3). The execution flow is determined by these two values. The first rule (4–8) is executed if the displacement of the pipe exceeds a threshold and the pipe is rotating clockwise. The actuation in this case corresponds to an extension of the pneumatic cylinder rod.

In case of counterclockwise rotation, the second rule (9–13) is executed, and the pneumatic cylinder rod is contracted. The third rule (14–18) and the fourth rule (19–22) follow the same structure, but are executed if the axial displacement is in the other direction. As in most process control systems, the control algorithm is performed by decomposition in three parts which are executed sequentially in a constantly running control loop.

4 Results

Below are the tests performed to show the difference in the axis displacement between the designed automatic

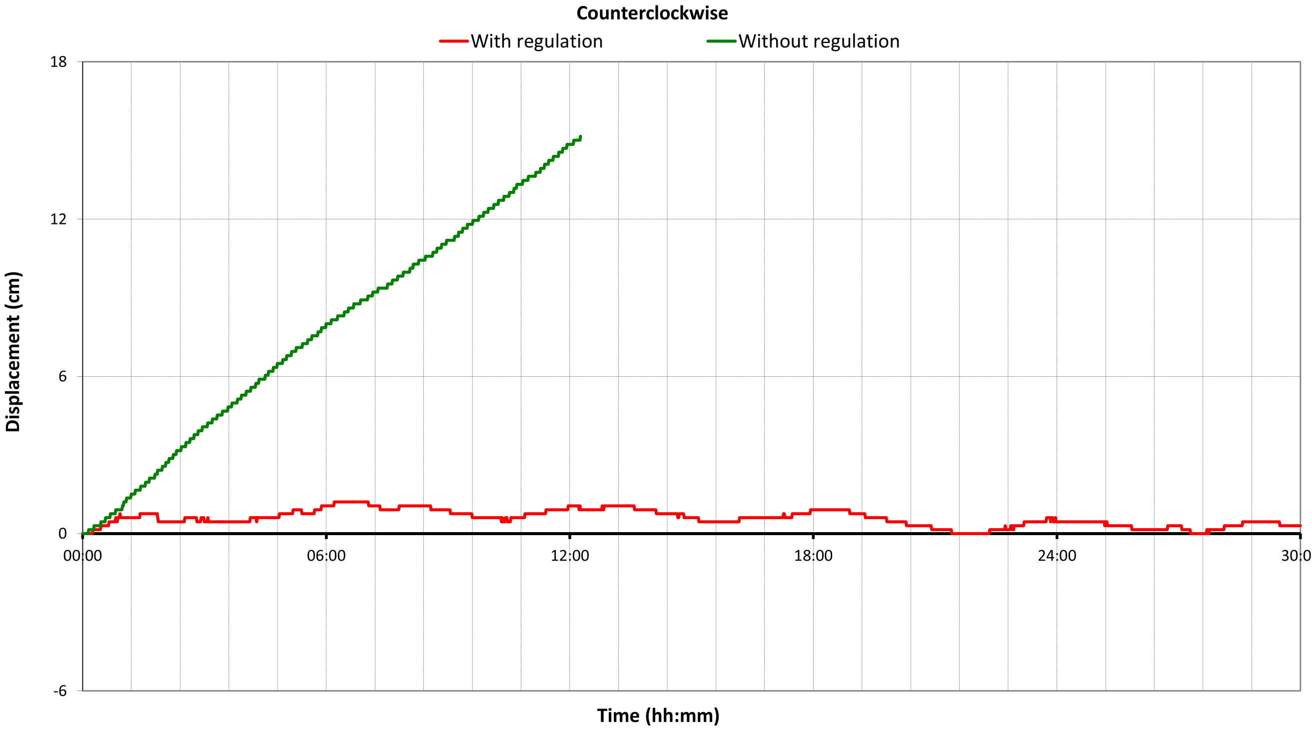

Fig. 14 Difference in the axis displacement between the designed automatic system and the system without regulation

Fig. 15 Difference in the axis displacement between the designed automatic system and the system without regulation

system and the same system without regulation. It can be seen how the axial displacement is detected and controlled by the system. Examples of validation tests can be seen in Figs. 14 and 15.

As can be seen, the proposed system is able to control the axial displacement. This axial displacement is always within an acceptable range of a few centimetres.

The change in the direction of rotation that is performed through a reversal of the supply voltage of the motors in the power turning roll is a factor that can be used to control axial displacement, as can be seen in Figs. 14 and 15. However, it involves a stop and start of the longitudinal welding in the other direction.

As can be seen in Figs. 14 and 15, the position of the pipe has been controlled in a range of about 1 cm in the clockwise direction and 2 cm in the counterclockwise direction. These charts correspond to an example that shows the proposed system is valid for controlling the position of the pipes over time. The proposed system is not intended to minimize the number of actuations on the pneumatic cylinder or to minimize displacement of the pipe, but to control the position of the pipes over time so that operators can carry out welding processes. Thus, repositioning tasks that involve loss of productivity will not be necessary.

In order to get a quantitative measure of the proposed algorithm, axial drift is adjusted according to a linear regression model. The equations that best fit the axial drift are shown below:

- Equation for drift displacement without regulation shown in Fig. 14 (counterclockwise)

$$y = 0.0205t + 0.2043\left(R^2 = 0.997\right), t = s, y = \text{cm} \quad (1)$$

- Equation for drift displacement without regulation shown in Fig. 15 (clockwise)

$$y = -0.0204t + 0.0268\left(R^2 = 0.9925\right), t = s, y = \text{cm}(2)$$

As can be seen, the correlation is close to 1 in both cases; thus, the predictions obtained from the model will be very reliable. After 1 h of operation for example, there will be an axial drift of 74 cm (Eq. 1) or −73.4 cm (Eq. 2). However, the axial drift will be less than 2 cm with the proposed system.

Although the minimization of displacement is not a key factor, there is a mechanical limitation in the welding head that allows a maximum correction of 32 cm on each side. Thus, the system allows a safety margin of 800 %. If the drift were longer than 32 cm, a relocation of the piece would be necessary using cranes and other machinery, with the consequent loss of productivity. The estimated time of inactivity may vary from 20 min to several hours. The first case corresponds to a simple relocation of the pipe. In the second case, a previous unsoldering of some components of the pipe may be needed. Ingenieria y Diseño Europeo SA estimates an average time of 50 min of inactivity.

5 Conclusions

In this study, a new automated control system to counteract axial displacement in pipes during the welding process was designed and tested. The system meets the requirements of simplicity, robustness and low cost, with no modification to the turning rolls.

Validation tests were carried out and show that axial displacement in pipes can be mitigated and controlled by using the longitudinal displacement caused by a pneumatic cylinder which moves the idle turning roll over the rail.

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