TAMPERE UNIVERSITY OF TECHNOLOGY

ENRIQUE ABAD PÉREZ

CONTROL AND MEASUREMENT SYSTEM FOR A COMPRESSING UNIT

Master of Science Thesis

Supervisor: Docent Juha Miettinen,
Prof. Erno Keskinen
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RESUMEN

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Las máquinas trituradoras necesarias para el proceso de obtención de papel tienen como primera etapa la compresión de bloques de madera. Este proyecto Fin de Carrera desarrolla e implementa un sistema de control y medida para una máquina de compresión que lleva a cabo esta primera etapa del proceso de obtención de papel. Para cumplir este objetivo, se desarrolla un control tanto manual como por ordenador.

El proyecto está dividido en tres partes. En la primera etapa se exponen las teorías necesarias para la total comprensión del trabajo de investigación. En dicha sección se detallan los métodos de control y medida así como el sistema hidráulico necesario para operar la unidad de compresión. En la segunda sección se desarrolla el método más adecuado para el sistema de control y medida que se va a implementar basado en un análisis de las variables que afectan al desarrollo del proceso. La última sección se centra en la implementación de dicho sistema de control y medida. En ella se detallan las principales características tanto del control manual como del llevado a cabo por ordenador. Además se expone y explica el código, desarrollado en Labview, necesario para el desarrollo de la interfaz usada para el control por ordenador. Finalmente, se efectúa una aproximación del sistema para la correcta toma de medidas durante el proceso de compresión. Para concluir se realizan diversos test de verificación que comprobarán el correcto funcionamiento del sistema en su conjunto.

Los resultados de este Proyecto Fin de Carrera sugieren que el sistema de control y medida satisface los requisitos necesarios para el desarrollo de futuras investigaciones en relación con dicha maquina de compresión. Los valores mostrados por el sistema de medida tanto del operador manual como del llevado a cabo por ordenador son similares a los esperados y además el sistema de control evita situaciones peligrosas debidas al proceso de compresión. Este Proyecto fin de Carrera sugiere, por tanto, futuras investigaciones para la mejora del sistema de control y medida desarrollado.

ABSTRACT

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Pulp for making paper is produced in grinding machines whose operation principle is based on the compression of logs against a grinding stone. The aim of this Master Thesis is to develop and implement a control and measurement system for a laboratory compressing unit which carries out this first step in paper making process. For this purpose, a hand drive and a computer interface are designed and configured.

The thesis is divided in three sections. In the literature study the theories involved in the research work are analyzed. Control and measurement methods are detailed as well as the hydraulic system needed to operate the compressing unit. In the second section the development of a control and measurement method suitable for the unit is carried out. It is based on the study of the most important variables involved in the process. Last section focuses on the implementation of the control and measurement system. A hand drive and a computer interface are considered. The latter is developed using LabView software. In this section, the hand drive design is analyzed and the LabView code is explained. In addition, a measurement approximation method is implemented in order to display the correct variable values. Finally a verification of the whole system is carried out.

The results of this study suggest that the control and measurement system satisfies the requisites needed to develop future researches related to this compressing unit. The values displayed by the hand drive and computer interfaces are similar to the theoretical ones and the control system avoids dangerous situations. This Master Thesis suggests future research work in order to improve the accuracy of the control and measurement system.

PREFACE

The work of this Master of Science Thesis was carried out in the Mechanics and Design Department at Tampere University of Technology as an agreement between both Escuela Técnica Superior de Ingenieros Industriales de Madrid and Tampere University of Technology with the assistance of the Erasmus Program.

I wish to express my sincere appreciation to Docent Juha Miettinen for this guidance and supervision throughout this Master of Science Thesis. I am also grateful to Professor Erno Keskinen for the support and advices along the research project. I want also to thank M. Sc. Pekka Salmenperä for his supervision throughout the Lab View program. I am also very grateful to Paula Cajal Mariñosa for excellently checking English language and literature of this Master of Science Thesis.

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Tampere, August 5th, 2010

Enrique Abad Pérez

C/ Cándido Mateos Nº 16, esc. 1ª, 5º A
C.P. 28035, Madrid, Spain

TABLE OF CONTENTS

NOMENCLATURE

ΔR_1	Resistance variation 1
ΔR_2	Resistance variation 2
ΔR_3	Resistance variation 3
ΔR_4	Resistance variation 4
ΔP	Pressure drop
Φ_i	Perpendicular magnetic field i
Φ_m	Parallel magnetic field m
Φ_r	Resultant magnetic field
ε	Relative strain
$\varepsilon_{\theta\theta}$	Circumferential strain
ε_a	Axial strain
ε_{rr}	Radial strain
ε_t	Transverse strain
φ_{CC}	Test cylinder diameter
$\varphi_{Cylinder}$	Cylinder diameter
π_L	Longitudinal piezoresistive coefficient
ρ	Resistivity
ρ_0	Resistivity for unstressed material
σ	Mechanical stress
σ_a	Axial stress
σ_f	Density of the fluid
σ_t	Transverse stress
σ	Mechanical stress

v	Poisson ratio
A	Cross-section area
A_{CC}	Test cylinder area
A_{Rod}	Piston rod area
B	Magnetic flux density
C	Bridgman's constant
C_d	Coefficient of discharge
E	Young´s modulus
E_{AB}	Voltage difference between A and B
E_{AD}	Voltage difference between A and D
E_i	Input voltage
E_o	Output voltage
E_s	Supply voltage
F_{CC}	Test cylinder provided force
$F_{Maximum}$	Maximum operation force
F_{PP}	Force applied on the pushing plate
F_{SP}	Force applied on the stop plate
G	Gain of the amplifier
G_1	Process 1
G_2	Process 2
G_{C1}	Controller of process 1
G_{C2}	Controller of process 2
I	Input signal
I_P	Current pulse

N	Number of detecting coil turns
P	Pressure
P_0	Supply pressure
P_1	Inlet pressure
P_L	Load pressure drop
$P_{Maximum}$	Maximum operation pressure
R	Resistance
R_0	Radius
R_1	Resistance 1
R_2	Resistance 2
R_3	Resistance 3
R_4	Resistance 4
S	Cross-section area
V_0	Detected voltage
X_2	Measurement point 2
X_3	Measurement point 3
$X_{\max}$	Maximum measured value
$X_{\min}$	Minimum measured value
X_r	Measured values average 1
X_{wr}	Measured values average 2
a	Orifice area
b	Relative reproducibility error
b'	Relative repeatability error
c	Constant of proportionality

h	Position of the throttling element
k	Gauge factor
l	Length
p_1	Disturbance 1
p_2	Disturbance 2
q	Flow
r_1	Intermediate variable reference value
r_2	Controlled variable reference value
u	Manipulated variable
y_1	Intermediate variable
y_2	Controlled variable

1. INTRODUCTION

Paper making process is based on pulp manufacturing. It obtains fibers from wooden logs to manufacture paper. For this purpose, groundwood process uses grinding machines. They achieve this goal by compressing wooden logs against a grinding stone which rotates continuously. A hydraulically driven pushing plate is in charge of this compression process. For studying the behavior of the logs during the compression process, a laboratory scale compressing unit has been built to simulate the situation. In the case study, a hydraulic operated cylinder presses log batches against a fixed stop plate inside a chamber delimited by two guiding walls. The laboratory compressing unit used in this study is shown in Figure 1.1.

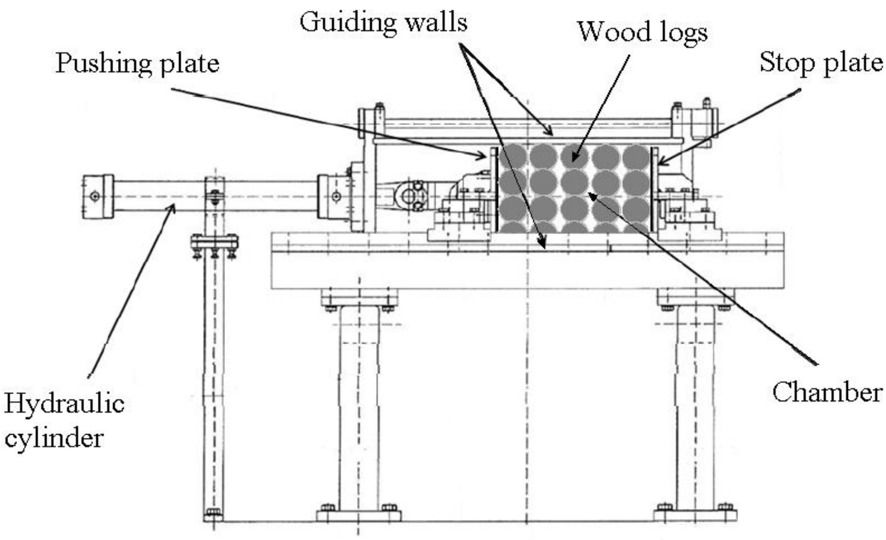


Figure 1.1 *The laboratory compressing unit used in this study.*

The aim of this Master Thesis is to develop a control and measurement system for the compressing unit in order to drive the unit in different ways and to collect process parameters for further studies of the behavior of the logs during the compression process. The machine contains different variables which have an effect on this compression process. The control and measurement of these variables is needed in order to obtain a better understanding of the logs behavior and protect the unit. For this purpose, control and measurement theories are used in order to design the most suitable method for the compressing unit. The outcome of this is the development of a hand drive and a computer interface programmed in LabView software. The necessary components and their connections in order to implement the control and measurement system are detailed in this Master Thesis.

In addition, real tests are needed to check the proper running of the whole system which consists of a compressing unit, components connection, hardware, and software. The results of these tests verify the accuracy of the control and measurement system and its behavior under real conditions. Furthermore, the conclusions explain the obtained results and the problems emerged during the research process. Finally, suggestions for future research works are considered in order to improve the accuracy of the results achieved by the control and measurement system developed during this Master Thesis process.

2. HYDRAULIC SYSTEM

A hydraulic system is in charge of converting, transmitting with control and applying fluid energy to perform useful work (Wolansky 1990). In a compressing unit the hydraulic system is in charge of providing the necessary flow of fluid for achieving the sufficient pressure in the cylinder to compress.

A fluid hydraulic system consists of a energy source, a prime mover or pump, a control mechanism or valve, a source of fluid which is oil in this case, an actuator, which is a double acting cylinder, and a load resistance (Sullivan 1975).

The operation principle of the hydraulic system is based on a valve which directs the high energy fluid from the prime mover, a pump, to the actuator, a cylinder, and returns the low energy fluid from the actuator to the fluid reservoir. In addition to this, the hydraulic system supplies the required energy in order to return the fluid through the valve back to the reservoir. This process involves cylinder's extension and contraction (Sullivan 1975). The actuator converts the energy from the fluid into a force in order to compress logs. As a result, the obtained force is used to overcome the load resistance (Sullivan 1975). The schematic diagram of a directional valve controlling a cylinder drive is shown by Figure 2.1.

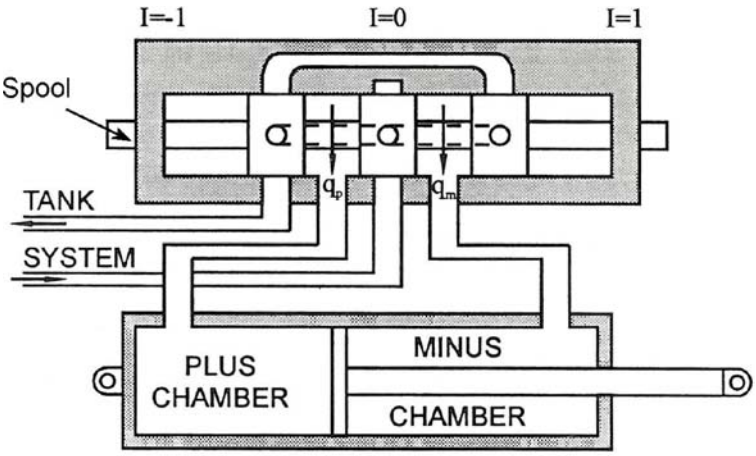


Figure 2.1 *Schematic diagram of a directional valve controlling a cylinder drive. When I = 0 the spool is in centre position, when I = 1 cylinder is pushing and when I = -1 cylinder is pulling.*

The valve is primordial in the development of the hydraulic system. The 4/3 valve which is used during the research work is shown by Figure 2.2.

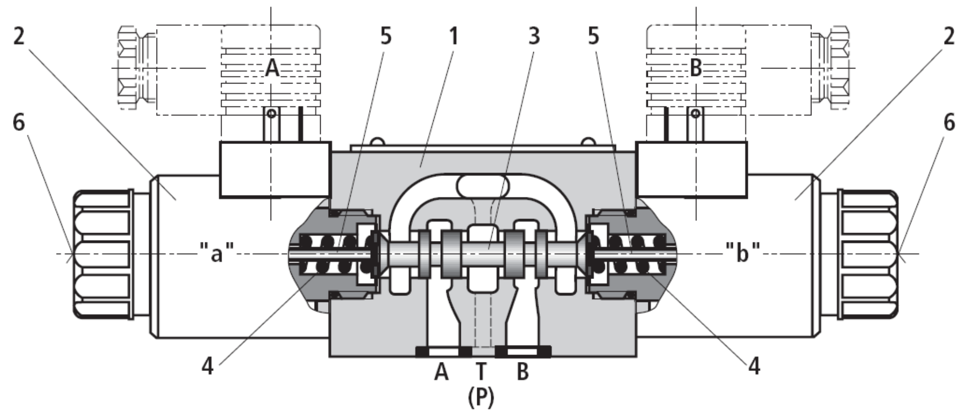


Figure 2.2 *Directional 4/3 valve with wet–pin DC or AC voltage solenoids.*

Figure 2.2 represents a directional valve which controls the start, stop and direction of the flow. This valve consists of housing (1), one or two solenoids (2), control spool (3), and one or two return springs (4). The initial or rest position of the valve is achieved when the control spool (3) is held by return springs (4).

The operation principle of the direction valve is based on a force in the solenoid (2) which pushes the control spool from its initial to its end position via plunger (5). This action provides the necessary flow direction from P to A and B to T or P to B and A to T. Finally, when the force of the solenoid (2) stops, return springs (4) push the control spool (3) to its initial position.

As it was explained before, the hydraulic supply system provides the cylinder via the valve with fluid in order to overcome a load resistance. Subsequently the actuator converts the energy from the fluid into kinetic energy. There are two main cylinder categories, pneumatic and hydraulic. The formers are operated by several types of gases, with compressed air as the most common. The latters are operated by a very large range of fluids, with petroleum based hydraulic fluid as the most common (NFPA 1998).

Cylinders are divided into two main components, a pressure containing envelope and a piston and rod assembly. Generally, the pressure containing envelope is fixed on the machine whereas the piston and rod assembly are in charge of the motion and force transmission. A common cylinder configuration is illustrated in Figure 2.3.

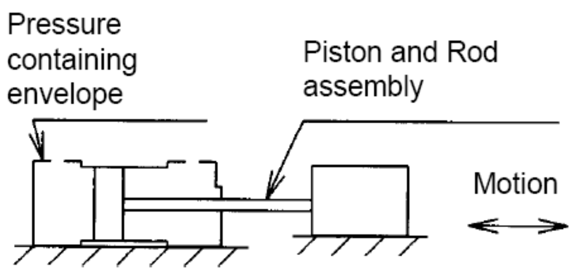


Figure 2.3 *Common cylinder configuration (NFPA 1998).*

The most common types of hydraulic cylinders used in industry are divided in two main categories. Firstly, they can be single or double acting. In case of single acting cylinders the pressure is applied only to one side of the piston while other sources, such as gravity or a spring, are used to push it back (NFPA 1998). This case is illustrated in Figure 2.4.

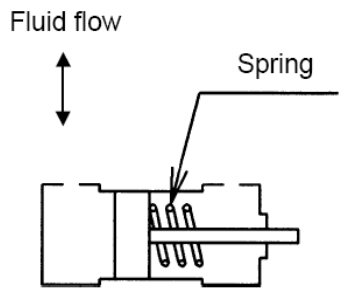


Figure 2.4 *Single acting cylinder (NFPA 1998).*

On the other hand, when the pressure is applied in both sides of the piston to extend or retract the cylinder as applicable, it results in double acting hydraulic cylinder. It is illustrated in Figure 2.5.

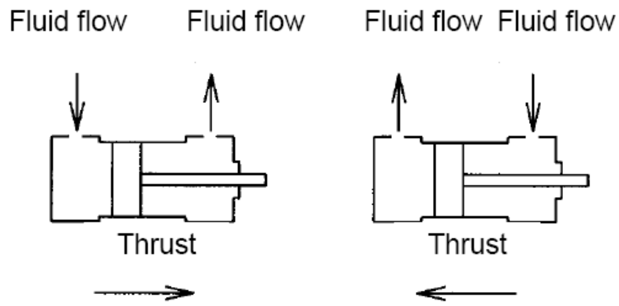


Figure 2.5 *Double acting cylinder (NFPA 1998).*

Secondly, they can be double or single hydraulic rod cylinders. Thus, when the applied load is on both sides of the cylinder, it is considered as a double rod cylinder. When the load is applied only on one side of the cylinder, it is obviously, a single rod cylinder. Double acting single piston rod cylinders are the most common type of hydraulic cylinders used in industry (NFPA 1998).

The choice of cylinder is based on the load resistance and the speed required during the operation. Subsequently, hydraulic cylinders in comparison with pneumatic cylinders are capable to reach larger forces but have lower speed (Bolton 2003).

In conclusion, based on the nature of the compression process and the concepts explained above, the unit uses a double acting, single rod hydraulic cylinder whose most important advantages are small specific weight (0.2–0.3 kg/kWt), fast change of operating modes (for instance, position 1 - neutral position - position 2) and protection from overloads (Ponomareva 2006).

3. CONTROL AND MEASUREMENT SYSTEM

The operation of the unit involves the action of different variables. Therefore, they have to be either controlled in order to protect the unit or measured to obtain a better understanding of the process development.

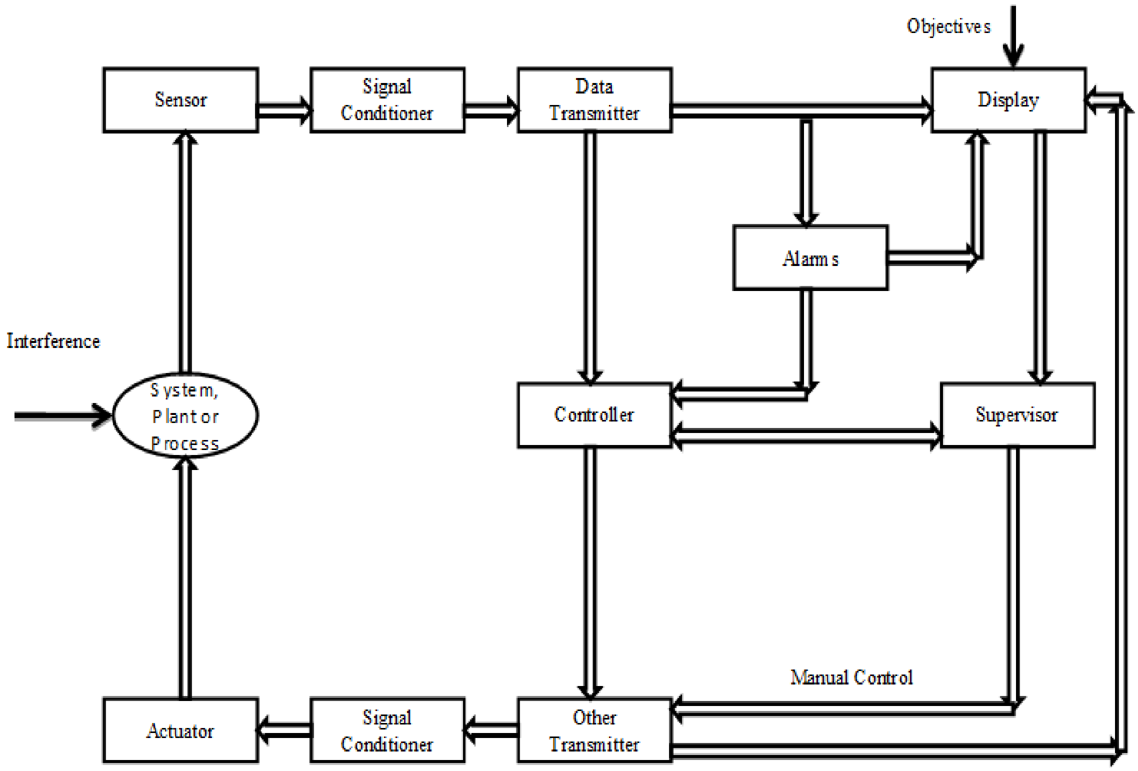


Figure 3.1 *Data flow in a control and measurement system (Pallàs-Areny 2001).*

As is shown in Figure 3.1, data flow starts from the measurement of a variable or set of variables involved in a particular process. Subsequently, the measurement system consists of a sensor, a signal conditioner, a data transmitter and a display. It receives the input values from the process variable which vary over time, as an input for the measurement system. Afterwards, it processes these values and shows them, as an output of the system, in a way that can be perceptible for the human senses (Pallàs-Areny 2001).

The values from these variables travel into a data transmitter during the measurement process. The data transmitter outputs are connected to the alarms and to the control system (Figure 3.1). The main goal of this control system is to modify the variable values by using an actuator if necessary. Therefore, Figure 3.1 shows that this control system consists of a control device, a data transmitter, a signal conditioner and an actuator which acts on an element of the process in order to keep this mentioned process working in safe conditions (Pallàs-Areny 2001). The alarm device receives the output from the data transmitter and evaluates these values according to the established limits. Therefore, if some variable exceeds its limits the unit will stop working.

The control of the unit is carried out either automatically, by computer devices, or manually, by a hand drive operated by a supervisor. As a matter of fact, in both cases the control system operates an actuator which modifies the interference value in case the values are considered dangerous for the unit.

4. MEASUREMENT THEORY

Measurement systems basically consist of four elements which are a sensor, a signal conditioner, a data transmitter and a display system (Pallàs-Areny 2001, Bolton 2003).

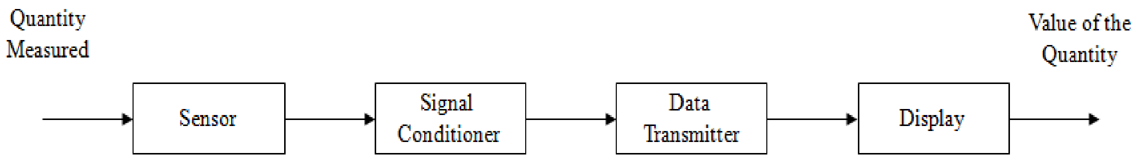


Figure 4.1 *Measurement system (Bentley 1988, Bolton 2003).*

Figure 4.1 shows the order in which these elements take part during the process. As can be seen, the system input is the quantity being measured of the study variable. The sensor gives an output signal whose value is related to this quantity being measured. The signal conditioner is used when the output signal from the sensor is not suitable for the data transmitter. For instance, a force sensor, containing four strain gauges distributed like a Wheatstone bridge system, gives an output signal which is not large enough to be used for the next step in the measurement system. For this case, an amplifier works in such a manner that it makes the output signal from the sensor large enough. The final step in the measurement system is the display. It displays the value of the quantity using, for instance, graphs or numerical values (Pallàs-Areny 2001, Bolton 2003).

The following chapters explain in a general way the different elements which are involved in every measurement system. In addition, they also describe particularly the ones used to develop the measurement system for the unit.

4.1. Sensor

A sensor produces a signal related to the values of a measured variable and a transducer converts a signal from one physical form, input of the transducer, to another physical form, output of the transducer (Pallàs-Areny 2001). Considering that most of the measurement systems are based on electric signals and hence, on sensors, electronic measurement systems take advantage of some properties such as:

1. Sensor can measure nonelectric quantities. A change in the nonelectric variable entails another change in an electric variable which is actually implied by the operation principle of the sensor.

2. Sensors and signal conditioners can be integrated in the same package due to their compatibility and it facilitates the structure of the measurement system.
3. Sensors are commonly used in measurement systems; therefore there is a wide variety of displays which can be used to display the variable values.
4. Electrical signals are the most suitable for signal transmission (Pallàs-Areny 2001).

The measurement system of the unit monitors different variables such as position, stress, pressure and force. Thereby, the following sections explain the operation principle of the sensors and transducers needed to carry out these measurements.

4.1.1. Position measurement

The control and measurement system is based on the position control, thus its measurement is a key factor during the process. Thereby, there are different ways to obtain values of a linear displacement of about 1m. There are many components for position measurement based on different working principles such as potentiometers, LVDTs, magnetostrictive, optical encoders and laser interferometers (Seco 2005). Their characteristics are shown in Table 1.

Table 1 *Characteristics of linear position sensors. The precision is related to a measuring range of 1000 mm for all of the sensors except for the LVDT (*), in this case it is related to a measuring range of 100 mm (Seco 2005).*

Sensor	Meas. range	Contact	Abs / Inc	Precision (μm)
LVDT	Small	No	Absolute	250 (*)
Potentiometer	Medium	Yes	Absolute	400
Magnetostrictive	Large	No	Absolute	200
Optical Encoder	Large	No	Incremental	5
Laser Interferometer	Very large	No	Incremental	0.1

Considering Table 1, the magnetostrictive (MS) linear position sensor is shown as a suitable option due to properties such as large measuring range, acceptable precision value, non–contact principle and absolute measurement. Furthermore, this type of sensor does not suffer from contamination impact unlike optical sensors when used in common industrial factory environment (Seco 2005). As a matter of fact, the magnetostrictive linear position sensor proves to be the best option to control and measure the position during the process. Its operation principle is shown in Figure 4.2.

Magnetostrictive linear position sensor is composed of a ferromagnetic waveguide, also called magnetostrictive wire, which covers all the measuring length, and a mobile part, consisted of magnets oriented perpendicularly. This mobile part can move forwards and backwards along the fixed waveguide. The position is estimated from the time–of–flight (TOF) of ultrasonic signals moving within the waveguide. These signals are generated by magnets and propagated along the waveguide from the mobile part to both ends of the waveguide (Seco 2005).

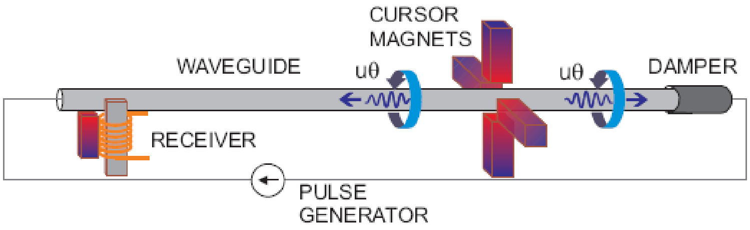


Figure 4.2 *Basic structure of a magnetostrictive linear position sensor (Seco 2005).*

As can be seen in Figure 4.3, a current pulse I_P induces a magnetic field Φ_i whereas the magnets produce another one, Φ_m, parallel to the waveguide. The interaction of both parallel and perpendicular magnetic fields generates the resultant field Φ.

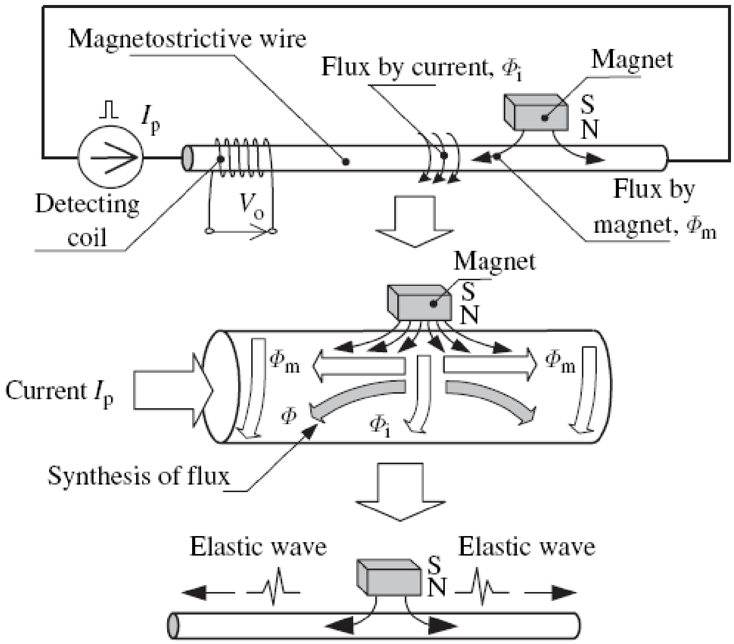


Figure 4.3 *Operation principle of a magnetostrictive linear position sensor (Chandra 2008).*

According to the Wiedenman effect, this resultant field creates ultrasonic waves which travel in both directions along the waveguide (Trémolet 1993, according to Seco 2005, Chandra 2008). The stress in the waveguide produces changes in the magnetic flux density when the wave arrives to the receiver. Therefore, this effect varies the value of the induced voltage which is calculated, based on the Faraday´s law, by the equation 4.1. The position value is obtained from the induced voltage

$$V_0 = -NS\frac{dB}{dt} \tag{4.1}$$

where V_0 is the detected voltage, N is the number of detecting coil turns, B is the magnetic flux density and S is the cross section area of the waveguide (Chandra 2008).

4.1.2. Strain measurement

The control and measurement system is designed to protect the unit against possible damages during the sub–processes formed in the main process. One of the system variables, which has to be controlled, is the strain. The measure of this variable is carried out using electrical resistance strain gauges. A strain gauge is a metal wire, metal foil strip or a strip of semiconductor material which is stuck onto the surfaces where it is needed to know the strain (Bolton 2003).

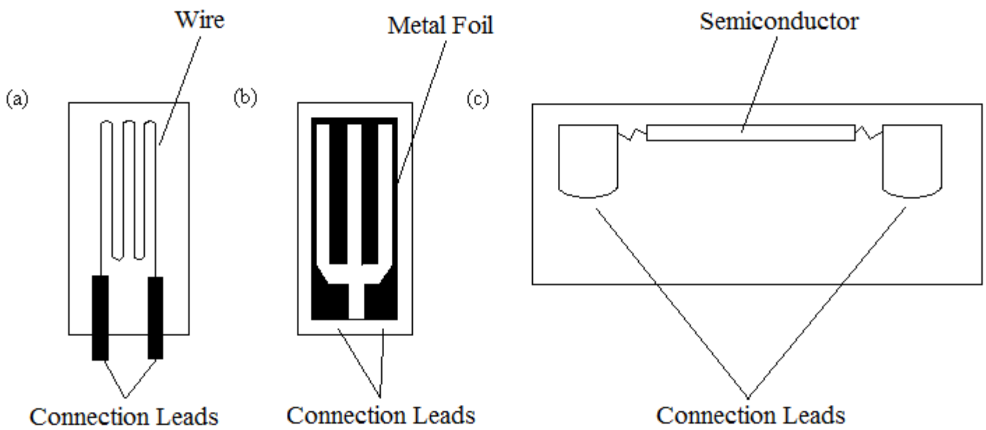


Figure 4.4 *Strain gauges (a) metal wire, (b) metal foil, (c) semiconductor (Bolton 2003).*

The operation principle of a strain gauge is based on the resistive effect. A variation in the strain to which the strain gauge is subjected produces a change in the resistance of its structure (Dally 1984, Bolton 2003). In case of the semiconductor use, the piezoresistive effect is taken into account.

As a matter of fact, the resistive effect indicates that an increase or decrease in the extension of the strain gauge produces a variation in the metal size of the mentioned strain gauge. The outcome of this is the change in the value of the resistivity. In conclusion, a variation of mechanical strain causes changes in the strain gauge resistance. The operation principle of the strain gauges is based on the studies of the effects occurring within conductors caused by external conditions such as mechanical strain.

The relation between the electric resistance of a wire R, its length l, its cross section A, and resistivity ρ is shown by equation (4.2)

$$R = \rho \frac{l}{A} \tag{4.2}$$

Moreover, longitudinal stress produces changes in the length l, cross section A, and resistivity ρ. Therefore, starting from equation (4.2), the electric resistance R of a wire is also altered. It is shown by equation (4.3)

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dl}{l} - \frac{dA}{A} \tag{4.3}$$

Additionally, when a force within the elastic limits is responsible for the change of length of a wire, Hooke´s law is applied

$$\sigma = \frac{F}{A} = E\varepsilon = E\frac{dl}{l} \tag{4.4}$$

where E is Young´s modulus, σ is mechanical stress, ε is the relative strain (Dally 1984, Pallàs-Areny 2001, Bolton 2003). The application of the resistive effect, which is explained above, and the equation (4.3) leads to equation (4.5) in isotropic materials (Pallàs-Areny 2001)

$$\frac{dR}{R} = \frac{dl}{l}\left[1 + 2v + C(1 - 2v)\right] = k\frac{dl}{l} = k\varepsilon \tag{4.5}$$

where k is gauge factor, v is Poisson ratio and C is Bridgman’s constant.

In conclusion, for a material deformation when the electrons travel along the stress axis, the equation (4.6) shows the proportional relation between resistivity and stress

$$\frac{\Delta\rho}{\rho_0} = \pi_L \sigma \qquad (4.6)$$

where π_L is longitudinal piezoresistive coefficient and ρ_0 is resistivity for unstressed material. Finally, the result which explains the operation principle of the strain gauges is shown by equation (4.7)

$$\frac{\Delta R}{R} = k\varepsilon \qquad (4.7)$$

As can be seen the resistance of the wire is proportional to the strain (Pallàs-Areny 2001).

4.1.3. Pressure measurement

The compression of log batches is achieved using a piston which is moved by a hydraulic system. The movement of the piston is connected with the pressure inside the valve. It can be said that under similar conditions greater pressure values leads to greater force values and faster movements of the pushing plate. Therefore, the pressure measurement is important in the development of the control and measurement system for the unit.

Pressure sensors are devices that convert pressure into electrical signals using a strain measurement (Dally 1984). As a matter of fact, these transducers consist of diaphragms, capsules, bellows or tubes by which the measurement of the elastic deformation is carried out (Bolton 2003). There are three different kinds of pressure measurements related to the sensors which use diaphragms: absolute pressure, which is characterized by measuring from zero-pressure; differential pressure, which is characterized by measuring pressure difference, and gauge pressure, which is characterized by a measure that takes barometric pressure into account (Bolton 2003).

The operation principle of pressure sensors based on strain measurement (to monitor the deformation of the diaphragms) is shown in the Figure 4.5. The difference of pressure between both sides of the diaphragm entails its movement and, as a result, a loose of its balance. According to Ding (1992) corrugations in the diaphragm increase the sensitivity of the entire transducer.

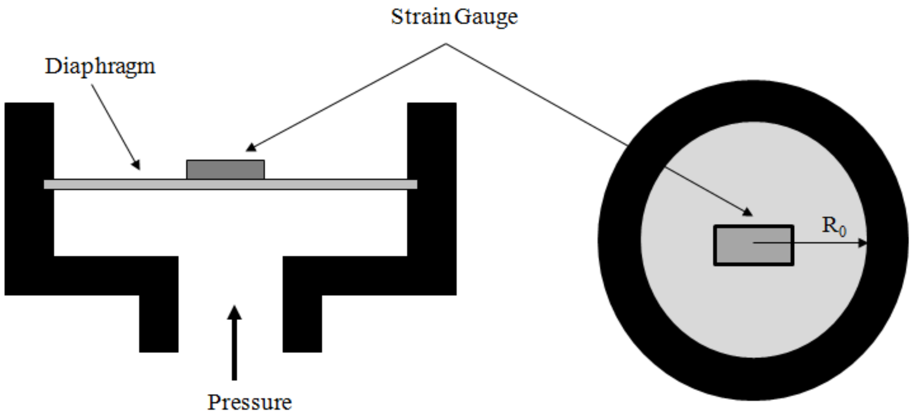


Figure 4.5 *Pressure sensor which is composed of a diaphragm and strain gauges (*Bolton 2003*).*

The operation principle of a pressure transducer is based on the measurement of the diaphragm movement. Generally, this measurement is carried out by using four strain gauges in a Wheatstone bridge configuration. Two of them (R_1 and R_3) measure the strain in circumferential direction, and the other two in radial direction (R_2 and R_4) (Bolton 2003). The strain in a diaphragm subjected to a constant pressure is given by the equations (4.8) and (4.9) taking both radial and circumferential directions into account (Dally 1984)

$$\varepsilon_{rr} = \frac{3P(1-\upsilon^2)}{8Et^2}(R_0^2 - 3r^2) \tag{4.8}$$

$$\varepsilon_{\theta\theta} = \frac{3P(1-\upsilon^2)}{8Et^2}(R_0^2 - r^2) \tag{4.9}$$

where P is the pressure, υ is the Poisson's ratio, R_0 is the outside radius and r is a position parameter.

As can be seen from the equations (4.8) and (4.9), whereas the circumferential strain $\varepsilon_{\theta\theta}$ is positive for each value of the position parameter, the radial strain ε_{rr} can take either the positive or negative values.

In this case, the calculation of the pressure measurement is generally carried out by substitution of a gauge factor $k = 2$ into the equation (4.10). As a result, equation (4.11) is obtained

$$\frac{\Delta R}{R} = k\varepsilon \tag{4.10}$$

$$\Delta E_0 = \frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)E_i \tag{4.11}$$

where R_1, R_2, R_3, R_4 are the resistors of the strain gauges, $r = R_2/R_1$ is a resistor ratio, E_i is the input voltage and E_o is the output voltage.

Hence pressure measurement is estimated by equation (4.12)

$$P = 1.22\frac{Et^2}{R_0^2(1\text{-}\upsilon^2)E_i}E_0 = CE_0 \tag{4.12}$$

Therefore, the resulting outcome shows that the pressure measurement P is proportional to the output voltage. This conclusion is obtained by equation (4.12) (Dally 1984).

4.1.4. Force measurement

The main goal of the compressing unit is to compress batches which are made of different materials. Therefore, it is important to study the forces occurred during the main process. For this purpose, the control and measurement system provides the values of the most important forces involved in the activity of the unit. They are the force applied on the pushing and stop plate and the forces caused by friction.

Strain gauge load cell is used in order to obtain the values of the force applied on the pushing and stop plate (Dally 1984, Bolton 2003). As shown in Figure 4.6, the sensor consists of a link in which two strain gauges are located in axial direction and the other two in transverse direction. In addition to this, they are wired using Wheatstone bridge configuration (Dally 1984).

The method is based on the resistance change of the strain gauge when forces are applied to the sensor either to stretch or compress it. This change leads to a variation of the output voltage from which the strain and consequently, the force values are obtained (Bolton 2003).

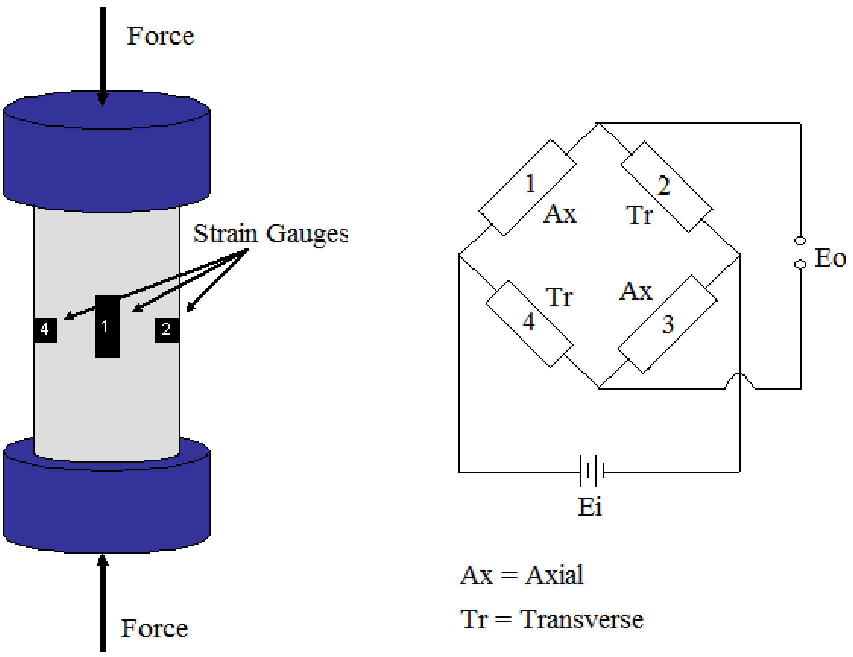


Figure 4.6 *Force sensor (Bolton 2003).*

The load is applied to the link and causes an axial and transverse strains ε_a and ε_t. They are calculated by following equations

$$\varepsilon_a = \frac{F}{AE} \qquad \varepsilon_t = -\frac{\upsilon F}{AE} \tag{4.13}$$

where F is the force A is the cross–sectional area of the link, E is the modulus of elasticity of the link material and υ is Poisson's ratio of the link material.

The changes in the strain gauges are proportional to the applied load as can be seen from the equations (4.14) and (4.15)

$$\frac{\Delta R_1}{R_1} = \frac{\Delta R_3}{R_3} = k\varepsilon_a = \frac{S_g P}{AE} \tag{4.14}$$

$$\frac{\Delta R_2}{R_2} = \frac{\Delta R_4}{R_4} = k\varepsilon_t = -\frac{\upsilon S_g P}{AE} \tag{4.15}$$

where $\frac{\Delta R}{R}$ is the relative resistance change and k is the gauge factor.

The output voltage of the sensor is also proportional to the applied load and it is obtained by substituting the equations (4.14) and (4.15) into equation (4.16)

$$\Delta E_0 = \frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)E_i \tag{4.16}$$

where $r = R_2/R_1$, E_i is the input voltage and E_o is the output voltage. As can be seen from the equation (4.17), under the condition that the four strain gauges are identical the output voltage is linearly proportional to the applied force (Dally 1984)

$$F = \frac{2AE}{k(1+\upsilon)E_i}E_0 = cE_0 \tag{4.17}$$

where c is the constant of proportionality. In conclusion, the output voltage is proportional to the force applied on either the pushing or the stop plate.

4.2. Signal conditioning

Signal conditioners receive the output signals from sensors and make them suitable for the next elements in the measurement chain, which are transmitters, displays or recorders (Pallàs-Areny 2001).

Signal conditioners are primarily used to protect systems, for instance, by limiting the current which goes through them or by controlling both the polarity and amplitude of the voltage, etc. (Bolton 2003).

Occasionally, the output signal of a sensor is not suitable for the following element in the system because either the signal type does not match with the input or its level is not large enough to be processed. In both cases the output signal of the sensors mentioned above has to be modified. If the signal type is not suitable, a Wheatstone bridge or an analog to digital converter should be used. The former converts a resistance change into a voltage change. The latter makes the output signal of a sensor suitable for a computer. On the other hand, if the output signal is not large enough, an amplifier is used in order to get the appropriate level of the given signal which is already suitable for the next element in the system (Pallàs-Areny 2001, Bolton 2003).

Moreover, signal conditioners are also used to filter induced noise from the useful signal which can be subsequently modified in order to, for instance, obtain linear dependence.

4.2.1. Amplifier

Amplifiers are signal conditioners used to obtain the proper signal level when it is not large enough for the following processing carried out by the data transmitter (Dally 1984). This data transmitter is the next step in the control and measurement system. The symbol of an amplifier is shown in the Figure 4.7.

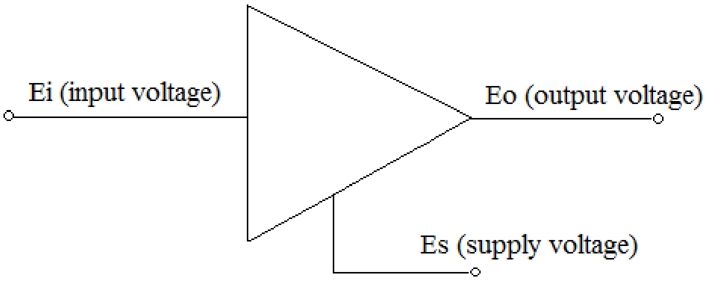


Figure 4.7 *Amplifier symbol (Dally 1984).*

where E_i is the input voltage, E_0 is the output voltage and E_s is the supply voltage. The output voltage is directly proportional to the input voltage as can be seen in equation 4.18

$$E_0 = GE_i \tag{4.18}$$

where G is the gain of the amplifier.

The linear proportion between the input and output voltages is finite and limited by the components of the amplifier and its supply voltage.

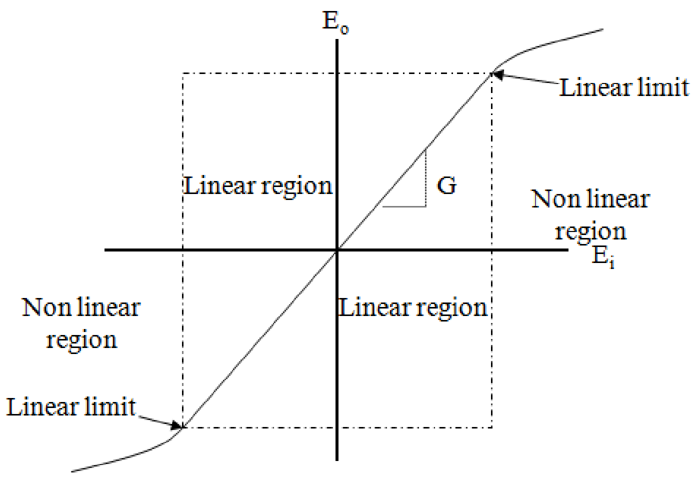


Figure 4.8 *Input/output voltage curve for an amplifier (Dally 1984).*

Figure 4.8 shows that this linear behavior between input/output voltages is limited to a specific range of values. Furthermore if the amplifier exceeds of this range the results are not accurate (Dally 1984). The linear limits are about 80 % of the supply voltage (Bateson 1991).

Nowadays there are different ways to amplify a signal which are based on the operational amplifier. Therefore, different connections of this operational amplifier with other passive components, such as resistors or capacitors, lead to different ways to amplify and consequently, different outputs. The operational amplifier is a high-gain dc amplifier whose gain varies from 10^4 to 10^7. A common used value is 10^5 (Bolton 2003). The inputs and outputs of an operational amplifier are shown in Figure 4.9.

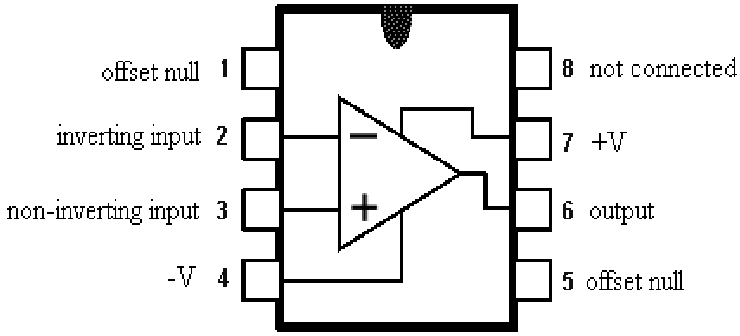


Figure 4.9 *Connections for an operational amplifier (Bolton 2003).*

The inputs of the operational amplifier are the inverting and non-inverting, positive (+) and negative (-) voltage supply and other two *offset null* which are used during the non linear behavior of the amplifier (Bolton 2003). As a matter of fact, the output varies in dependence on the connections between the inputs, especially between the inverting and non-inverting inputs. Furthermore, the voltage supply, with pins labeled as +V and –V in Figure 4.9, is required to amplify the signals which come from sensors (Bateson 1991).

4.2.2. Wheatstone bridge

The Wheatstone bridge is used to convert a change of resistance into an output voltage (Dally 1984, Bolton 2003). Wheatstone bridge basic structure is shown by Figure 4.10.

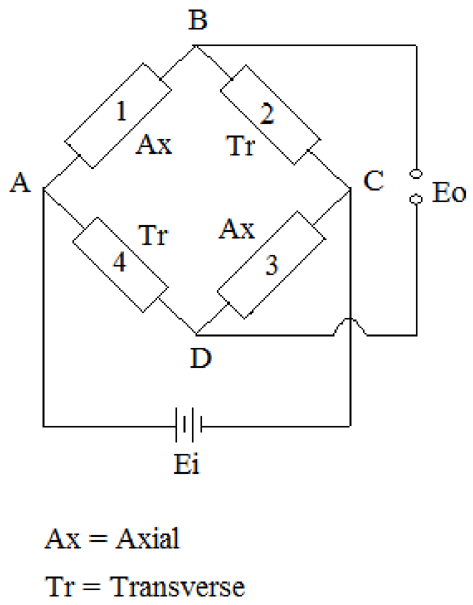


Figure 4.10 *Wheatstone bridge (Bolton 2003).*

The Wheatstone bridge is composed of two individual voltage dividers. The first one consists of the resistances R_1 and R_2, and the second one consists of R_3 and R_4. This concept leads to the calculation of the voltage between A and B, and A and D

$$E_{AB} = \frac{R_1}{R_1 + R_2} E_i \tag{4.19}$$

$$E_{AD} = \frac{R_4}{R_3 + R_4} E_i \tag{4.20}$$

where R_1, R_2, R_3 and R_4 are the resistances of the Wheatstone bridge, E_{AB} and E_{AD} are the difference of voltage between A and B, and A and D respectively and E_i is the input voltage (Dally 1984, Bolton 2003). In addition, the output voltage E_0, which is the voltage difference between B and D, is obtained using equations (4.19) and (4.20)

$$E_0 = E_{BD} = E_{AB} - E_{AD} = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_2)(R_3 + R_4)} E_i \tag{4.21}$$

where E_0 is the output voltage.

Equation (4.22) is then obtained by substitution the output voltage E_0 in equation (4.21)

$$R_1R_3 = R_2R_4 \tag{4.22}$$

It is said that the Wheatstone bridge is balanced when the equation (4.22) is satisfied. Thus, starting from a balanced Wheatstone bridge, a variation of the resistance values leads to a change of the output voltage. Considering ΔR_1, ΔR_2, ΔR_3, ΔR_4 as the variation of the resistances from the initial values of R_1, R_2, R_3 and R_4, and using the equations (4.21) and (4.22), the output value is calculated using the equation (4.23)

$$\Delta E_0 = \frac{r}{(1+r)^2}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right)E_i \tag{4.23}$$

where

$$r = \frac{R_2}{R_1} \tag{4.24}$$

In conclusion, if there is no load resistance across the output, this approximation implies that a particular change in the output voltage is proportional to a particular change in the resistances (Dally 1984, Bolton 2003).

4.3. Data transmission

Sensor outputs or, if necessary, signal conditioner outputs are fed into data transmitters in order to make the signal suitable for the analysis by the next element of the measurement system which is, for instance, a PC. Computer plug-in boards are widely used to provide computers with signals from sensors in order to transform them by computing and obtain them in a way so that they can be perceptible for the human senses (Pallàs-Areny 2001).

According to Bolton (2003) some questions should be asked with the purpose of choosing the appropriate DAQ board. These are, for instance, related to the type of software, the connectors needed, the number and range of the analog inputs, the number of digital inputs, the resolution, the sampling rate, etc.

Finally, drivers are required to connect the board with the computer and vice versa. Furthermore, an application software, for instance LabView, can be used to design the control and measurement system. The aim of this application software is to interact with the process by analyzing the data from the sensors and controlling the proper running of the system using actuators.

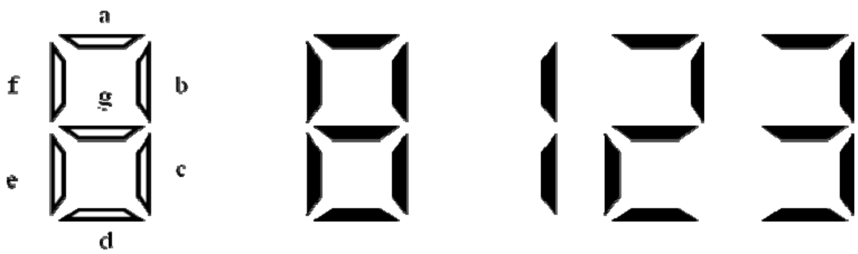
4.4. Display

Displays are one of the last elements in the measurement system whose purpose is to visualize the measured variables. Alphanumeric displays or light indicators (which signalize on–off status) are widely used (Bolton 2003). Another option is to use graphs in order to analyze the behavior of a specific variable over time.

4.4.1. Alphanumeric display

This kind of indicator, as the term suggests, visualizes data by letters of alphabet and numbers from 0 to 9 with decimal points.

According to Bolton (2003), seven-segment display is widely used and it based on a 4-bit binary code. This input code provides the necessary inputs to switch on the specific segments, labeled by letters (a-g), in order to obtain the desired displayed value. Figure 4.11 illustrates the distribution of the seven segments, which are switched on so that some particular number is displayed. Figure 4.11 also shows the numbers displayed corresponding to a 4-bit code.



Binary Input				Segments Activated							Number Displayed
				a	b	c	d	e	f	g	
0	0	0	0	1	1	1	1	1	1	0	0
0	0	0	1	0	1	1	0	0	0	0	1
0	0	1	0	1	1	0	1	1	0	1	2
0	0	1	1	1	1	1	1	0	0	1	3
0	1	0	0	0	1	1	0	0	1	1	4
0	1	0	1	1	0	1	1	0	1	1	5
0	1	1	0	0	0	1	1	1	1	1	6
0	1	1	1	1	1	1	0	0	0	0	7
1	0	0	0	1	1	1	1	1	1	1	8
1	0	0	1	1	1	1	0	0	1	1	9

Figure 4.11 *Seven – segment display (Bolton 2003).*

As can be seen in Figure 4.11, the combination of the 4-bit code leads to the visual representation of the values measured by sensors.

4.4.2. Alarm indicator

Alarm indicators are used in order to inform that a dangerous activity occurs during the process. The alarm indicator takes an analog output from a sensor or a signal conditioner, if needed to be used, and converts it into an on/off signal. In this case, this on/off signal means a light switched on/off as applicable. The alarm system takes the input and compares it with a reference value. If the current value being measured exceeds the limits, logic 0 or 1 signal activates the indicator and, for instance, an alarm light is switched on (Bolton 2003).

5. CONTROL THEORY

Control systems have been developed in order to protect components, machines or processes against problems that can occur during a particular operation.

5.1. Logic control

In Control Theory, control systems are designed on the basis of events which occur during the operation. Therefore, depending on the current conditions, they either let the system continue or stop the working process. Logic control involves digital signals when only two signal levels are possible. Basically, they are high and low signals and they are represented by 1 and 0 (Bolton 2003). In addition, if the nature of the process is taken into account, they can symbolize levels on or off, open or close, true or false, etc. An example of this concept is shown in Figure 5.1.

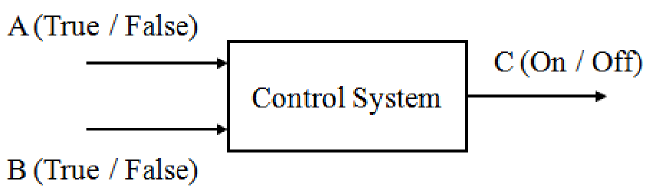


Figure 5.1 *Logic control system with two inputs signals and one output signal.*

As can be seen in Figure 5.1, this system has two input signals A and B, which are either true or false signals; and one output signal C, which is an on/off signal. In this example, the control system's function is to switch on only when both of the inputs are true.

The term combinational logic control is used to define a control system which is based on the combination of two or more logic gates such as AND, OR, NAND, NOR or XOR in order to obtain the required function. Both input and output signals are represented by 1 and 0 just like logic control systems. An example of this concept is shown by Figure 5.2.

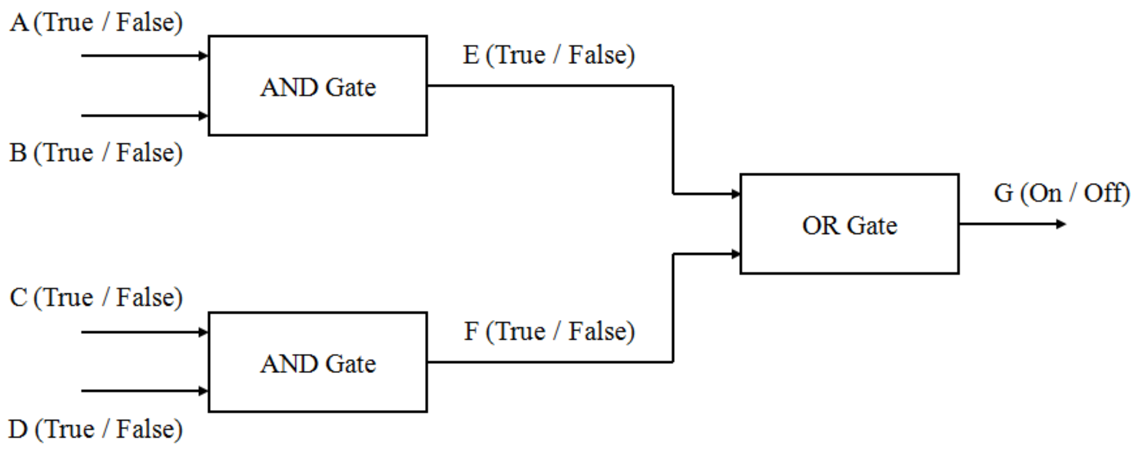


Figure 5.2 *Combinational logic control.*

As can be seen in Figure 5.2, the combinational logic control system can be set up of three different gates. In this case, when either the inputs A and B are both true, or the inputs C and D are both true, the control system has been developed, for instance, to switch on the device or to activate an operation. In conclusion, the output of these systems is determined by the combination of different inputs at a particular instant of time (Bolton 2003).

5.2. Closed–loop control

Closed–loop control is based on the comparison between the current and the desired value of a variable. The operation principle of this control is to monitor the variable disturbances involved in the process and keep them within a range of values which ensure the proper running of the system (Phillips 1990). Closed–loop control system uses the feed-back concept in order to correct variations in the proper behavior of the system caused by disturbances (Bateson 1991). As can be seen in Figure 5.3, the term feed-back comes from the fact that the output signal is compared with the input value. The input signal is desired to be the same as the output signal. Figure 5.3 also shows that the signal begins at the output of the process and ends at the input of the controller whose output feds back into the process.

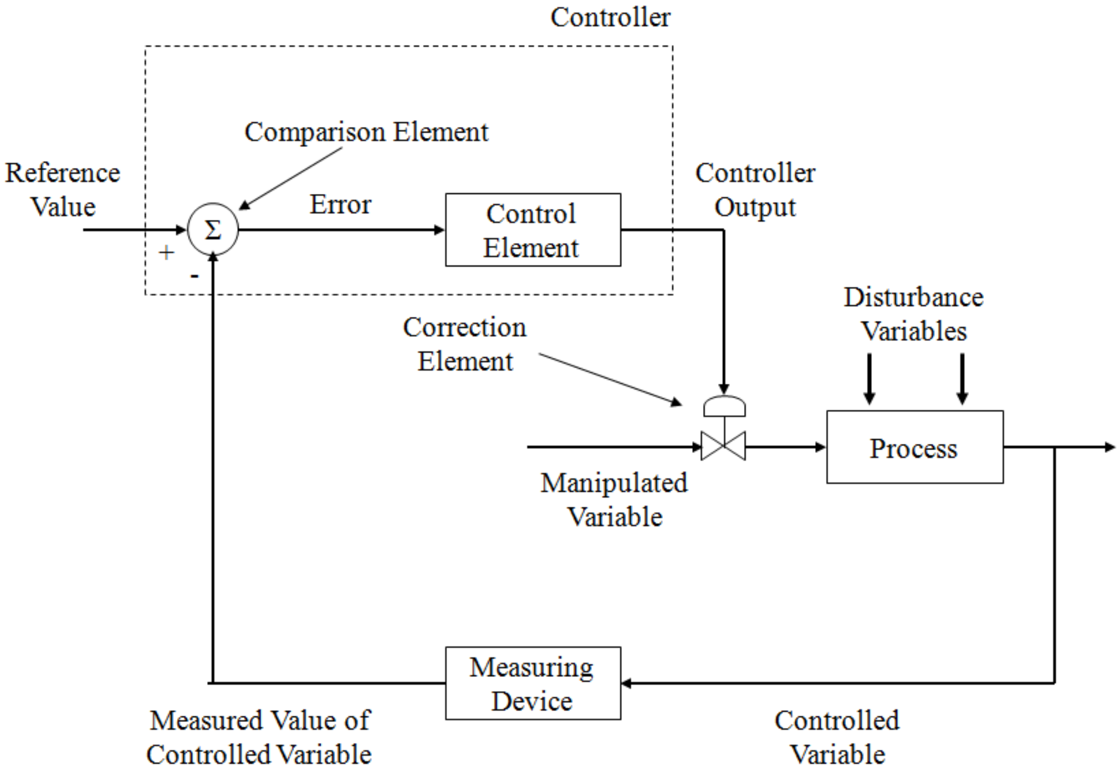


Figure 5.3 *Block diagram of a close –loop control system (Bateson 1991).*

Processes are affected by external disturbances. Closed–loop systems utilize a measuring device to obtain the actual value of the controlled variable which is evaluated with the reference value using the comparison element. The result is an error signal calculated by equation (5.1)

$$\text{ErrorSignal} = \text{ReferenceValueSignal} - \text{MeasuredValueSignal} \qquad (5.1)$$

The error signal is fed to the control element which monitors it and decides if a corrective action is needed to keep the process working properly. Therefore, if the error signal is out of the permitted range the control element sends a signal to the actuator which modifies the current situation. On the basis of the control element working principle, it can be used to manipulate the flow through a valve in order to control the position of a piston. These concepts are used in the compressing unit (Dally 1984, Bateson 1991, Bolton 2003).

Figure 5.3 also shows the connection between the control and the correction elements that provides the control of the situations out of the established limits. Therefore, this correction element receives a signal from the control element and produces a change in a manipulated variable when the work conditions are not within the permissible range. It modifies the current process conditions which results in the system return to a proper working situation. The correction element usually uses an actuator to transform electrical energy into some other kind in order to carry out the control action over the process (Dally 1984, Bateson 1991, Bolton 2003).

The next step in a closed–loop control system is the process which is being controlled. The controlled variables involved in it are influenced by other variables called disturbances (Dally 1984, Bateson 1991, Bolton 2003). Finally, the action of the disturbances, the failures and also the proper running of the process leads to changes in the controlled variable. Therefore, the measuring device closes the loop of the variable block diagram, measures its value and feeds it into the comparison element in order to obtain the error mentioned above (Bateson 1991).

5.3. Cascade control

Systems with one input and multiple outputs can be controlled by using cascade control (Lestage 1999). In this case, one output must reach a given reference value while the others must remain stable inside an established range of values. Actually, single close–loop control (Chapter 5.2) can be improved by using cascade control. As a matter of fact, processes have control delays and consequently, the feedback can be affected and the system cannot be controlled properly. In this situations, the delay in the feedback and, therefore, in the control of the system, allows other variables, disturbances, to affect the main process (Wang 2008).

This chapter addresses two methods to solve these control system problems, serial cascade control and parallel cascade control (Boyce 1996, according to Lestage 1999). Both of them use two feedbacks, the first one is in charge of the principal variable and the second one is the secondary variable. This secondary variable is also called disturbance and it affects the system faster than the principal one is monitored. Therefore, the mentioned secondary variable must be controlled inside the principal feedback (Lestage 1999, Flores 2009).

On the basis of the previous paragraphs, it can be said that cascade control has two loops, the first one is called primary loop and the second one is called secondary loop. The latter works faster than the former.

5.3.1. Serial cascade control

Serial cascade controllers are widely used in order to control different kind of processes. As can be seen in Figure 5.4, serial cascade control is based on the concept that the manipulated variable u affects the intermediate variable y_1 in the same way this intermediate variable modifies the behavior of the controlled variable y_2 (Flores 2009).

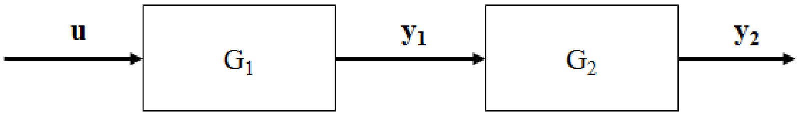


Figure 5.4 *Serial cascade process. Manipulated variable (u) affects the intermediate variable (y_1) which affects the controlled variable (y_2) (Flores 2009).*

In this case, the use of a serial cascade controller is better than a single–loop one only when the dynamic response of the process G_1 is faster than the dynamic response of the process G_2. Therefore, the design of the serial cascade controller starts from the control of the process G_1 and finishes with the control of the process G_2 (Flores 2009).

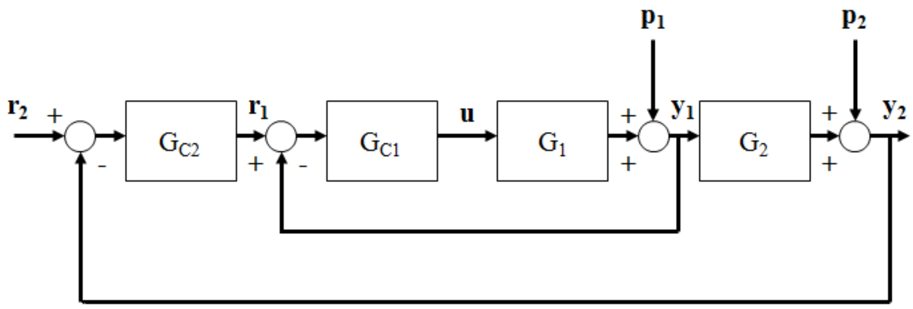


Figure 5.5 *Serial cascade controller (Lestage 1999).*

Serial cascade controller uses two controllers G_{C1} and G_{C2}. G_{C1} regulates the output of the secondary loop which is y_1, and G_{C2} modifies the secondary loop reference value r_1, in order to control the final controlled variable y_2 (Lestage 1999). As can be seen in Figure 5.5, the outcome of this kind of control is the ability to cancel the disturbance p_1 faster than a single–loop controller do (Caldwell 1959, according to Lestage 1999).

5.3.2. Parallel cascade control

The design of serial cascade control is not always possible due to the nature of the process. In this case, parallel cascade control is sometimes used (Luyben 1973, according to Shen 1992; Yu 1998 according to Shen 1992). There are systems in which the manipulated variable u is related to an intermediate variable y_1 but this one does not affect directly the controlled variable y_2 (Flores 2009).

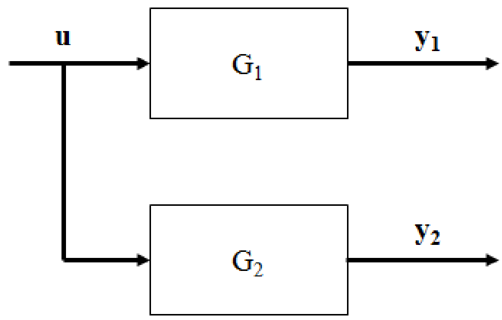


Figure 5.6 *Parallel cascade process. Manipulated variable (u) affects both the intermediate variable (y_1) and the controlled variable (y_2) (Flores 2009).*

Figure 5.6 shows that the manipulated variable u influences directly the controlled and the intermediate variable, which are y_2 and y_1. In the same way as serial cascade control, the use of a parallel cascade controller is better than a single–loop one only when the dynamic response of the process G_1 is faster than the dynamic response of the process G_2. Therefore, the design of the parallel cascade controller starts from the control of the process G_1 and finishes with the control of the process G_2 (Flores 2009). It uses G_{C1} to regulate the output of the secondary loop y_1, and G_{C2} to remain stable the output of the primary loop around the reference value (Lestage 1999). The objectives of parallel cascade controllers are both to maintain the output of the primary loop y_2 at the set point and to control the disturbances by using secondary loops (Shen 1992). These secondary loops are designed to overcome a specific disturbance by changing the intermediate variable which is, in this case, the manipulated variable (Hsu 1990, according to Shen 1992).

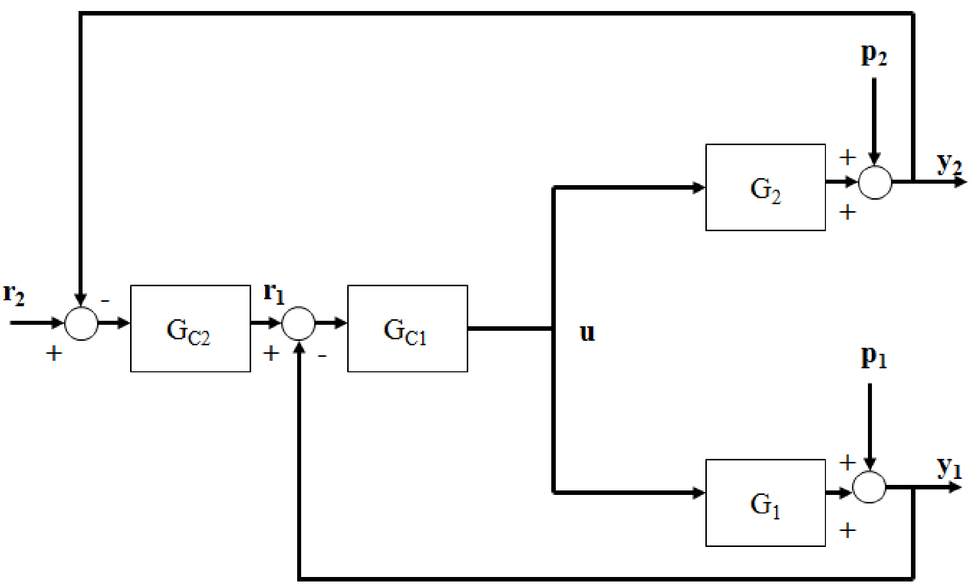


Figure 5.7 *Parallel cascade controller (Lestage 1999).*

Figure 5.7 shows that in spite of that the intermediate variable does not influence directly the controlled variable, it can affect the values of this controlled variable due to the feedback of the secondary loop. In conclusion, if more than two loops are cascaded, the indirect influence that the inner controllers exert to the outer ones has to be taken into account (Lestage 1999).

5.4. Principles of flow control

The position control system needed to the proper running of the unit uses the flow rate in order to remain stable the working conditions. Hydraulic control system operation principle is based on the conversion from the internal energy of the fluid into kinetic energy (Walters 1991). This goal is carried out controlling the flow by throttling the fluid passing through an orifice or orifices of a valve.

The type of flow inside the valve determines its features and its values during the working process. For this reason, a turbulent flow is mainly dependent on the pressure differential, the density of the fluid, the coefficient of discharged, the orifice area. In addition to this, it is significantly independent from fluid temperature. On the other hand, a laminar flow is sensitive to viscosity and, therefore, to fluid temperature variations. On the basis of this, valves are designed in order to avoid laminar flow and hence sensitivity temperature variations (Walters 1991). The relation between valve opening, pressure drop and flow rate is calculated by equation 5.2

$$q = C_d a \sqrt{\frac{2}{\sigma_f}} \sqrt{\Delta P} \tag{5.2}$$

where q is the flow through the orifice, a is the orifice area, ΔP is the pressure drop across the orifice, σ_f is the density of the fluid and C_d is the coefficient of discharge.

A three–way valve in charge of the control of a differential cylinder position is shown by Figure 5.8. It is used to explain the operation principle of a flow control system.

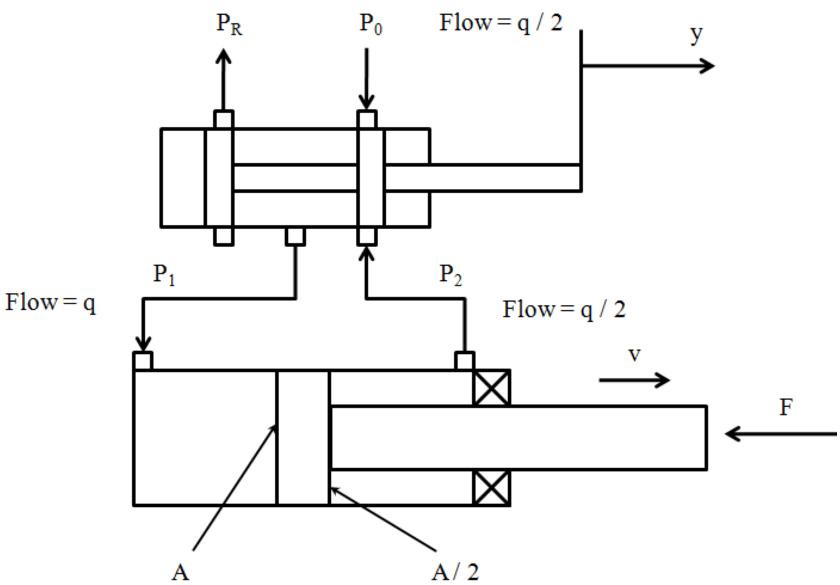


Figure 5.8 *Three–way valve controlling differential cylinder (Walters 1991).*

On the basis of equation (5.2) and taking the distribution shown in Figure 5.8 into account, the flow of the three–way valve is obtained in equation (5.3)

$$q = C_d a \sqrt{\frac{2}{\sigma_f}} \sqrt{P_0 - P_1} \tag{5.3}$$

Where P_0 and P_1 are the supply and inlet pressure. Considering that

$$P_L = \frac{F}{A} = P_1 - \frac{P_0}{2} \tag{5.4}$$

and by combining equations (5.3) and (5.4) the flow is calculated by equation (5.5)

$$q = C_d a \sqrt{\frac{2}{\sigma_f}} \sqrt{\frac{P_0}{2} - P_L} \tag{5.5}$$

where P_L is the load pressure drop across the cylinder (Walters 1991).

The equations developed above are also applicable when the valve and therefore, the actuator movements, are reversed. In this case, it is necessary to pay special attention on the direction of the forces and the pressure gradients.

5.5. Methods of control system by using a servo valve

The goal of any hydraulic control system is to control one or more of the variables involved in the main process such as direction, velocity, acceleration, deceleration, position or force. Thereby, the control element remains the principal variable stable by acting on the hydraulic parameters, pressure and flow (Walters 1991). On the basis of the concept explained above, the following chapters explain different kind of control system. They can be used in order to improve the suitable control system for the compressing unit, in case that a servo valve would be used.

5.5.1. Position control

A control valve, based on a position control system, consists of the manipulation of a throttling element and a valve (Pyötsiä 1991).

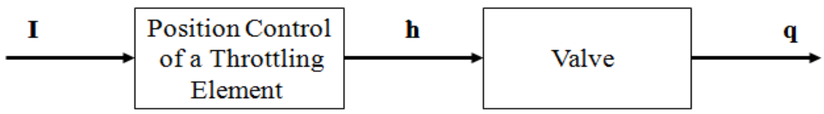


Figure 5.9 *Control valve consists of position of a throttling element and a valve (Pyötsiä 1991).*

As can be seen in Figure 5.9, the position control receives an input signal I according to the error between the current position and its reference value. In this case, if the error signal is not appropriated the position of the throttling element h is modified and therefore, the valve flow q varies proportionally (Pyötsiä 1991). Subsequently, the position control system is based on both the monitoring of the current position, for instance a piston position; and the flow correction due to the error obtained in the comparison element.

Position control method is based on the comparison of the current position value, provided by a measuring device, and the reference position value, given as an input. This comparison leads to the position error of a mechanism or machine. It is fed to an analog to digital converter in order to obtain a suitable signal for the next step of the position control system, the control element. Either if the position error does not remain stable inside an established range or the measured value of the position does not match up with the reference value, the control element provides the correction element with a controller output in order to correct the current error inside the process. As a matter of fact, the controller output is fed to a digital to analog converter to be suitable for the correction element. This correction element acts on the manipulated variable of the process, in this case the flow rate, and modifies the process conditions going back to the proper running of the process (Dally 1984, Bateson 1991, Bolton 2003).

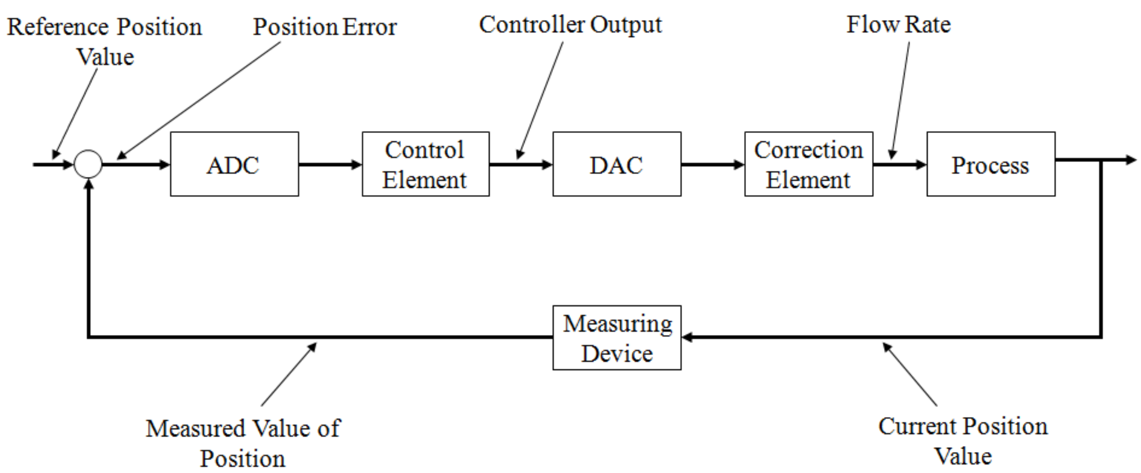


Figure 5.10 *Position control system (Bateson 1991, Phillips 1990, Bolton 2003).*

As be seen in Figure 5.10, the position control system uses control theory concepts mentioned in previous chapters such as closed–loop, feedback or cascade control if different disturbances are taken into account.

5.5.2. Pressure control

Pressure control system operation principle is based on maintaining the balance between a current pressure value, which is measured, and a reference pressure value established previously (Bateson 1991).

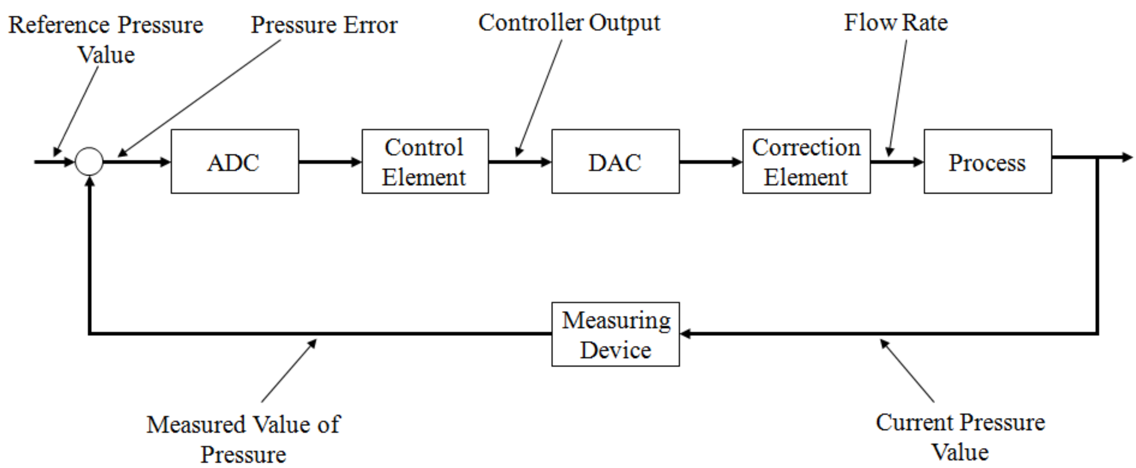


Figure 5.11 *Pressure control system (Bateson 1991, Phillips 1990, Bolton 2003).*

The operation principle of the pressure control system is based on the same theories and concepts as the position control system. In this case, the variable which is measured and compared to a reference value is the pressure inside the valve. The controller output is fed in the correction element which modifies the flow rate inside the valve, if needed. The outcome of this is a variation in the pressure inside the valve in order to achieve the reference pressure value or remain stable inside the required range of pressure values (Dally 1984, Bateson 1991, Bolton 2003).

5.5.3. Force control

Force control system is based on the same theories as position control system. The difference between force control and the position and pressure control is the way to act on the process. Position and pressure control systems use the flow rate as a variable to achieve a controlled value similar to a reference value or inside an established range of values. On the other hand, the force control system uses pressure as a variable to achieve the same goal (Walters 1991).

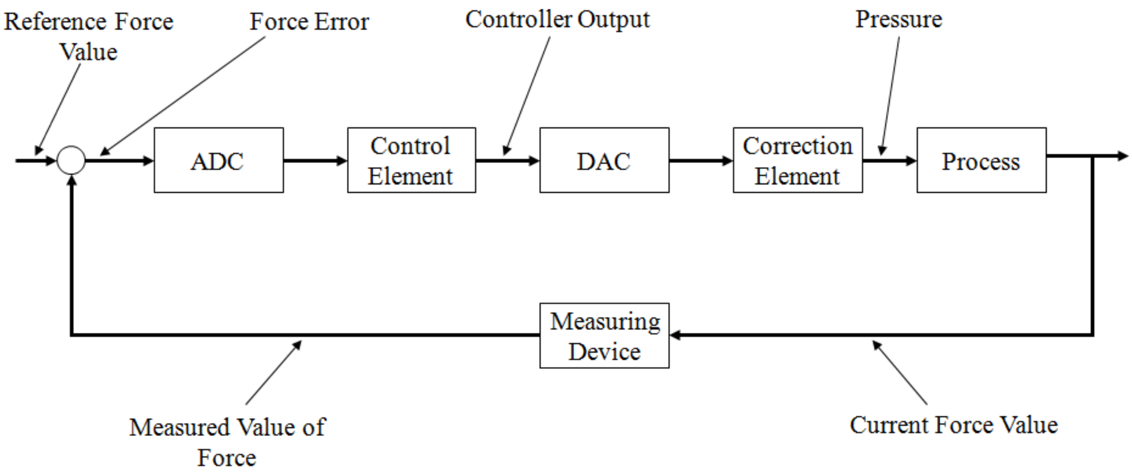


Figure 5.12 *Force Control System (Bateson 1991, Phillips 1990, Bolton 2003).*

Figure 5.12 shows that the comparison element obtains the error between the current force value, which is measured, and a reference force value established previously. The controller element receives this error and provides the correction element with a controller output if it is necessary to act on the manipulated variable in order to modify the process conditions. In this case, the correction element changes the pressure inside the valve and consequently, inside the piston. The outcome of this is a variation of the current force value (Dally 1984, Walters 1991, Bateson 1991, Bolton 2003).

6. CONTROL INTERFACES

Control interfaces are developed in order to carry out the control and measurement system. For this purpose, a hand drive and a computer interface are designed. The following chapters explain their operation principle.

6.1. Hand drive interface

The hand drive is a control which allows a supervisor to operate the unit manually. It consists of buttons related to the different activities that the compressing unit has to carry out, and displays which show the most important variable values. In addition, lights can be used to report on a dangerous situation or to show the user that a particular unit activity is carrying out. For instance, a red light can report that a variable has exceeded its limit values or a light can be switched on when the user presses the button used to drive the compressing unit.

The hand drive can be divided in different parts depending on the type of activity. The first part is related to the operating control used to drive the compressing unit. It consists of the on/off, the manual/automatic and the directional buttons. The first one is in charge of switching on/off the unit and a light can be used to show that the hand drive and consequently, the unit are working. The second one activates the manual or automatic mode of work. The manual mode allows the user to drive the compressing unit by hand drive and the automatic one is used to drive it by LabView software. The third one consists of the forward and the backward buttons. They allow the user to drive the pushing plate. In addition, they can only work when the manual mode is activated and their functions are carried out when they are pressed. The second part is related to the emergency system. It consists of an emergency button which stops the working process when the user presses it. An emergency light can be switched on when this user carries out this action. The third part is related to the displays. They show the values of the most important variables which are analyzed to configure the control and measurement system.

The nature of the compression process and the unit design entail the assembly of the components needed to activate the relays which drive the directional valve. In addition, the displays related to the force and strain measurements can have installed the necessary amplifiers inside them in order to simplify the hand drive structure.

6.2. Computer interface

LabView software is a graphic programming software used to acquire, analyze, display and control data. Its programs are based on block diagrams and it uses icons and graphic symbols in order to configure the applications. The LabView programs are termed Virtual Instruments (VIs) because its appearance and working principle are similar to real instruments. The VIs is divided in two parts. The former is used to interact with the supervisor and the latter is related to the source code. In addition, the VIs can be connected with other VIs in order to use common variables.

Every VI has a front panel and a block diagram. Both of them have a palette with all the icons used to create and modify the VIs. The controls palette is used in the front panel and it contains the controls and indicators which are needed to create the interface between the VI and the user. The functions palette is used in the block diagram and it contains the icons needed to the implement the VI program. In addition to this, the tools palette can be used in both the front panel and the block diagram and it contains the tools to edit and debug them.

Firstly, the front panel is a graphic interface between the VI and the user. This user can interact with the front panel in order to act on the application. In addition to this, it can display the outputs from the program. The front panel consists of buttons, graphs, etc. They can be defined as controls or indicators. The formers are used to provide the VI with parameters and the latters are used to display the results. Secondly, the VI source code is programmed in the block diagram. It carries out the implementation of the VI program in order to configure the front panel controls and indicators which were created previously in this front panel. The block diagram includes functions and structures from the LabView libraries.

The controls and indicators which were located previously in the front panel have their own icon in the block diagram. The connection between the icons is carried out by virtual wires in which the data flows. These wires transfer the data flow and they have different colors depending on the type of data which flows though them. LabView software has a function library which contains arithmetic and comparison functions, others related to the data analysis, input/output functions, etc. It also has structures such us while, case or for loops, MathScript structures, etc.

7. SYSTEM DESCRIPTION

The study of the compressing unit operation principle leads to the control and measurement method used to achieve the goal of this Master Thesis. The following chapters analyze the compressing process and detail the proper method in which this control and measurement system is based on.

7.1. Description of the machine

Pulp for making paper is produced in grinding machines whose operation principle is based on the compression of logs against a grinding stone. In order to understand the force transmission and the compression state of the logs the unit has been constructed. This unit is used in the research case and is composed of a hydraulic cylinder which drives a pushing plate; a chamber in which the process takes place; and the necessary structure used to hold the cylinder and the chamber above mentioned. Figure 7.1 shows the layout of the compressing unit.

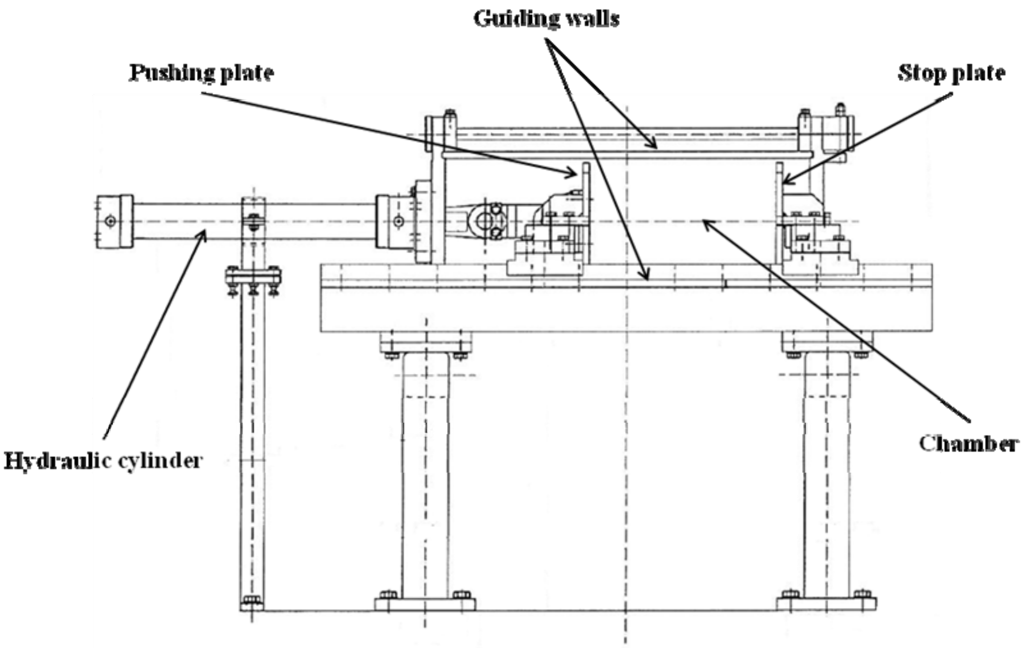


Figure 7.1 *The layout of the compressing unit.*

As can be seen in Figure 7.1 a pushing plate is assembled to the hydraulic cylinder and its start position is placed closed to this hydraulic cylinder mentioned above. The pushing plate is a mobile plate and is in charge of the logs compression against a stop plate. This stop plate is fixed and is placed in front of the pushing plate at the end of the chamber. In addition to this, the chamber working area is delimited by the pushing plate, the stop plate and two horizontal guiding walls. Due to the motion of the pushing plate it is continuously changing. The logs are set and test inside this working area.

The guiding walls dimensions are a length of 730 mm, a width of 286 mm and a height of 15 mm. They are made of S355JR steal and they are bent during the compression process. The cylinder stroke length is 60 mm and its rod diameter is 63 mm (see chapter 7.5.2). In addition to this, the chamber dimensions without the pushing and stop plate assemblies are a length of 730 mm, a width of 286 mm and a height of 286 mm. These dimensions and others related to the machine are in the appendix A.

7.2. Description of the process

The nature of the compression process and the unit design determines the working conditions. According this, the main process, which is related to the compression, is divided in different sub–processes. Basically, the hydraulic system provides the cylinder with the necessary pressure to start the operation. The cylinder converts this pressure into the force applied on the pushing plate which is used to carry out the compression. Furthermore, the compression of the logs produces the motion of the pushing plate, the development of axial forces parallel to the cylinder axle, and the bending of the guiding walls.

On the basis of the previous description of the unit working operation principle, it can be said that the whole process is divided in four sub–processes. Figure 7.2 shows these sub–processes and the necessary connections between them in order to form the whole process.

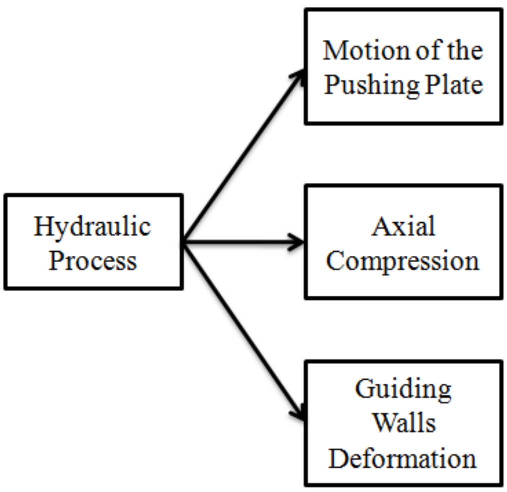


Figure 7.2 *The compression of the logs consists of four sub–processes.*

Firstly, the hydraulic system converts the energy from the fluids into force applied on the pushing plate. Secondly, this force applied on the pushing plate carries out the next sub–process which is the axial compression of the logs. It consists of the interaction of three forces which are directly related to each other. As can be seen in Figure 7.3, they are the forces applied on the pushing and the stop plate and the forces caused by friction.

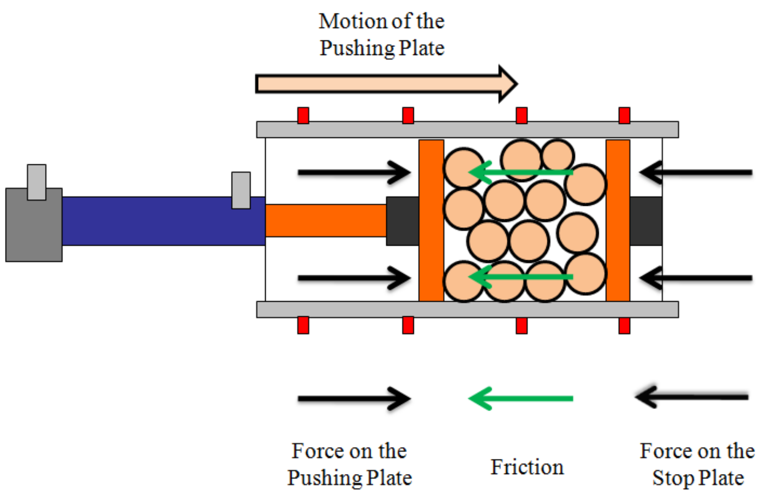


Figure 7.3 *Sub–processes related to the axial compression and the motion of the pushing plate.*

Thirdly, the hydraulic system provides the cylinder with flow rate and pressure in order to obtain the necessary force applied on the pushing plate to make the compression of the logs possible. Therefore, when the force is high enough to achieve this goal, the pushing plate moves forwards and subsequently the motion of the above mentioned pushing plate occurs. Finally, the motion of the pushing plate causes the movement of the logs. The unit crushes and compresses them inside the chamber and, as a result, normal forces act on the guiding walls causing the subsequent sub–process, the guiding walls deformation. Figure 7.4 illustrates this sub–process. The guiding walls are made of a softer material compared to the one in the pushing and stop plate and consequently, they are able to withstand lower forces.

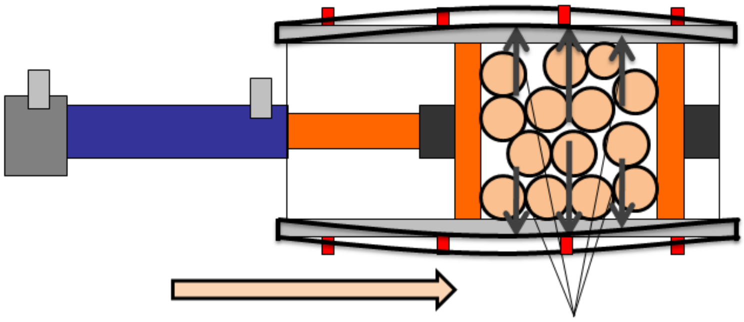


Figure 7.4 *Sub –process related to the guiding walls deformation.*

In conclusion, the whole process, which is the compression of the logs, is divided in four sub–processes. They are the conversion from hydraulic to mechanical energy, the motion of the pushing plate, the axial compression, and the deformation of the guiding walls due to normal forces.

7.3. Analysis of the variables involved

The synergy of the sub-processes explained in chapter 7.2 represents the unit's main goal. Therefore its control and measurement system has to take them into account in order to protect the unit. The first step in the development of this control and measurement system is the analysis of the different variables involved in the process. These variables are divided in four different groups according to the way in which they are monitored.

7.3.1. Controlled variables

The first group consists of the variables which are controlled during the compression. For this purpose, a combinational logic control system (chapter 5.1) is developed. Basically, it monitors these parameters in order to modify the main process conditions when the current situation seems to be dangerous for the unit. For this purpose, two relays drive the valve to its neutral position to stop the hydraulic supply when these particular situations occur. The outcome of this is a compression process based on safe working conditions.

Regarding the main process, the first controlled variable is the pressure. It takes place inside the valve and varies due to the flow rate which passes through it. This pressure leads the process to the next variable monitored by the control system, the force applied on the pushing plate. The variation of its values affects the development of the compression process. For instance, if the same batch is tested continuously, an increase in the force on the pushing plate leads to a time reduction in the whole process. As a result, this whole process is carried out faster.

The increase of pressure inside the valve entails the change of the pushing plate position. This variable is directly related to the distance between the pushing and the stop plate and its changes during the process. The control system of the unit is based on the pushing plate position which is considered the principal variable of the compression process. The rest of the controlled variables are termed as secondary variables.

The compression process implies the control of two other variables. These are the force applied on the stop plate and the stress. The force applied on the pushing plate and the resistance of the logs lead to the force applied on the stop plate. This variable can damage the measurement system thus it has to be controlled. In the same way as the force applied on the pushing plate, the stress in the guiding walls has to be monitored by the control system in order to protect the unit.

The main process and its development entail the interaction of sub–processes which are characterized by different variables. Furthermore, as the proper running of the unit continues, these variables change their values depending on the requirements of the current process conditions. In addition to the concepts explained above, it is necessary to emphasize that time is a variable which influences on the rest of the parameters. Therefore, the control system uses it to monitor the development of the process during the different steps in which it is consisted of. In addition, the controlled variables are not only controlled but also measured during the compression process.

7.3.2. Measured variables

The second group of variables in combination with the first group explained above forms the measurement system. This second group involves the parameters which are monitored for a better understanding of the working process. Therefore, the measurement system can be used to analyze the behavior of the compressing unit when it works with different materials and within different conditions. The force applied on the pushing plate, which is modified according to the changes in the valve pressure, leads to the variation of the force applied on the stop plate. Furthermore, the measurement system uses it to obtain the friction which is required to understand the behavior of the batch. This value is calculated by equation (7.1)

$$Friction = F_{PP} - F_{SP} \tag{7.1}$$

where F_{PP} is the force applied on the pushing plate and F_{SP} is the force applied on the stop plate.

The compression process entails the interaction between the log batch and the unit guiding walls. It causes the action of normal forces which causes the bending of the guiding walls. As a consequence, the strain in these guiding walls can be considered as a measured variable.

7.3.3. Indirect variables

The third group of variables is related to the parameters that can affect the system indirectly or, in other words, the variables which are not considered inside the process but can modify its expected behavior. The mass, density or volume, and the quality of the logs belong to this group and can affect the process. For instance, either a low density or a small volume of the log batch can produce a sudden movement of the pushing plate and consequently, a particular damage in the compressing unit.

In the same way as the variables mentioned above, the humidity and the temperature can modify the process behavior and as a result, damage the unit. These parameters can appear during the process due to the proper running of the unit (for instance, the friction between the batch and the guiding walls) or the malfunctioning of the unit (for instance, the friction between the different unit components). The pushing plate velocity and the acceleration should also be considered because high values of these variables lead to sudden movements during the process.

7.3.4. Future variables

The development of the unit control and measurement system entails the analysis of the different variables involved in the main process. Despite the fact that these variables have been explained above, this research emphasizes others which can be interesting for future studies. For this purpose, it is recommended to take the stress distribution inside the batch or the motion of the logs into account. These parameters can be used to achieve a better understanding of the development of the sub–processes such as the deformation of the guiding walls or the forces caused by friction inside the chamber. The studies of these variables provide the improvement of the comprehension of the logs’ behavior inside the chamber and therefore, an accurate control and measurement system.

The estimation of the energy that the compressing unit consumes is also possible. It can show the amount of energy that it needs to carry out the logs compression. Studies about the energy that each process needs can be used to save it in order to increase the efficiency of the unit operation.

7.3.5. Variables diagram

The different variables can be analyzed according to the part of the unit in which they take place. Therefore Figure 7.4 shows where the considered parameters are more influential during the processes.

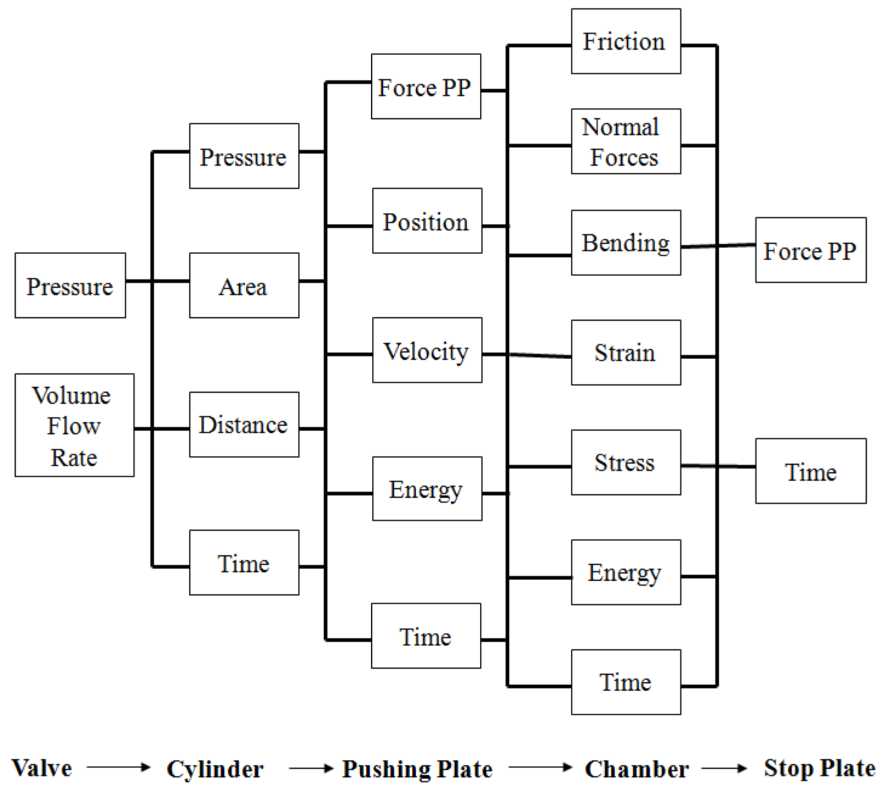


Figure 7.5 *Flow diagram of elements used in system design strategy.*

The compressing unit consists of a valve, a cylinder, a pushing plate, a chamber, and a stop plate. The hydraulic system which feeds oil into the valve and makes the process possible is not taken into account due to that it is already controlled by an external system. Figure 7.5 shows the variables required to design the control and measurement system. It is also important to analyze the indirect variables because they can affect the proper running of the unit.

7.4. Analysis of the control and measurement method

The previous analysis of the variables involved in the compression process points out that they are divided in three different groups depending on their specific function. Therefore, the controlled variables are defined in order to protect the unit and the control and measurement system against the damage produced by their possible high values. Furthermore, the measured variables provide the information about the development of the sub–processes that form the main process. In addition, the indirect variables identify the outer disturbances, apparently unconnected with the activity that the unit carries out, which can affect the proper running of the compressing unit.

As a result of the variable analysis explained in Chapter 7.3 and based on Figure 7.5, a control and measurement system has to be developed. The first step to achieve this goal is to study the unit working principle with regard to the sub-processes involved in the logs compression. These sub-processes have been selected according to the variable analysis and the studies completed in the previous step of the research work.

The sub-processes related to the logs compression and the most important variables involved in them are shown by Figure 7.6.

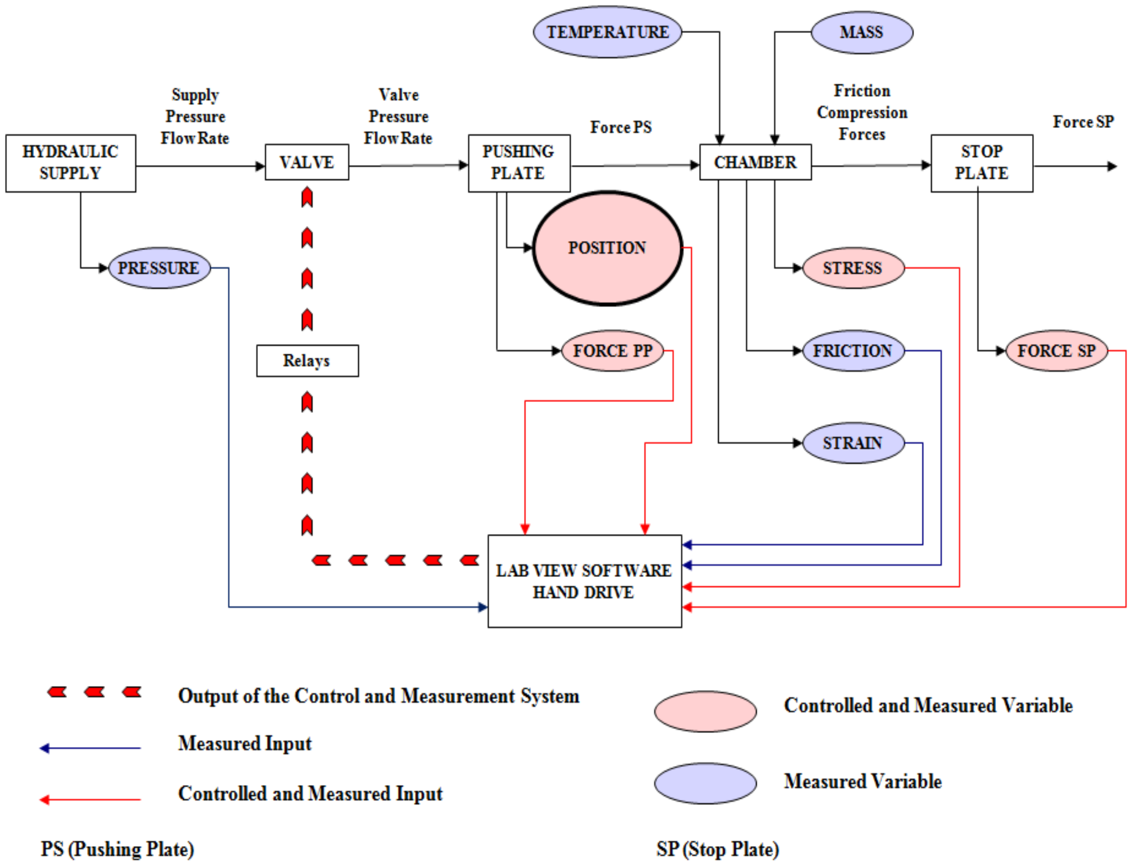


Figure 7.6 *Control and measurement system for the log batch compressing unit.*

As can be seen in the Figure 7.6 the understanding of the main process is facilitated because the sub–processes are related to each other and connected in a correct order. Furthermore, as was explained in Chapters 7.2 and 7.3, the unit working process starts with the action of the hydraulic system which provides the cylinder through the on/off valve with pressure and flow rate. As a result, the cylinder starts moving forwards or backwards, as applicable. If it moves forwards, the compression of the logs will start, the force applied on both the pushing and the stop plate will increase. The forces inside the chamber caused by the friction will also rise due to the contact between different logs and between the logs and the unit guiding walls. Regarding the sub-processes and the different variables, the control and measurement system is developed.

The design of the control and measurement system is based on the position of the pushing plate because it is used to delimit the working area. As a consequence, the unit can only operate inside a position range of values which are exposed in the following chapters. The rest of the controlled and measured variables are monitored during the compression process when it occurs inside the working area mentioned above. The following chapters explain the control and measurement system operation principle and its different parts.

7.4.1. Control method

The compression process is divided in different sub–processes which follow one another. The most important is the pushing plate movement and it is controlled by monitoring the pushing plate position. This value is related to the variation of the distance between its current and start position. Furthermore, as is mentioned above, the control and measurement system monitors continuously the current position, obtained by using a position sensor, and checks if the unit operates inside the safe working area.

As a matter of fact, the control and measurement system samples the pushing plate position over time and compares it with the limit values. If these values match up, the on/off valve will be driven to its neutral position and the unit will stop working. In addition, the control and measurement system only allows the unit to start working again if the user changes the direction of the pushing plate movement or, in other words, if the user tries to avoid the dangerous situation for the unit. An example of this occurs when either the user compresses soft logs or there is no log inside the chamber. As a consequence, the pushing plate reaches the position limit located near to the stop plate. In this case, when both values, the pushing plate position and the limit match up, the valve will be driven to its neutral position. From that moment, the control system only allows the user to push the cylinder back to try to avoid the possible crash between the pushing and the stop plate.

The compressing unit entails the activity of different variables, thus the control and measurement system only based on the pushing plate position seems to be insufficient. As is explained before (see chapter 7.3), there are variables which can damage the unit when it operates inside the safe working area. Therefore, they have to be controlled. As a result, the logic control system is improved. It is achieved by taking into account all the potential variables dangerous for the unit. Thereby, the control and measurement system consists of a main logic control and secondary controls. While the former is in charge of the principal variable, in this case the pushing plate position, the latters monitor the activity of the other potential variables dangerous for the unit and check if their values exceed the established limits.

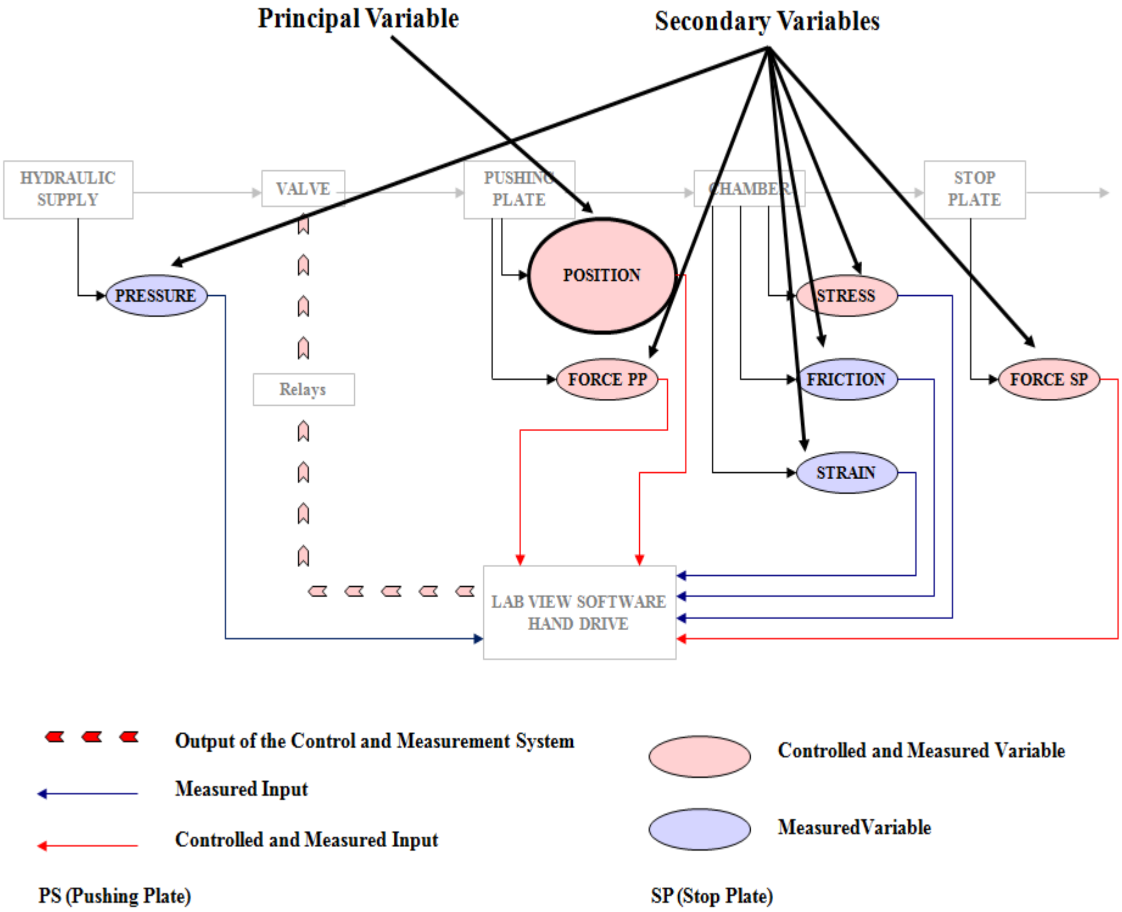


Figure 7.7 *Logic control of the compressing unit, principal and secondary variables.*

The logic control system can be divided in two parts concerning to the dependency between variables. Accordingly, there are variables which are directly related to each other (Figure 5.4) and others which are simply indirectly related (Figure 5.6).

An illustration of the variables directly related is given by Figure 7.8. It shows the dependency between the different axial forces involved in the process. In the same way as these axial forces, it illustrates the direct relation between the strain and the stress in the guiding walls. According to the chapter 5.3.1, this kind of relationship is based on the concept that a first variable affects a second one in the same way that this second one affects a third one and so on. Therefore, the actions of the directly related variables on the process are considered as serial operations because a variation in the first step of the group leads to a direct change in the next ones.

Based on the concepts explained above, the unit compression process starts with a particular supply pressure. As a consequence, a valve pressure is produced and different forces involved in the activity of the unit appear. As can be seen in Figure 7.8., these forces are the force applied on the pushing plate, the force applied on the stop plate, and the forces inside the chamber caused by friction. In the case study machine, the forces caused by friction are the difference between the forces applied on the pushing and stop plate. As a consequence, this difference is obtained because the control and measurement system monitors both of them by using the corresponding sensors. In conclusion, the different forces involved in the compression process are considered dependent to each other because an increase in the force applied on the pushing plate leads to an increase in the force applied on the stop plate. It usually produces an increase in the forces caused by friction.

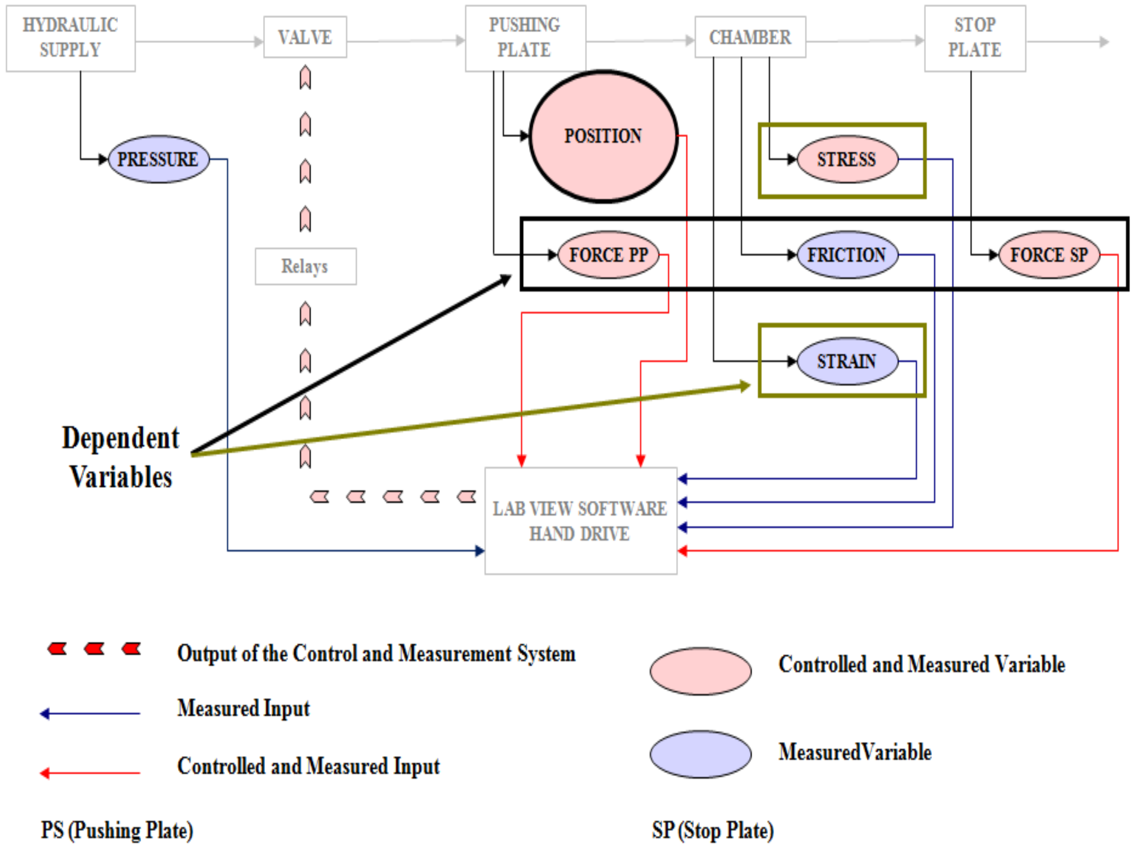


Figure 7.8 *Variables directly related to each other in which the first one affects the second one in the same way this second one affects the third one and so on.*

The stress is directly related to the increment of the strain in the guiding walls. Therefore, a variation in the guiding walls strain entails a change in their stress distribution. In conclusion, both variables, strain and stress act in serial on the process.

On the other hand, Figure 7.9 shows the variables which are indirectly related to each other. According to the chapter 5.3.2, this kind of relation is based on the concept that a first variable affects other variables but these ones do not affect each other directly. Therefore, their acts on the process are considered as parallel operations. In this case, as can be seen in Figure 7.9, the pressure inside the valve and the position act on the compression process in parallel with the dependent variable systems. As a result, the different sub–processes are controlled and measured at the same time.

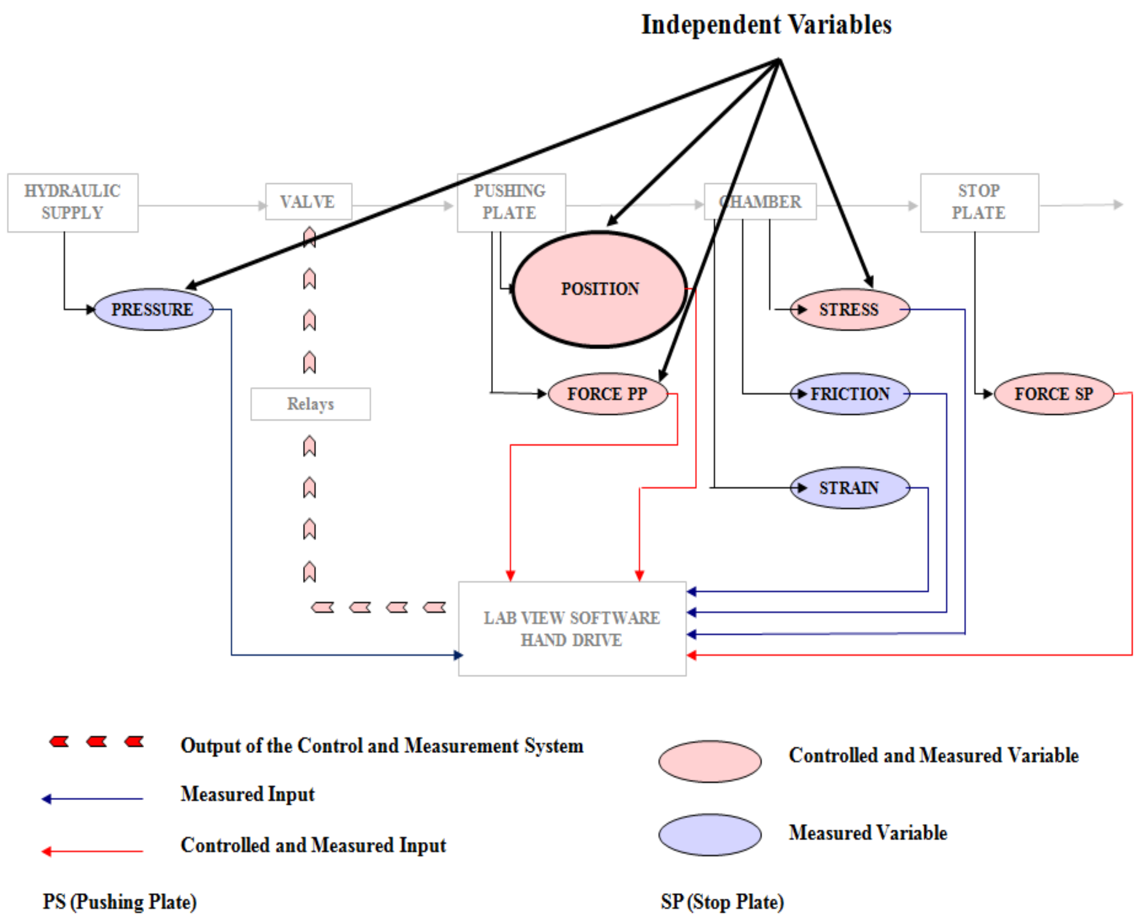


Figure 7.9 *Control based on the control in parallel in which the first variable affects other variables which do not affect each other directly.*

The control system uses control theory (chapter 5) and, particularly, logic control (chapter 5.1) to carry out the main goal that is to protect the compressing unit. The control and measurement system is based on the monitoring and comparison between the current values of different variables and their limits. The outcome of this is the development of a 1 or 0 system. As a result, if the comparison of the variables is true, which means that the limits have been exceeded, the unit working process will stop because the output of the system is 1. On the contrary, if the comparison of the variables is false, which means that the limits have not been exceeded, the unit working process will continue because the output of the system is 0.

In conclusion, the control system stops the activity of the unit when the measured values exceed the limit values because this working condition is considered dangerous for the unit.

7.4.2. Measurement method

The measurement system not only monitors the variables which are not needed to be controlled but also the controlled ones. It facilitates future researches related to the behavior of batches subjected to compression processes because it leads to a better understanding of the behavior of batches made of different materials. In addition, the pressure inside the valve is calculated using the force applied on the pushing plate and the rod area of the cylinder. This variable is controlled by an external system and therefore it is only monitored for a better understanding of the process. Figure 7.6 shows the variables which are only measured and not controlled, such as the forces caused by friction and the strain in the guiding walls. It also illustrates that the indirect variables, if they are taken into account, are only measured and as a consequence, they are not controlled.

7.4.3. Indirect control method

The environment that surrounds the activity of the unit can be affected by variables which, at a first glance, are not related to any sub–process. These variables have been mentioned above such as indirect variables (chapter 7.3.3). Despite the fact that the indirect variables are neither controlled nor measured in the case study unit, the research work emphasizes that they can affect the proper running of the unit. For instance, an increase in the chamber temperature can lead to wrong strain gauges measurements. As a consequence, it would be indispensable the use of temperature compensators to correct these errors. In addition to the temperature, another variable can be considered as an indirect one, the mass of the logs. The knowledge of whether there are logs inside the chamber or not, avoids the unit to work when there are not and, as a consequence, prevents sudden movements of the pushing plate when the flow rate is high. Figure 7.10 shows that these variables take place inside the chamber.

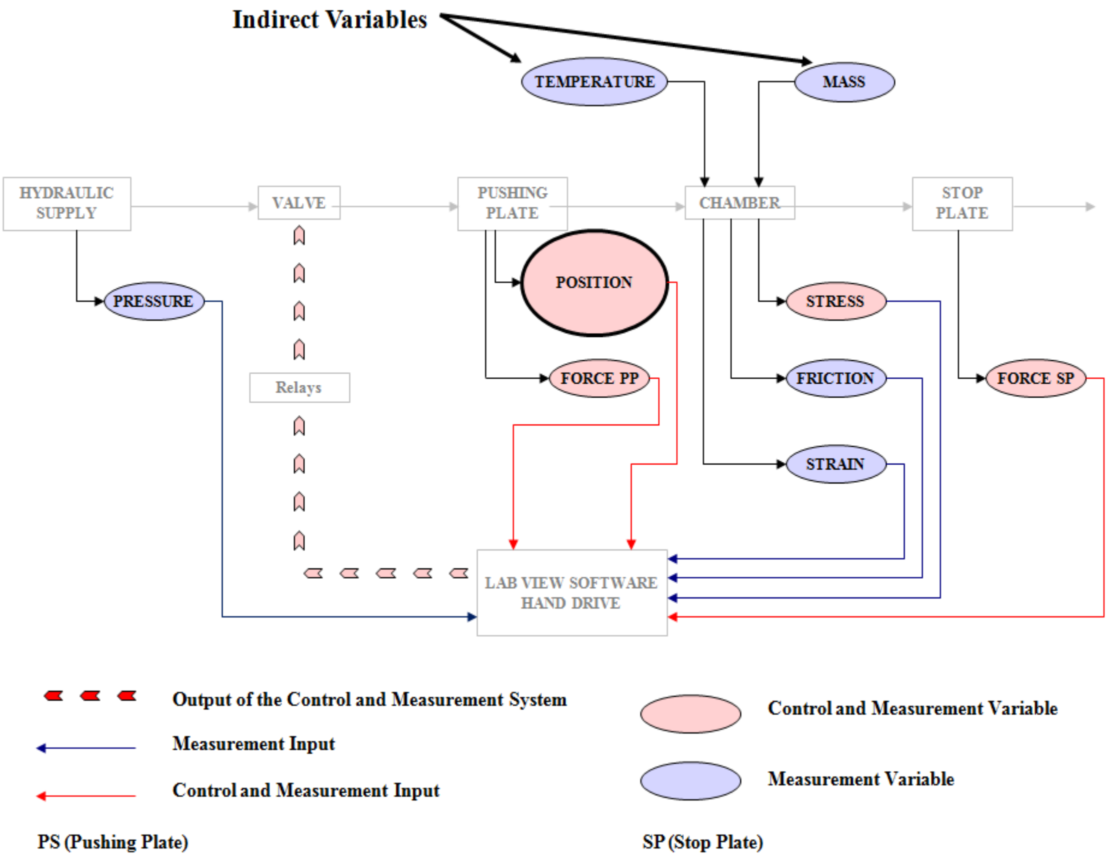


Figure 7.10 *Indirect control for the log batch compressing unit.*

Subsequently the addition of indirect variables to the control and measurement system can improve it and avoid possible measurement errors and dangerous situations. In addition to the variables set out, others appear in order to develop the control and measurement system. For instance, the pushing plate velocity or acceleration can be controlled in order to avoid sudden movements of the cylinder when the flow rate is high. Similarly, the humidity of the logs can also affect the unit working process and can be dangerous for it. In conclusion, these variables should be measured and controlled in future research works, especially when the compressing unit uses a servo valve.

7.5. Description of the control and measurement system

The compression process entails the action of different variables which have to be controlled and measured. According to the concepts explained (chapter 3), the structure of a control and measurement system is based on the dataflow of the variables values. This information travels first of all through the measurement system, secondly through the control system and finally it returns to the process by an action of an actuator (van Varseveld 1997, Liu 2004).

Concerning to the goal of the research case, the unit control and measurement system monitors the most relevant variables according to the level of damage that they can cause to the compressing unit. As a consequence, a control and a measurement system is developed. The measurement system calculates and displays the current values of the variables involved in the compression process. In addition, the control system compares continuously these current values with the established limits in order to protect the unit against any possible damage. As a result, if one of the variables raises its limits, the control system will act on the actuator to change the position of the on/off valve and, consequently, stop the compression. According to the main goal of this research work, the behavior of the unit can be controlled by using either LabView software or hand drive interface. Therefore, they can modify the direction of motion of the pushing plate and carry out the control and protection of the unit.

7.5.1. System description

The system is composed of a hydraulic system, which provides the cylinder with flow; a control and measurement system, which main goal is to protect the unit, and the unit itself. The valve can change the flow rate, in this case manually, in order to act on the cylinder behavior.

On the basis of the concepts pointed out in the previous chapters (chapters 3, 4, 5), the schematic diagram of the control and measurement system and its flow of inputs and outputs is shown by Figure 7.11.

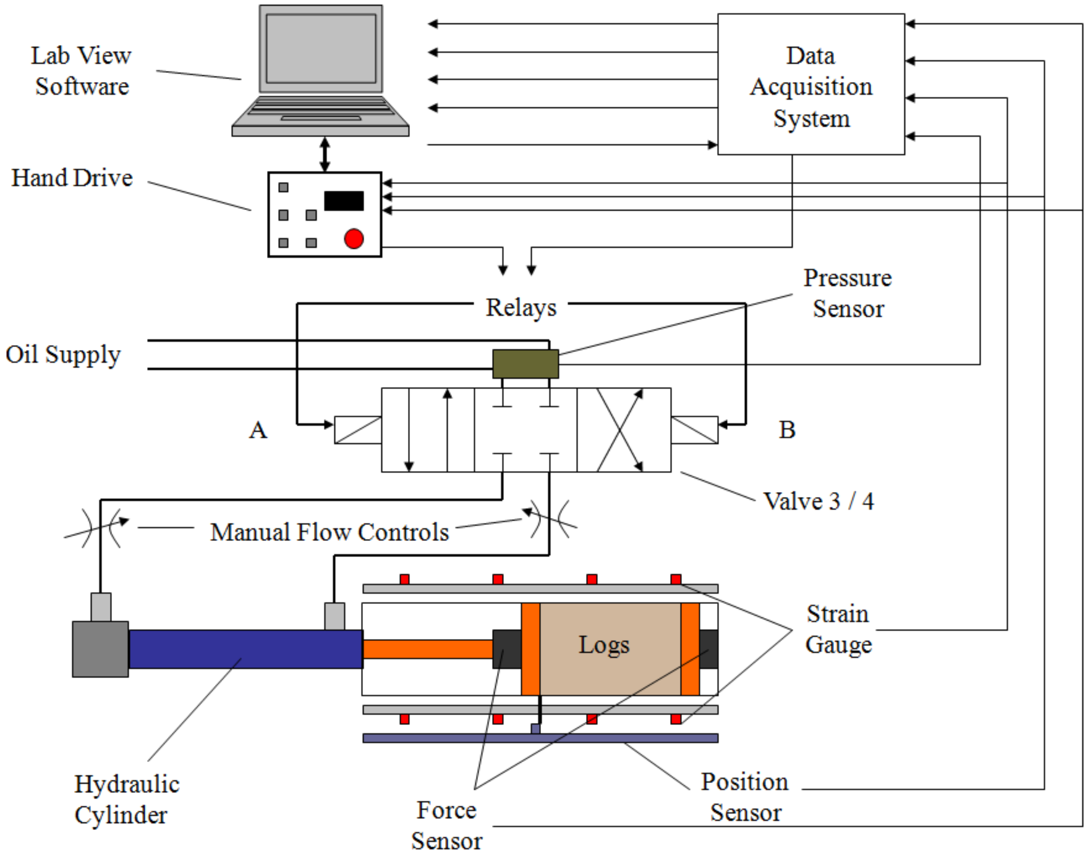


Figure 7.11 *Schematic diagram of the developed control and measurement system.*

As can be seen in Figure 7.11, the oil supply provides the 4/3 solenoid operated valve with flow. The valve has three different positions and depending on them, the hydraulic cylinder behaves in a different way. In order to control the movement of the cylinder either a LabView software or a hand drive has been developed. These two ways to operate the unit can not work at the same time. Therefore, if the LabView software is used to control the movement of the pushing plate, the hand drive has to be disconnected. The outcome of this is that both the LabView software and the hand drive are able to change the direction of motion of the pushing plate.

The operation principle of the system starts when the user presses the button which indicates the direction of motion of the pushing plate. As a consequence, an output travels from either the LabView software or the hand drive. The output acts on the relay according to the mentioned direction. Thus, the solenoid A or B (Figure 7.11) is activated and the valve changes its position to provide the hydraulic cylinder with flow. Consequently, it starts moving forwards or backwards, as applicable.

Concerning to the control and measurement system, either a LabView software or a hand drive receive sensor signals as inputs during the process. Finally, the output of the control and measurement system will change if either the user wants to modify the direction of motion of the pushing plate or one of the controlled variables raises the limit values. In both cases the output will act on the other relay or will stop the previous action in order to drive the valve to its opposite or neutral position.

In this research work both the hand drive and the LabView software are able to change the direction of motion of the pushing plate. In addition, they can monitor and control the variables involved in the process. The outcome of this is that both systems can be considered as control and measurement devices. Therefore, it can be said that there are two independent ways to operate and protect the unit during the compression process.

7.5.2. Hardware design

The case study is composed of the compressing unit and both the hydraulic and control and measurement system. The hydraulic system is formed of a supply system, a valve, and a cylinder. It converts hydraulic energy into kinetic energy and it is controlled independently inside the laboratory. Furthermore, it uses oil supply and it can reach 300 bars. The on/off valve connects the hydraulic supply system mentioned above and the cylinder. Basically this is the first stage in the compressing unit operation. The valve is a 4/3 solenoid operated valve and its flow rate is modified manually. It has been chosen according to the nature of the compression process and the research work. Considering the main goal of the research work an on/off valve is the best choice due to its cost represents a 20:1 reduction with comparison to a servo valve. According to the requirements, the valve should have a quick response time when one of its solenoids is activated and it should withstand the hydraulic system pressure during the logs compression. In addition, it should avoid the overlapping during operation (Noack 2004). On the basis of the valve features explained above, the chosen valve is the Rexroth 4/3 directional valve with reference number R900561278. Its appearance is shown by Figure 7.12.

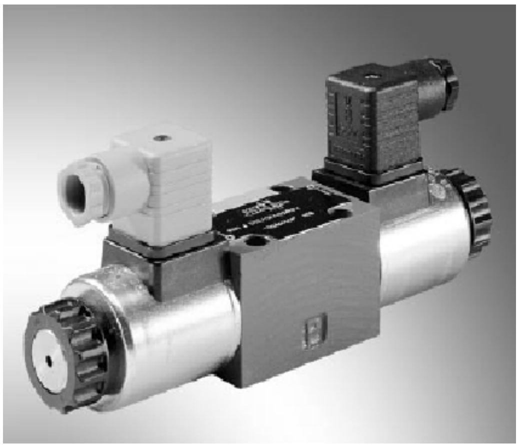


Figure 7.12 *4/3 Rexroth solenoid operated directional valve with manual flow control.*

The most important features of the chosen valve are a maximum operating pressure of 350 bars, a maximum flow of 80 l/min (using DC voltage) or 60 l/min (using AC voltage 50/60 Hz), a switch on time between 25 and 45 ms (using DC voltage) or between 10 and 20 ms (using AC voltage 50/60 Hz), and a switch off time between 10 and 25 ms (using DC voltage) or between 15 and 40 ms (using AC voltage 50/60 Hz), (ISO 6403 according to Bosch–Rexroth 23178 / 08.08).

The next step in the hydraulic system is the hydraulic cylinder which should withstand the pressure provided by the hydraulic system through the valve, should provide the force required to compress the logs and it also should be long enough to carry out the compression successfully (Nyein 2008). On the basis of the requirements explained above and the advantages pointed out in chapter 2, the chosen cylinder is the Rexroth double acting cylinder with reference number R407999226. Its appearance is shown by Figure 7.13.

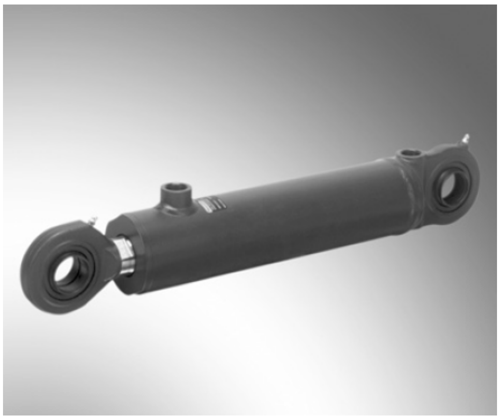


Figure 7.13 *Rexroth double acting cylinder.*

The most relevant features of the chosen cylinder, related to the compression process, are a maximum operating pressure of 160 bars, a maximum force of 50000 N (operating at 160 bars with a rod diameter of 63 mm), and a stroke length of 60 cm (Bosch–Rexroth 17325 / 07.09). The hydraulic cylinder is, basically, the link between the hydraulic system and the unit (see chapter 7.2). Furthermore, its piston rod carries out the compression process which is continuously monitored by the control and measurement system.

Based on the concepts explained in chapters 3, 4 and 7.5, the control and measurement system consists of different sensors connected to both a computer and a hand drive. According to chapter 4, the output of some sensors, such as force sensors or strain sensors need the action of an amplifier. Furthermore, a data acquisition system is also required to make the signals from either sensors or amplifiers suitable for the LabView software.

Based on the studies of the variables involved in the compression process (chapter 7.3) and the analysis of the control method (chapter 7.4), the sensors which are used are a position sensor, a pressure sensor, two force sensors, and twelve strain gauges. First of all, the magnetostrictive (MS) linear position sensor with 60 cm length (Temposonics E–Series with reference number 1008 1403) monitors the pushing plate position. It is assembled on both one side of the unit by using screws and the pushing plate outline by using a soldered joint. The position sensor assembly on the unit is shown by Figure 7.14.

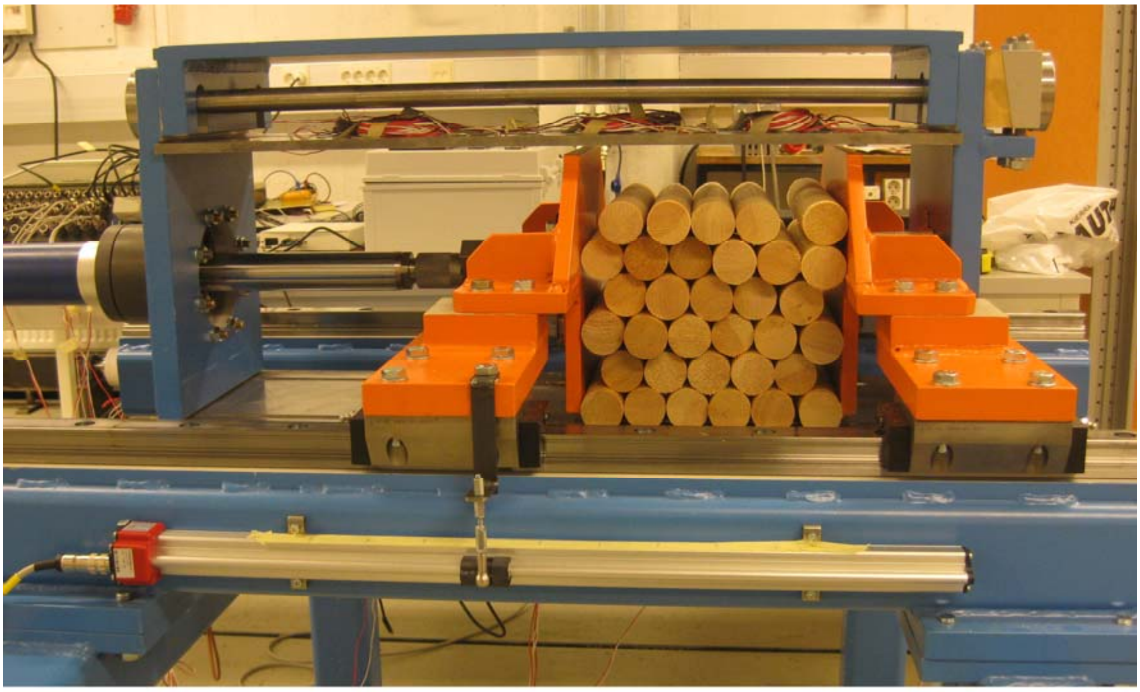


Figure 7.14 *Temposonics E–Series position sensor assembly on the unit.*

Secondly, the force sensors (SCAIME ZF with reference number 050967 and Hottinger Baldvin Messertechnic) measure the force in both pushing and stop plate. Whereas the maximum force value that the pushing plate force sensor is able to withstand is 50000 N and the stop plate force sensor maximum measured value is 20000N. Assuming that the pushing plate force sensor is subjected to the highest force during the compression, it can be said that its maximum measurable value during the compression process is greater than the one related to the stop plate. The location of both pushing and stop plate force sensors is shown by Figure 7.15.

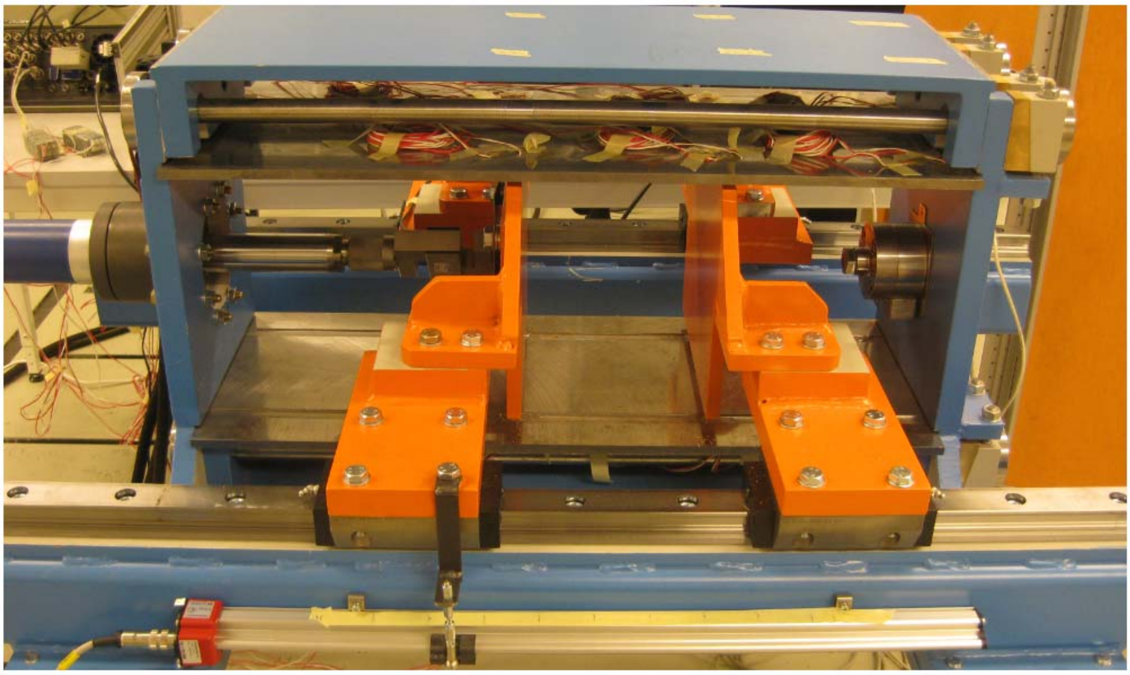


Figure 7.15 *Pushing and stop plate force sensors assembly on the unit.*

As can be seen in Figure 7.15, the pushing plate force sensor is located between the cylinder and the pushing plate itself. It is assembled on the pushing plate central position aligned to the cylinder axel. Considering the stop plate force sensor, it is assembled on the stop plate central position and it is also aligned to the cylinder axel.

Finally, the strain gauges monitor the guiding walls behavior. The unit crushes the logs and compresses them inside the chamber. This causes the guiding walls deformation and consequently, the increase in their stress. The strain gauges (KYOWA with reference number KFG–2–120–D16–11L3M2S) measure it by using the Wheatstone bridge configuration (chapter 4.2.2). As can be seen in the Figure 7.16, two strain gauges are located longitudinally and transversally oriented on each test point on the guiding walls. Not only is the longitudinal strain taken into account but also the transversal one. It is due to the fact that the longitudinal stress is affected by both of them.

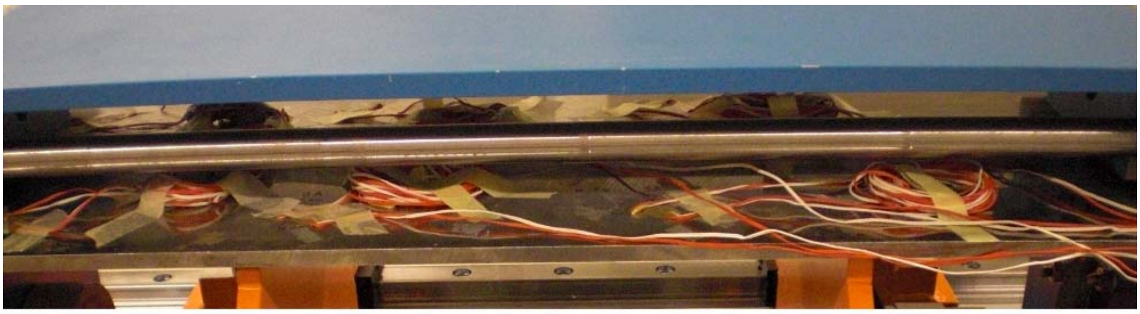


Figure 7.16 *Longitudinally strain gages on the guiding walls.*

In addition, each Wheatstone bridge consists of four strain gauges. The other three which are connected to the ones located on the guiding walls are not located on the guiding walls. Figure 7.17 shows that the assembly and joints of these three strain gauges are protected by a cover.

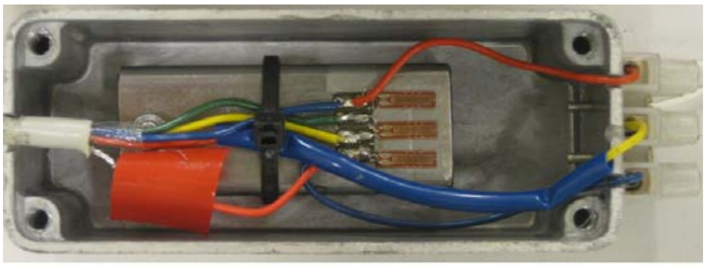


Figure 7.17 *Cover which protects strain gauges assemblies and joints.*

The strain measure is carried out in different positions in the guiding walls because each strain gauge is only able to measure the deformation of a particular point in a particular direction. According to Launis (2005) a reasonable optimal distance between measure points is 0.025 m. Finally, the selected distance to start the measurements is 0.20 m. From these first tests the optimum strain gauges will be placed on the guiding walls based on reference studies mentioned above. Their location on the guiding walls is shown by Figure 7.18.

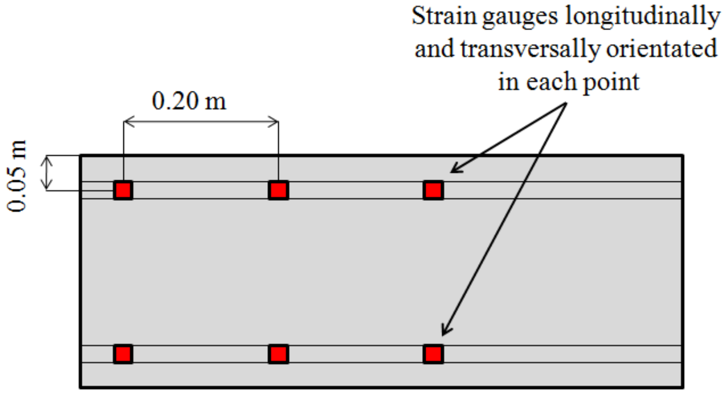


Figure 7.18 *Strain gauges location on the guiding walls*

In conclusion, Figure 7.19 shows the final configuration of the necessary sensors.

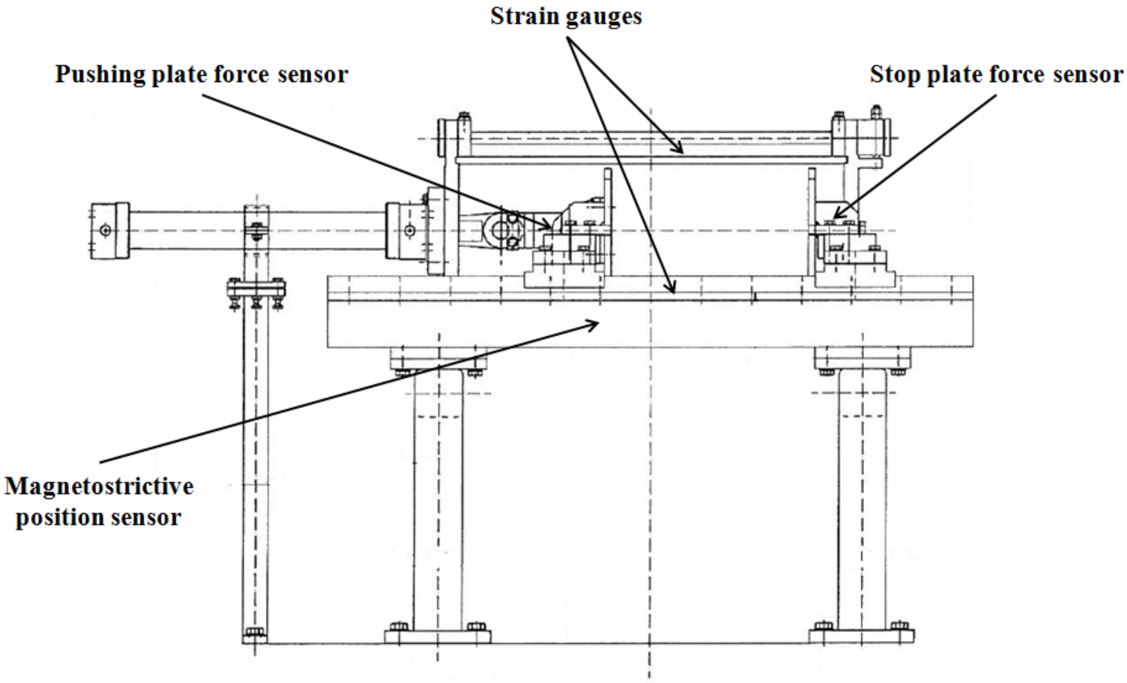


Figure 7.19 *Sensor positions installed in the machine.*

On the basis of the theoretical concepts explained in chapter 4, the control and measurement system uses amplifiers in order to make both force and strain sensor signals suitable for the LabView software. Concerning to the hand drive, this amplifier is not needed, in case of force measurements, because the hand drive itself has its own amplifiers installed (chapter 8.1). Furthermore, a MMC–16 A amplifier with thirteen channels is only required to operate using LabView software. In the same way as the MMC-16 A amplifier, the data acquisition system, NI-USB–6221, is needed. Finally, the last stage of the control and measurement system is carried out by either a computer, with the required LabView software interface installed, or a hand drive. For the purpose of a better understanding of this last stage, the following chapters analyze their operation principle and both their most important components and features.

8. IMPLEMENTATION OF THE CONTROL AND MEASUREMENT SYSTEM

The implementation of the control and measurement system leads to the development to a hand drive and a computer interface. The following chapters analyze their most important features and explain the code needed to program of the computer interface. An approximation and a verification of the control and measurement system is also carried out in order to check the proper running of the system.

8.1. Hand drive design

The hand drive interface is a device used to drive the unit, control and measure the variables which have an effect in the compression process. It consists of buttons which are to operate the unit and displays to show the behavior the variables mentioned above. The first step in the implementation process is to design a hand drive interface. This first design is shown in Figure 8.1. As can be seen the operating buttons are located on the left side and the displays in the right side.

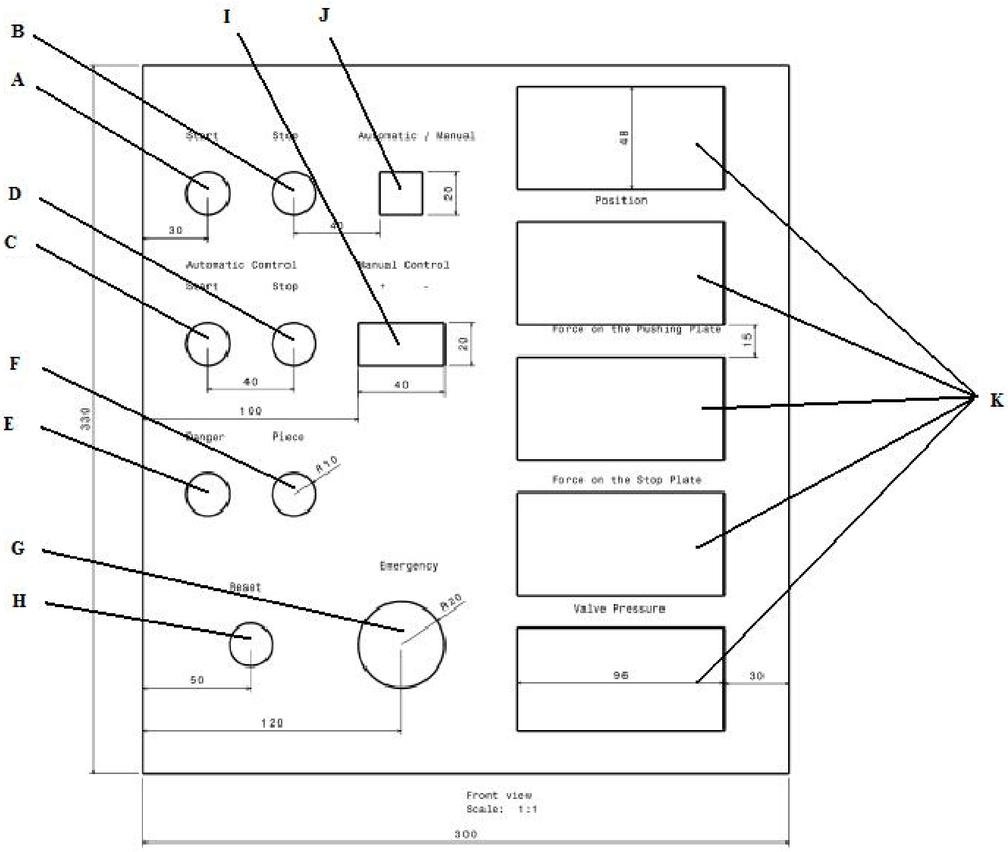


Figure 8.1 *First hand drive design*

The hand drive is divided in different parts depending on the type of activity. The first part is the related to the general control. The buttons related to this part are a start button (A) which is in charge of switching on the compressing unit, and a stop button (B) which is in charge of switching off the unit. Both of them have a signal light installed inside them. It shows if they are working. In addition, the start button is related to a green light and the stop button to a red light. Moreover, an automatic/manual button (J) is also included in this part and it activates the manual or automatic mode of work. The second part is related to the manual control. It consists of a press button (I) which drives the pushing plate forwards or backwards. The third part is related to the automatic control. It consists of a start button (C) which activates an automatic program to drive the unit. For instance, the unit can work only until a second reference position. In addition, a stop button (D) is also included in the automatic control and it stops the running of the automatic program. The fourth part is related to the safety control. This part consist of a emergency button (G) which stops the running of the unit if an emergency occurs, a danger light (E) which lights when the values of the variables and their limits are nearly, and the piece light (F) which lights when there are logs inside the chamber. Displays (K) are located in the right side of the hand drive and they show the behavior of the most important variables needed to implement the control and measurement system.

The final hand drive design differs from the first one in the operations that it can carry out. The difficulty to implement features such as the automatic program mentioned above and the simplification of buttons leads to the final hand drive design. Its interface is shown by Figure 8.2.

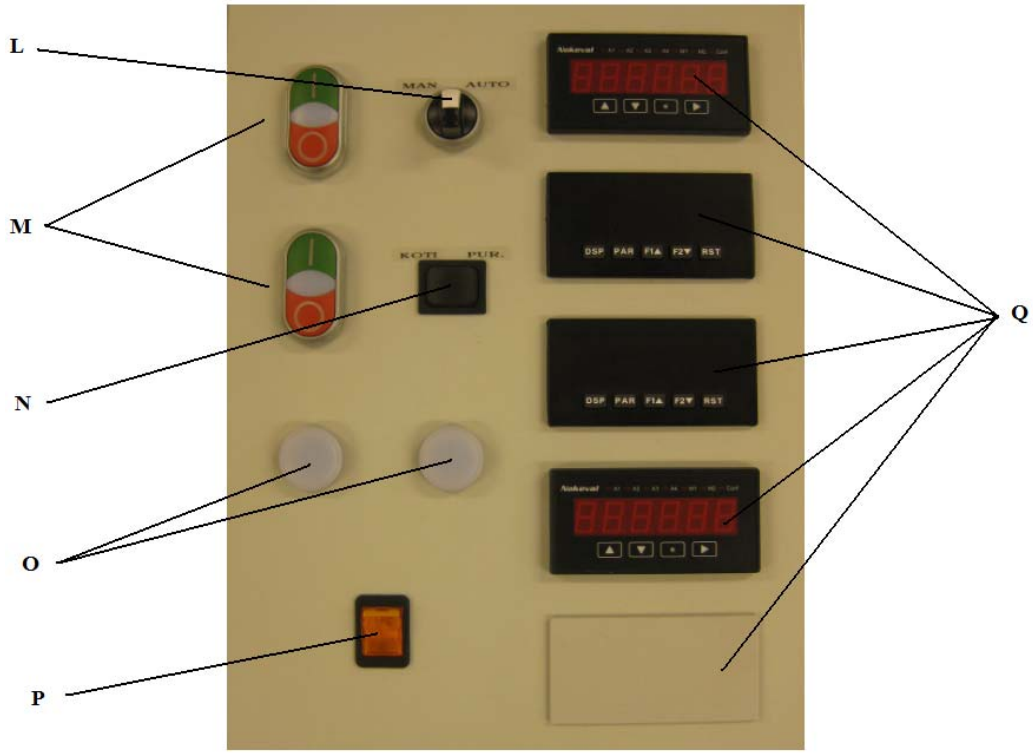


Figure 8.2 *Final hand drive design.*

The location of the buttons and displays are the same as in the first hand drive design. The emergency button is simplified and instead of this an on/off button (P) switched on/off the hand drive, if needed. An automatic/manual (L) button is used to activate the working mode. Its operation principle changes the way to operate the relays. It is done either by hand drive or by computer. If the manual working mode is selected the compressing unit is driven by a forward/backward button (N). This design avoids the use buttons explained in the first design. It leads to a hand drive design simplification and it reduces the security during its use. The lights (O) can be configured in order to be switched on if an emergency occurs or if the manual mode is activated. In addition, on/off buttons (M) are installed but they are not configured. They can be used to improve the security operation of the hand drive. For instance, the manual mode does not work until one of these buttons is pressed. Finally, the displays monitor the variables which have an effect during the compression process. They consists of two Scaime PAX S which displays the forces applied on the pushing and stop plate, and two Nokeval 2010 which displays the position and the strain measurements.

8.2. LabView software design

LabView software has been designed in order to develop a control and measurement system for the compressing unit. A combination of logic control theory and LabView software has been used to achieve the unit protection. In conclusion, this LabView software carries out the control and measurement of the variables involved in the process and drives the pushing plate. As a matter of fact, the LabView software has been divided into two levels also called high and low level. As a consequence there are two different LabView files. Their operation principle and the interaction between each other are shown by Figure 8.3.

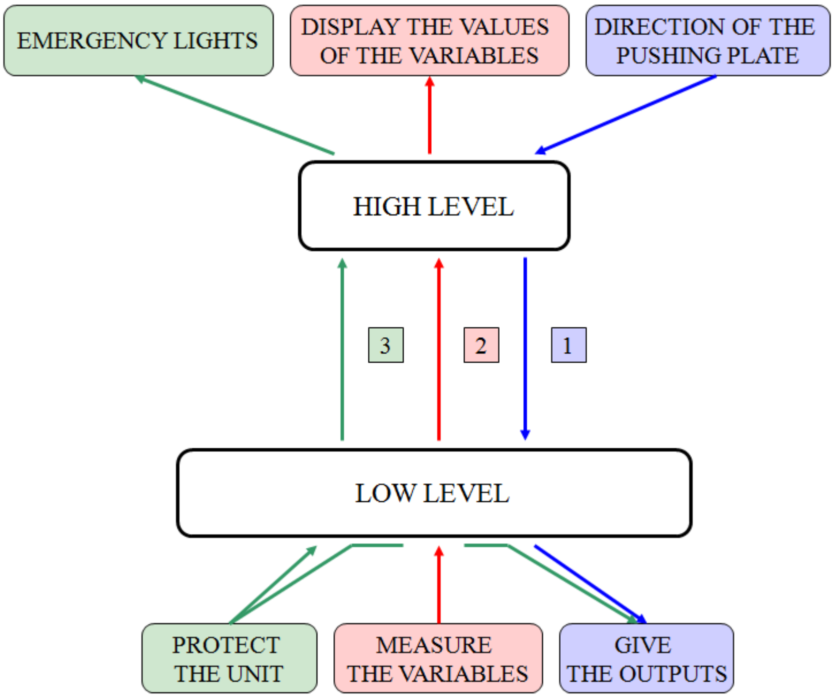


Figure 8.3 *High and low level operation principal in the LabView software.*

The supervisor interacts with the high level because its front panel contains the variable displays, the emergency lights and the controllers to operate the compressing unit. Furthermore, the low level monitors the variables and gives the proper output to the valve according to both the user's needs and the unit protection.

Figure 8.3 shows the three main interactions between both levels. First of all, the supervisor starts the compression process (blue line) by pressing the virtual controllers located in the high level front panel. This high level communicates with the low level. As a result, this low level gives the proper output to the valve in order to push the cylinder forward. From this point, the compression begins and the low level starts monitoring the variables involved in the process (red line). The measurement of these variables flows from the low level to the high level to be suitable for the user's analysis. Finally, in case the variables exceed their established limits (green line), the low level gives the proper output to the valve in order to avoid the particular dangerous situation.

In addition to this, it also communicates with the high level to switch on the emergency lights and consequently, let the supervisor know about this dangerous situation.

8.2.1. Front panel

LabView software is a computer interface which allows the supervisor to interact with the compressing unit. One controller operates the front panel of the software in which the controls are located. Although the user may not know how to program in LabView, it has to be easy to work with the application. For this purpose, the LabView interface must be easy to use. Figure 8.4 shows the appearance of the LabView front panel using by the operator in order to interact with the compressing unit.

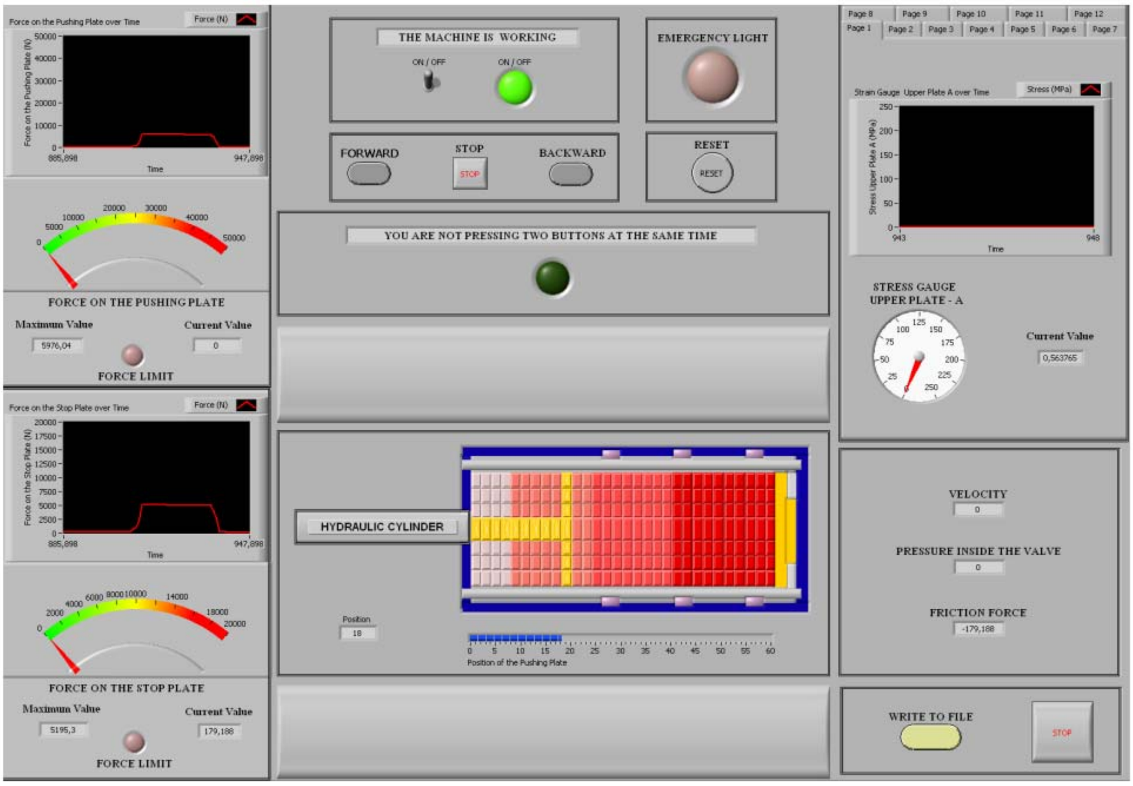


Figure 8.4 *LabView front panel which operates the compressing unit.*

As can be seen in Figure 8.4, the front panel is principally composed of the operating controls, the displays of the variables involved in the compression process and the emergency lights.

The operating controls are used to drive the cylinder and consequently, the pushing plate. It consists of an on/off controller and a directional control panel. It is shown by Figure 8.5.

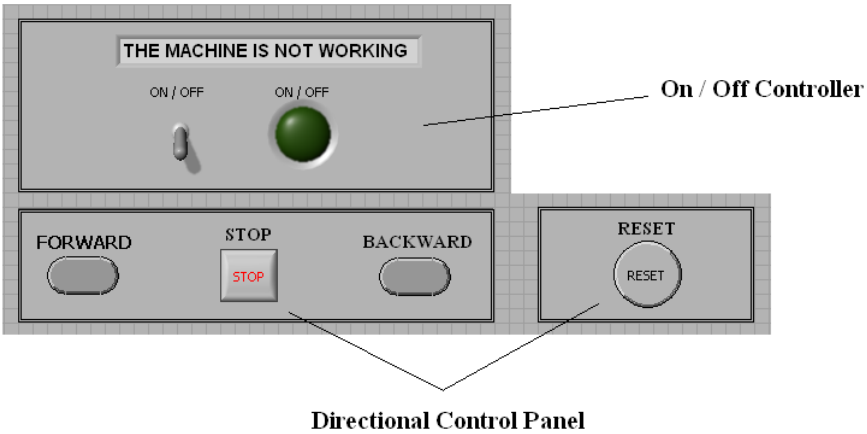


Figure 8.5 *Operating controls used to drive the compressing unit.*

The on/off controller switches on/off the compressing unit. It has a light and a label indicator which shows whether the unit is working or not. The directional control panel is composed of a forward, backward, stop, and reset button. The forward button is pressed to start the compression or, in other words, to act on the relay which changes the valve position in order to move the cylinder forward. As it is done with the forward button, the backward one is pressed to push the cylinder back, if necessary. The stop button changes the valve position to the neutral one. Furthermore, the reset button acts on a particular relay in order to push the cylinder back to its initial position. Additionally the buttons related to the directional control panel light on in case they are pressed. It facilitates the use of the front panel because the supervisor knows which buttons are pressed at each particular moment of time.

The displays of the variables involved in the process are carried out graphically and numerically. Figure 8.6 shows an example of this displays used in the LabView front panel.

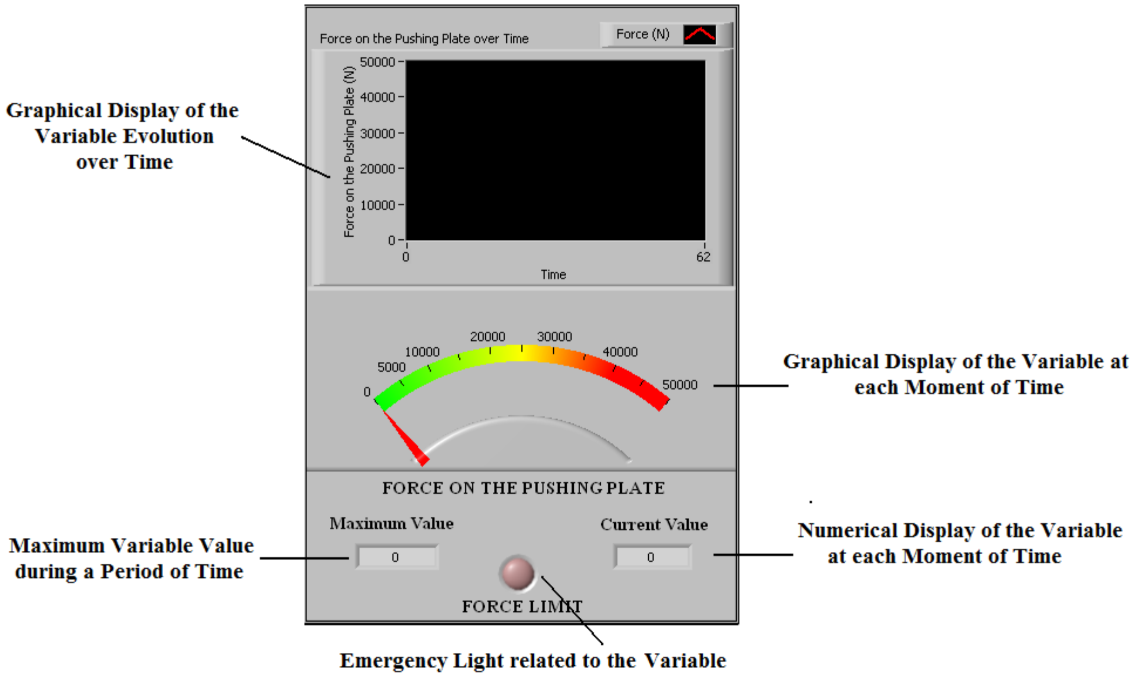


Figure 8.6 *Display used to monitor the variables involved in the compression process.*

As can be seen in Figure 8.6, the display monitors the evolution of the mentioned variable and its value at a particular moment of time. This display also has an emergency light which is switched on when the variable values exceed its imposed limits. Furthermore, it displays the maximum variable value during the compression process.

The emergency lights are located in different places in the front panel. As can be seen in figure 8.6, each display has its own emergency light in order to find easily which variable has exceeded its established limits. In addition to this, a general emergency light is switched on in case it occurs. It is located on the top of the front panel. The front panel also uses both label and light indicator in order to alert the supervisor to the fact that two directional buttons are pressed at the same time.

Finally, the front panel monitors the pushing plate position and displays it in a way that facilitates the understanding of the unit behavior. This case is illustrated in Figure 8.7.

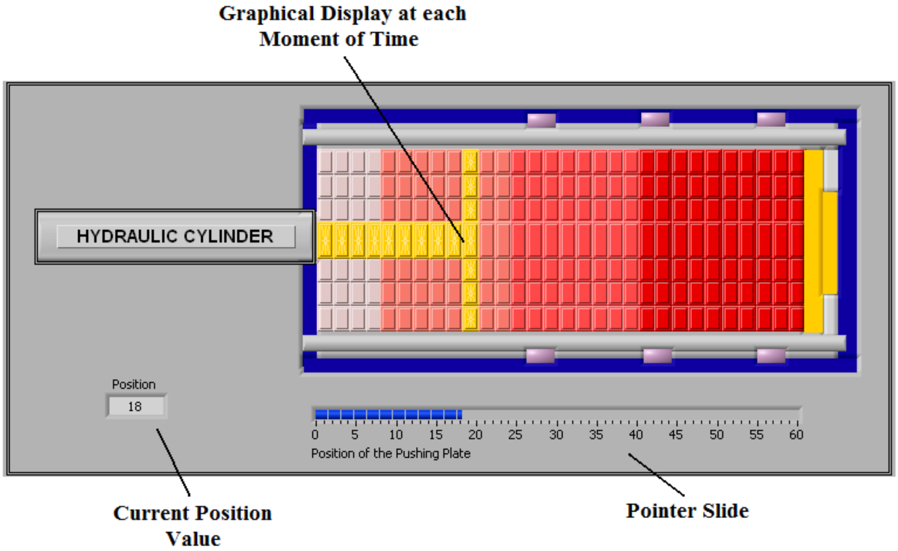


Figure 8.7 *Display of the pushing plate position in the front panel.*

The display consists of lights which are switched on or off depending on the current pushing plate position. In addition to this, a pointer slide and a numerical indicator show this current position value.

8.2.2. Block diagram

The block diagram of the LabView software designed for the compressing unit works based on the operation principle of Figure 8.3. It contains the necessary code to implement the actions associated with the virtual controls. First of all, the supervisor acts on the virtual controls and switches on/off the unit. Figure 8.8 shows the code associated with the on/off button.

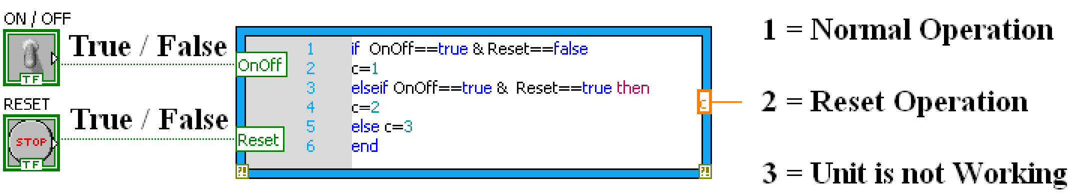


Figure 8.8 *On/off block diagram code.*

In case it is switched on, two different cases can occur, the unit normal operation or the reset operation. The first case associated code is illustrated in Figure 8.9.

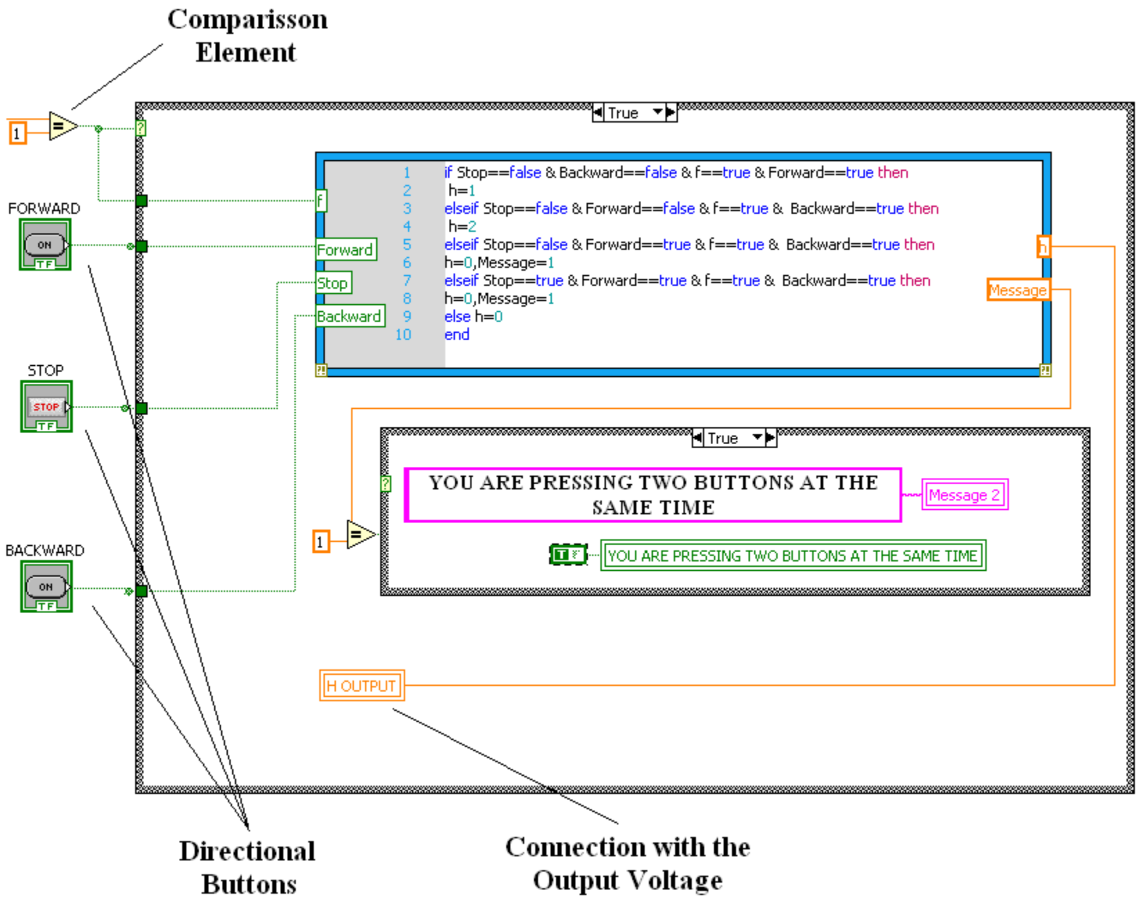


Figure 8.9 *Normal operation block diagram code.*

As can be seen in Figure 8.9, a comparison element makes the case structure true/false. In case of a unit normal operation, this case structure implements the true possibility. In addition to this, the action related to press the virtual buttons on the front panel causes true/false signals from the directional buttons to the case structure above mentioned. Finally, a local variable, which is connected to the output voltages, changes its value depending on the current working process. Figure 8.10 shows the behavior of the output voltage according to the local variable value. As a matter of fact, the final output values are connected to the low level which is in charge of the relays activation.

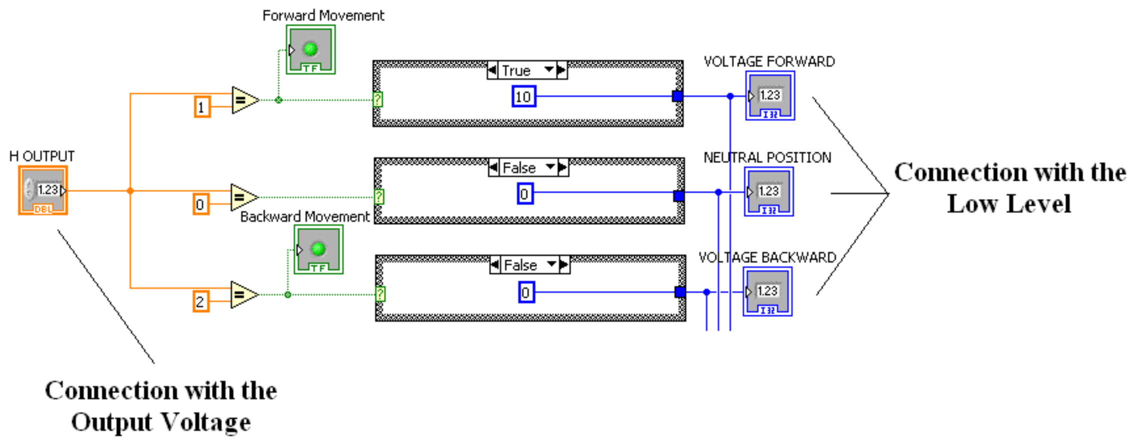


Figure 8.10 *Normal operation output block diagram code.*

As an example of this configuration, the supervisor can press the on/off button and consequently, the unit starts working. Afterwards, they can press the forward button which makes true the case structure and gives an output voltage value to the low level. The reset operation is illustrated in Figure 8.11.

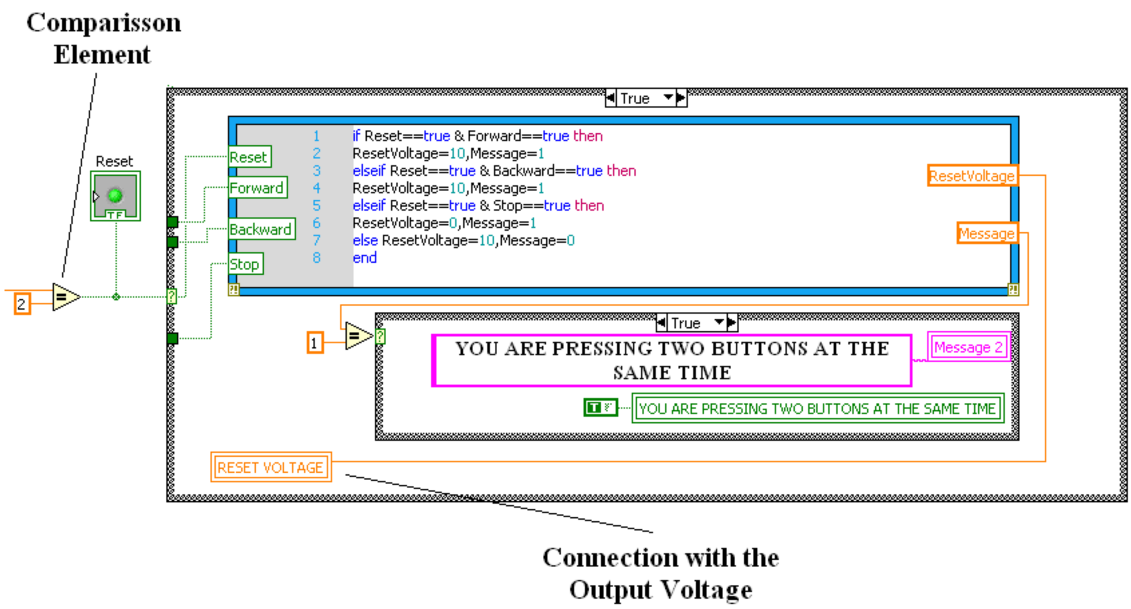


Figure 8.11 *Reset operation output block diagram code.*

Despite the reset operation is based on the same working principle as the normal operation, the reset output is independent with respect to the normal operation ones. In addition to this, this reset output is also connected with the low level.

The operations explained above are related to the high level because they are based on the interaction between the supervisor and the software. From this point, the low level carries out the measurements and the variables control. Furthermore, it gives output signals from the program to the relays.

The data acquisition system receives the measurements from the sensors and provides the LabView software with them. It has a virtual tool called DAQ assistant which is configured in order to obtain the suitable signals for the LabView program. As can be seen in Figure 8.12, the DAQ assistant's rate value must be at least three times higher than the number of samples in order to avoid Aliasing in the signals. In addition to this, these values should have high enough ratio value to achieve proper measurements. The final chosen values are a number of samples of 100 and a sample rate of 10000.

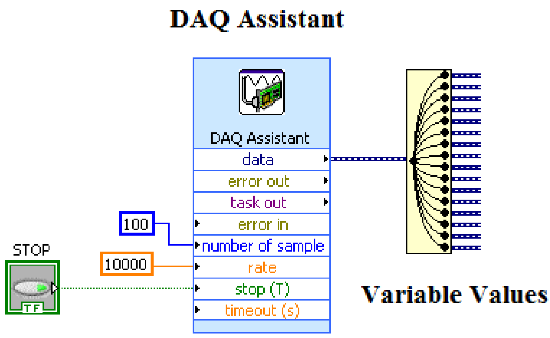


Figure 8.12 *DAQ assistant used in LabView program in the block diagram.*

Figure 8.12 also shows that the DAQ assistant's data contains the dynamic measured values of the variables involved in the process. The data virtual wire is divided into sixteen virtual wires according to the number of measured variables. Furthermore, each of them is connected to the part of the program related to its measurements. As can be seen in Figure 8.13, the dynamic signal, which contains the measured variable values, is converted from voltage into the appropriate unit of measurement. As an example of this, Figure 8.13 shows the ratio used to convert voltage into centimeters in case the measured variable is the pushing plate position. Afterwards, the connection losses are removed from the mentioned signal in order to avoid errors.

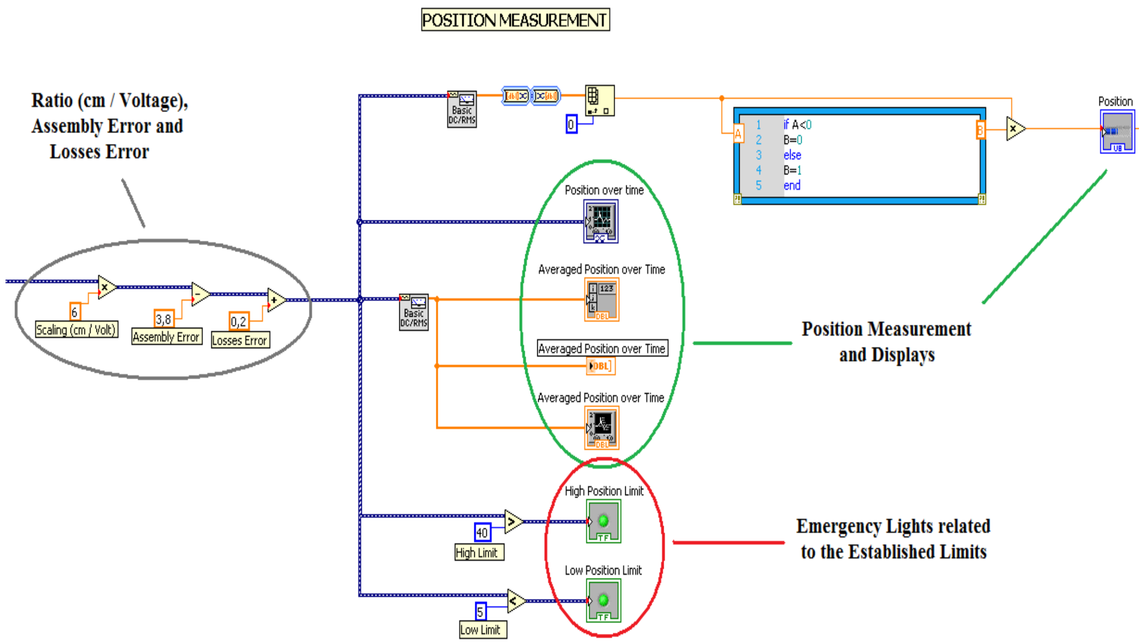


Figure 8.13 *Position measurement system block diagram code.*

The measurement system block diagram code consists of the icons which are the virtual displays, indicators and emergency lights in the front panel. Figure 8.13 shows an example of the icons configuration. In this case, the emergency light icons in the block diagram receive a true value when the positions limits are exceed. As a consequence of this, the front panel light connected to this icon is switched on. This measurement system is located in the low level. As a consequence, the virtual displays, indicators and emergency lights above mentioned have to be also connected to the high level in order to interact with the supervisor. This connection is explained by Figure 8.14.

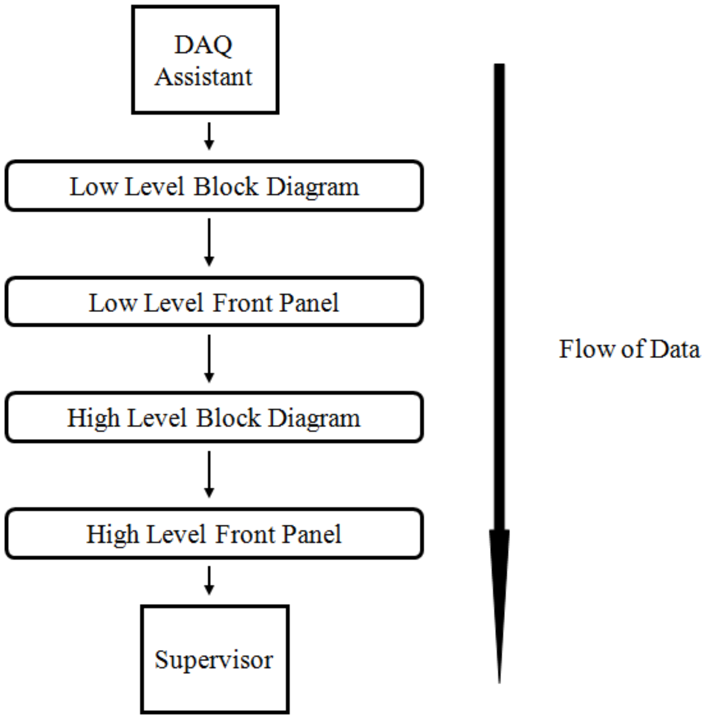


Figure 8.14 *Connection between the high and low level in the LabView program.*

The operation principle of this connection is based on the flow of data from the low level block diagram to the high level front panel. It means that the DAQ assistant obtains the dynamic signal in the low level bloc diagram. It is both graphically and numerically displayed in the low level front panel. Afterwards, it travels to the high level block diagram and it is finally displayed in the high level front panel in which the supervisor can interact with the unit. In the same way as the position measurement code the rest of the variables are monitored. In addition, their values can be recorded in a file in order to study the compressing unit operation.

The control system is located in the block diagram low level and it is connected to the emergency lights of the front panel high level in the way illustrated in Figure 8.14. First of all, the supervisor presses a directional button and immediately, a signal travels from the high level front panel, in which the virtual buttons are located, to the block diagram low level. The code shown in Figure 8.15 evaluates this signal and gives the output according to the desired pushing plate movement.

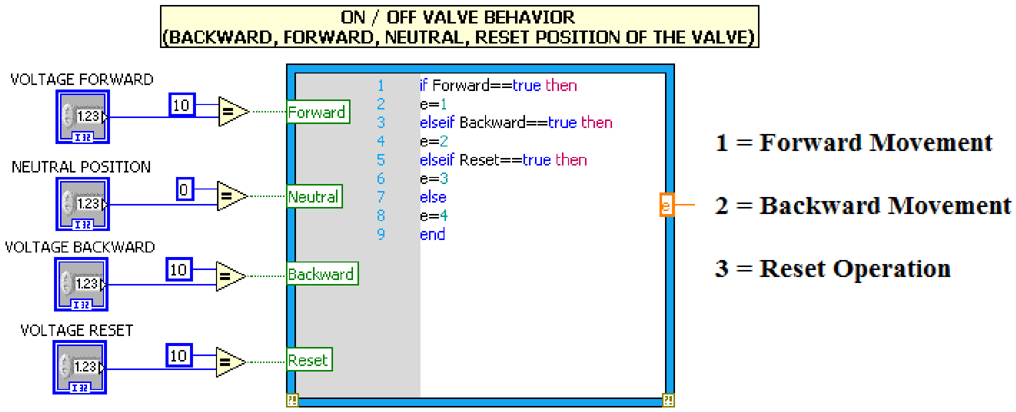


Figure 8.15 *Block diagram code related to the pushing plate movement.*

Afterwards the output code illustrated in Figure 8.15 travels through the control system code in order to evaluate the variables' values and avoid dangerous situations for the unit. These variables' values are continuously compared with the established limits in the control system (chapter 8.3).

The position control system code is shown in Figure 8.16. It checks the current pushing plate position and compares it with its limits. As a result, the working area is delimited. Furthermore, the pushing plate can be driven forward and backward freely inside this area.

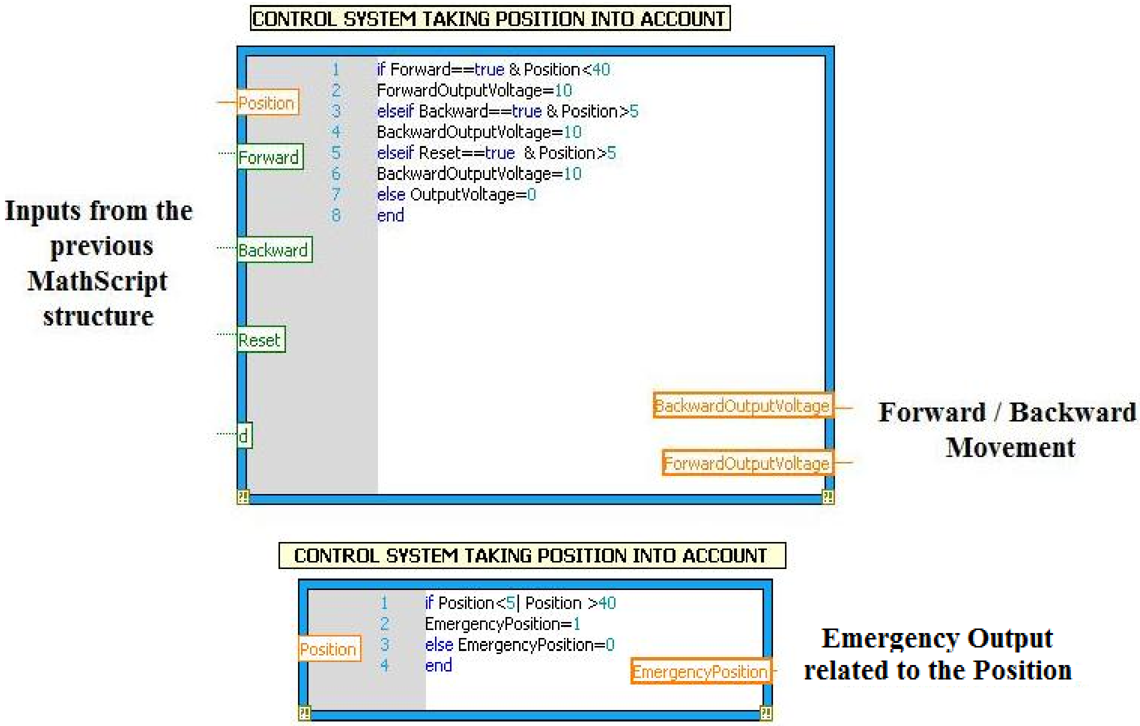


Figure 8.16 *Block diagram code taking the position control system into account.*

At the same time that the position variable, the force applied on the pushing and stop plate, and the stress in the guiding walls are evaluated and compared with their established limits. Figure 8.17 shows the code related to the force applied on the pushing and stop plate.

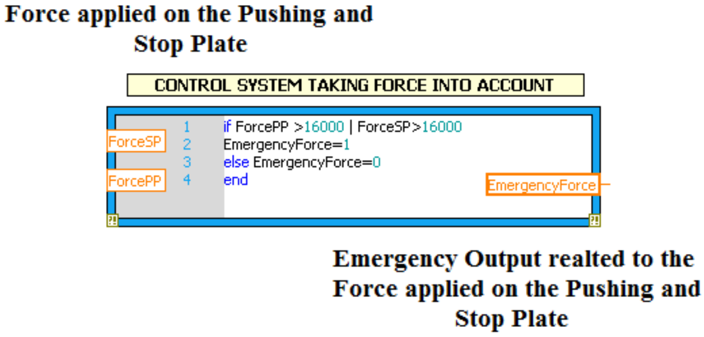


Figure 8.17 *Block diagram code taking the force control system into account.*

The output of this code, termed emergency force signal, is a 1–0 value according to the current situation. Therefore, an emergency situation means a 1 output and a normal one means a 0. In the same way as the force control system, the stress control system operates. Figure 8.18 shows the code related to the control of this variable.

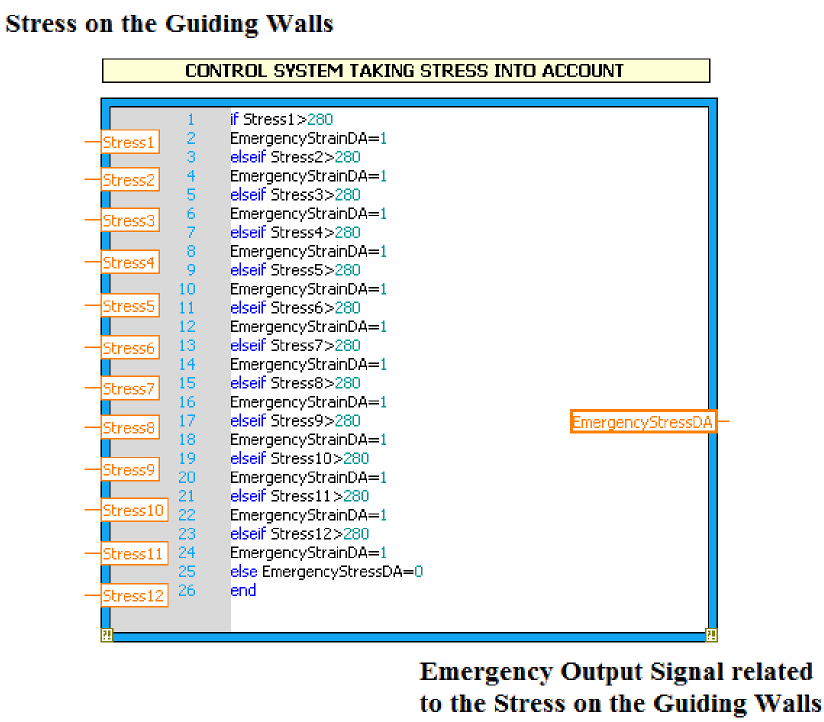


Figure 8.18 *Block diagram code taking the stress control system into account.*

The output of this code is the emergency stress signal and its values are 1–0 in the same way as the emergency force signal.

The following step in the control system is to adapt the action on the relays to the current situation. In order to achieve this goal the code shown in Figure 8.19 has been programmed. This code analyses the emergency signals mentioned above and gives the proper output values to the next step of the control system. In addition to this, it switches on the emergency light in the high level front panel, if needed.

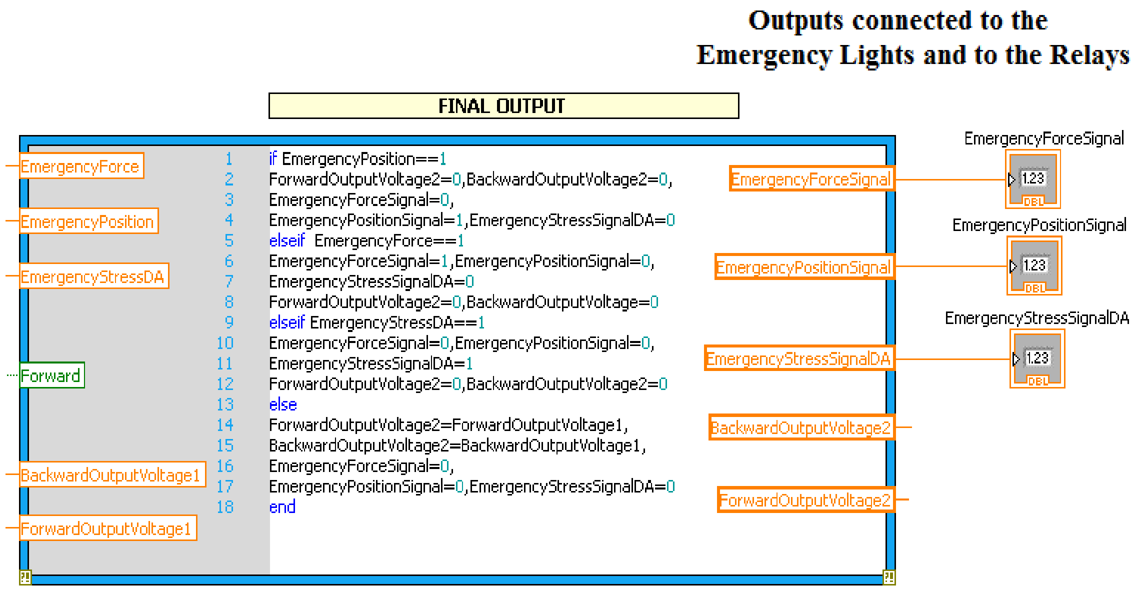


Figure 8.19 *Block diagram code related to the final output voltages taking the control systems into account.*

The last step in the control system takes special situations into account and gives the final output values to the LabView structure in charge of the relays activation.

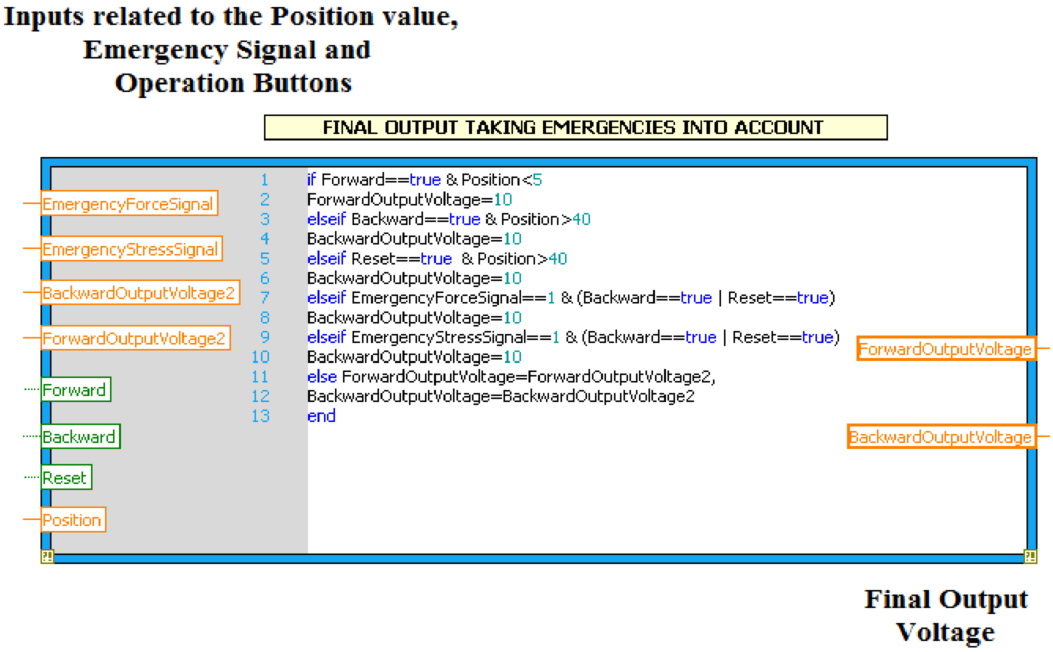


Figure 8.20 *Block diagram code related to the final output voltages taking the special situations into account.*

The special situations mentioned above occur, for instance, when the variable's values exceed the imposed limits. There can be two possible situations. In the first one, the supervisor is only allowed to drive the cylinder backwards in order to avoid possible dangerous situations. It happens when the pushing plate compresses the log batches. In the second one the cylinder is pushed back and the pushing plate position reaches its limit. From this moment the supervisor is only allowed to drive the cylinder forwards.

Finally the control system output travels to the structure shown in Figure 8.21.

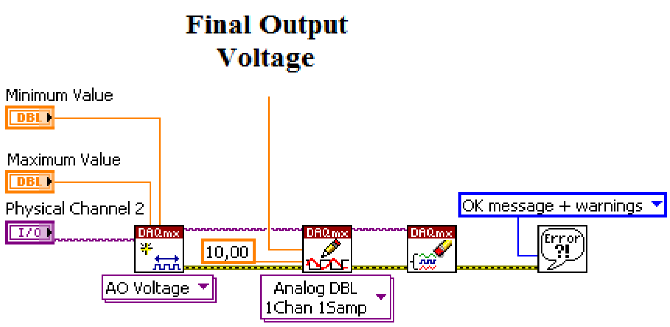


Figure 8.21 *LabView structure in charge to give the suitable output to activate the relays.*

This LabView structure is configured in order to provide the relays via the data acquisition device with the suitable signal in order to activate them.

8.3. Theoretical limits for the variables

The analysis of the compression process points out the variables which have to be controlled in order to protect the unit, the hydraulic components and the measurement devices such as sensors or transducers. Chapter 7.3 analyses the necessary variables to develop the control and measurement system. On the basis of this, the hand drive and the LabView software are programmed. In addition, the theoretical limits for the variables mentioned above have to be established.

The pushing plate position, which is the principal variable, defines the unit working area. Consequently, its limits set the start and the end positions of the hydraulic cylinder. They have to avoid the crash between the pushing and the stop plate when the rod of the cylinder is totally extended and they also have to stop the backward movement when it is completely fitted into the pressure containing envelope. According to the previous explanations the position limits are 5 cm and 40 cm over the total extension which is 60 cm. Therefore the working area is located between these limits and there is no activity of the unit out of them.

The forces applied on the pushing and stop plate have to be controlled in order to protect the sensors in charge of measuring them. The hydraulic supply system maximum pressure is 30 MPa and the cylinder forward and backward operation is only able to withstand 16 MPa. From this point, the pressure inside the cylinder limits the forces during the process. The following calculations shows the maximum force value that this 16 MPa can provide the piston rod and consequently to the pushing plate.

The cylinder maximum operation pressure $P_{Maximum}$ and its diameter $\varphi_{Cylinder}$ are calculated by equations (8.1) and (8.2)

$$P_{Maximum} = 160\frac{Kp}{cm^2} = 16MPa \tag{8.1}$$

$$\varphi_{Cylinder} = 6.3cm = 63mm \tag{8.2}$$

Equation 8.3 calculates the rod area of the cylinder

$$A_{Rod} = \frac{\pi\varphi_{Cylinder}^2}{4} = 3117mm^2 \tag{8.3}$$

Finally the maximum force applied on the pushing plate $F_{Maximum}$ according to this cylinder maximum pressure $P_{Maximum}$ is calculated by equation 8.4

$$F_{Maximum} = P_{Maximum}A_{Rod} = 49870N \approx 50000N \tag{8.4}$$

The limit value for the forces applied on the pushing and stop plate can be established according to the previous calculations and taking into account the maximum forces that these sensors can withstand. In this case, whereas the pushing plate force sensor is able to measure forces below 50000 N, the stop plate force sensor is only able to measure forces below 20000 N. As a result, the limit value is established according to the lower force value. Theoretically, the difference between the forces applied on the pushing and stop plate will not be high enough to impose two different limits for these variables. In conclusion, both limits are related to the maximum force that the stop plate force sensor is able to withstand. The chosen limit value is 20 % lower than this maximum because the forces can increase rapidly and the control system can not act on the valve via the relays instantaneously.

The guiding walls are located in the upper and down part of the unit delimiting the chamber. They are made of S355JR steal and the maximum stress value that they can withstand without permanent deformation is 350 MPa (Airila 1997). In the same way as the force, the stress limit value is 20 % lower than this maximum.

The control and measurement system samples the strain over time. Therefore the longitudinal or transversal stress are calculated from the sampled strain values by equations 8.5 and 8.6

$$\varepsilon_a = \frac{(\sigma_a - \upsilon\sigma_t)}{E} \tag{8.5}$$

$$\varepsilon_t = \frac{(\sigma_t - \upsilon\sigma_a)}{E} \tag{8.6}$$

where ε_a and ε_t are the axial and transverse strain, σ_a and σ_t are the axial and transverse stress, E is the Young Modulus which value is 210 GPa, and υ is the Poisson's ratio which is 0.3.

Finally, Table 2 shows the maximum and minimum values which the sensors or the unit are able to withstand and the limits related to them.

Table 2 *Maximum, minimum and limit variable values.*

VARIABLE	MAXIMUM VALUE	LIMIT VALUE
Position (cm)	50	40
Force applied on the Pushing Plate (N)	50000	16000
Force applied on the Stop Plate (N)	20000	16000
Stress (MPa)	350	280
VARIABLE	**MINIMUM VALUE**	**LIMIT VALUE**
Position (cm)	0	5

In conclusion, the variable limits mentioned above are established in order to protect the unit and the control and measurement system. As a result, changes in one of them entail the variation of these limits.

8.4. Measurement system approximation

The approximation of the measurement system is carried out in order to display the correct variable values. Considering that the relation between the forces and the input voltages that are fed into the hand drive displays are linear, the pushing and stop plate force sensors are configured. These hand drive displays give the output signals related to the measured forces to the data acquisition system. Finally it transmits these signals to the computer.

The first step in the approximation consists of the measurement of two known forces. In this case these forces are 0 N and 4970.73 N. For this purpose, an ENERPAC RSM-50 hydraulic cylinder is used. Its maximum pressure is 5 tons and its area is 5.067 cm^2. It is calculated in equation 8.7

$$A_{CC} = \pi \frac{\varphi_{CC}^2}{4} = \pi \frac{1^2 inch^2}{4} \frac{6.4516 cm^2}{inch^2} = 5.067 cm^2 \tag{8.7}$$

where A_{CC} is the cylinder area and φ_{CC} is its diameter.

The applied pressure is 100 kp/cm^2. The force related to this pressure is 4970.73 N and it is calculated in equation 8.8

$$F_{CC} = 100 \frac{kp}{cm^2} 5.067 cm^2 9.806 \frac{N}{kp} = 4970.73 N \tag{8.8}$$

where F_{CC} is the force that the hydraulic cylinder provides to the pushing and stop plate.

The force sensors are tested ten times without load and applying a force whose value is 4970.73 N. Table 3 and Table 4 show the relation between the forces used for the approximation and both the input voltage which is fed into the hand drive displays from the force sensors and the output voltages that they give to the data acquisition system.

Table 3 *Measurements for the approximation of the pushing plate force sensor.*

Force (N)	Input Voltage (mV)	Output Voltage (V)
0	0,1	0
4970,73	3,9	1
0	0	0
4970,73	4	1,005
0	0,1	0
4970,73	4	1,003
0	0,1	0
4970,73	4	1
0	0,1	0
4970,73	4,1	1,002
0	0,1	0
4970,73	4	1
0	0,1	0
4970,73	4,1	1,001
0	0	0
4970,73	4,1	1,002
0	0	0
4970,73	4,1	1,001
0	0	0
4970,73	4,1	1

Table 4 *Measurements for the stop plate force sensor approximation.*

Force (N)	Input Voltage (mV)	Output Voltage (V)
0	-2,7	0
4970,73	1,5	2,494
0	-2,7	0
4970,73	1,6	2,497
0	-2,7	0
4970,73	1,6	2,5
0	-2,7	0
4970,73	1,6	2,498
0	-2,6	0
4970,73	1,5	2,5
0	-2,7	0
4970,73	1,7	2,496
0	-2,7	0
4970,73	1,6	2,496
0	-2,7	0
4970,73	1,6	2,5
0	-2,7	0
4970,73	1,6	2,499
0	-2,6	0
4970,73	1,6	2,497

The hand drive displays related to the measurement of the forces applied on the pushing and stop plate have assembled the necessary amplifiers inside them. As a result, the input voltages fed into the hand drive display from the force sensors are given in miliVolts and the output of this displays are given in Volts. These amplifiers makes their output signals suitable for the data acquisition system (0-10 V) and consequently to the LabView software. They also give the proper signal to the displays in which they are installed.

The average values related to the measurements mentioned above are shown in Table 5 and Table 6.

Table 5 *Averaged measurements for the pushing plate force sensor approximation.*

Averaged Input Voltage (0 N) (mV)	0,06
Averaged Input Voltage (4970,73 N) (mV)	4,04
Averaged Output Voltage (0 N) (V)	0
Averaged Output Voltage (4970,73 N) (V)	1,0014

Table 6 *Averaged measurements for the stop plate force sensor approximation.*

Averaged Input Voltage (0 N) (mV)	-2,68
Averaged Input Voltage (4970,73 N) (mV)	1,59
Averaged Output Voltage (0 N) (mV)	0
Averaged Output Voltage (4970,73 N) (mV)	2,4977

The averaged values are used to calculate the linear relation between the input values and the forces applied on the pushing and stop plate. As a result, a particular force value can be displayed according to its input value.

Figure 8.22 and 8.23 show the linear relation between the input voltage and the forces applied on the pushing and stop plate.

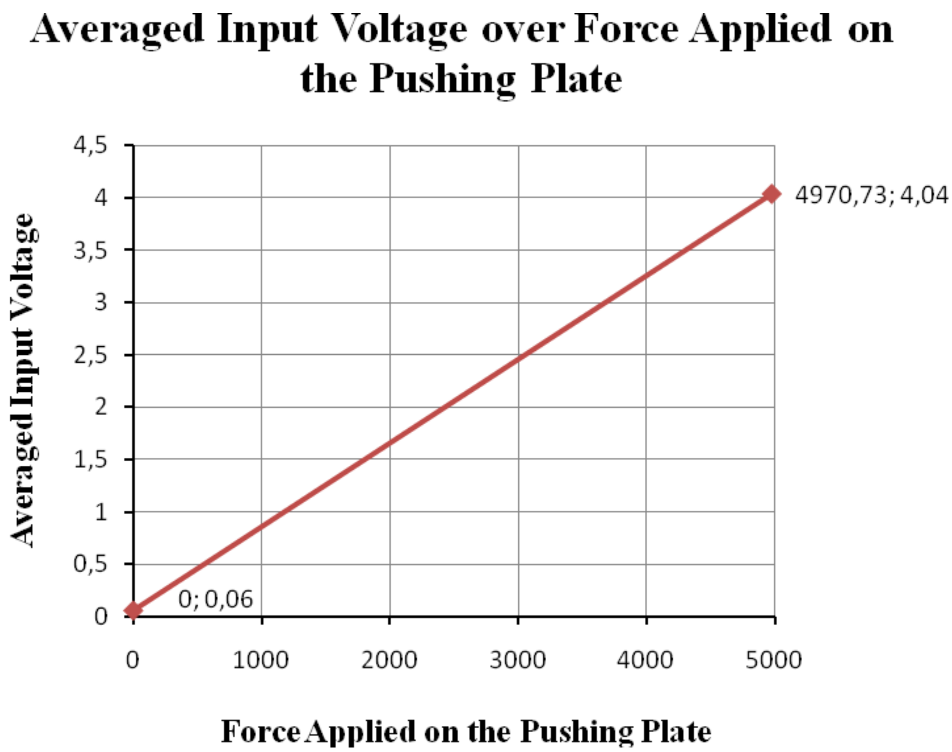


Figure 8.22 *Averaged input voltage over force on the pushing plate.*

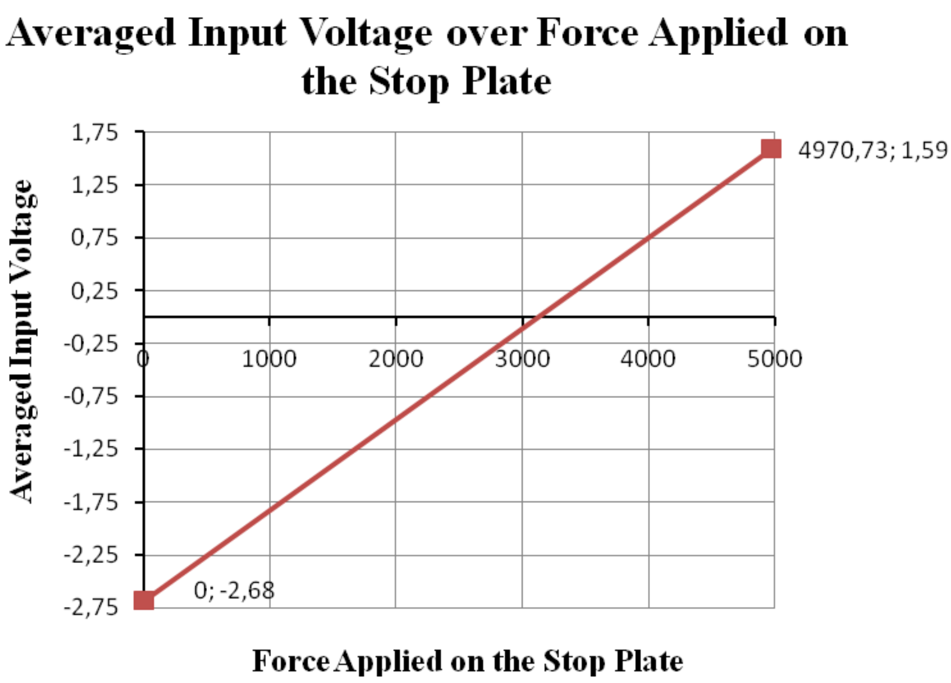


Figure 8.23 *Averaged input voltage over force on the stop plate.*

The values used to obtain this linear relation are programmed in the hand drive displays. For instance, if there is no force applied on the pushing plate (0 N) the input value of the hand drive display will be 0.06 mV. Therefore it is programmed to display 0 N by associating the known force with the expected input from the sensor. In the same way as the 0 N tests, the second known force is configured. As a result the linear relation between the force and the voltage is obtained and the hand drive displays the force values correctly.

The hand drive displays related to the force measurements have the necessary amplifiers assembled inside them. Furthermore these displays are able to give outputs which can be programmed from 0 to 10 Volts. They are fed into the data acquisition system and consequently, into the LabView software. For this purpose, these outputs have to be programmed in order to give the correct signal values to the computer.

The relation between the measured forces and the output values are shown in Figures 8.24 and 8.25.

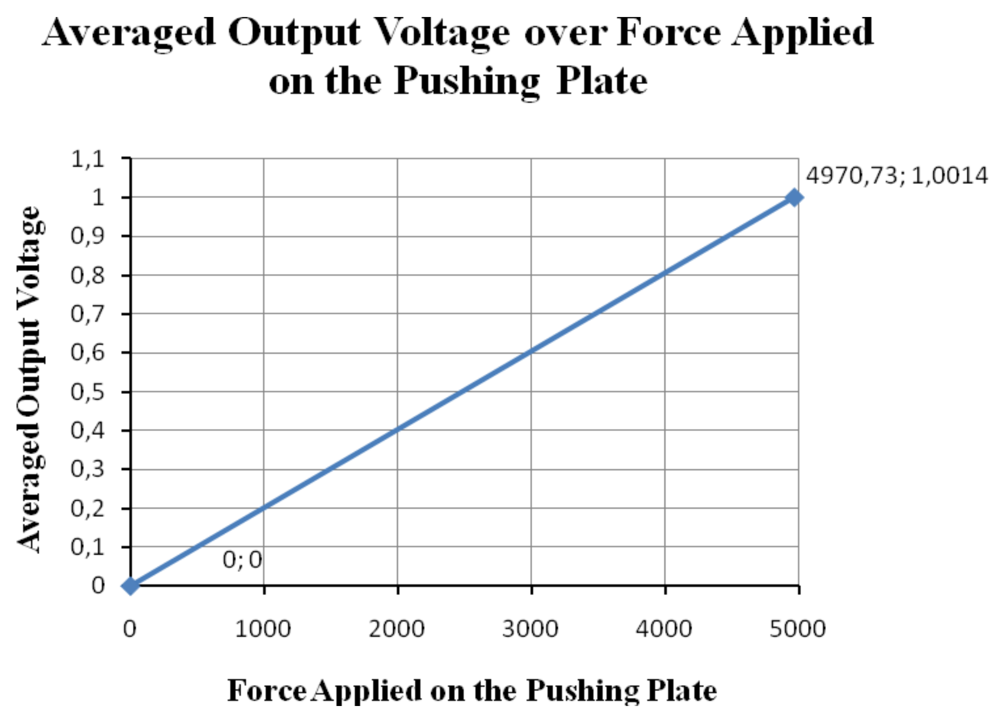


Figure 8.24 *Averaged output voltage over force on the pushing plate.*

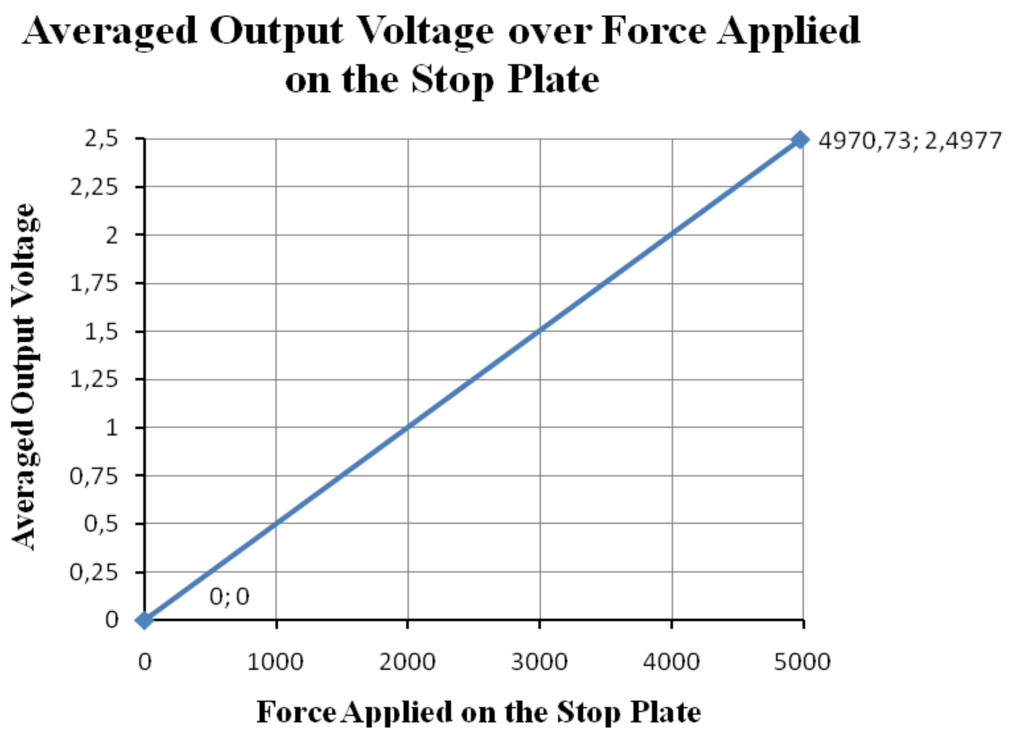


Figure 8.25 *Averaged output voltage over force on the stop plate.*

The position sensor approximation is carried out in the same way as the force sensors. First of all, the working area is delimited. Finally the signals from the position sensor related to these positions are measured in order to obtain their relation. It is calculated from the values showed in Table 7.

Table 7 *Measurements for the position sensor approximation.*

Measurement Number	Position (N)	Input Voltage (V)
1	0	0,54
1	47	8,43
2	0	0,54
2	47	8,42
3	0	0,52
3	47	8,44
4	0	0,53
4	47	8,45
5	0	0,56
5	47	8,43
6	0	0,55
6	47	8,43
7	0	0,54
7	47	8,42
8	0	0,56
8	47	8,43
9	0	0,55
9	47	8,45
10	0	0,54
10	47	8,43

The average values obtained from Table 7 are shown in Table 8.

Table 8 *Averaged measurements for the position sensor approximation.*

Averaged Input Voltage (0 N) (mV)	0,543
Averaged Input Voltage (4970,73 N) (mV)	8,433

In conclusion, the relation between voltage and position is calculated. It is shown in Figure 8.26. In addition, the position sensor output is given in Volts and it is not needed to be amplified. Therefore it is fed into the hand drive display and LabView software without being conditioned.

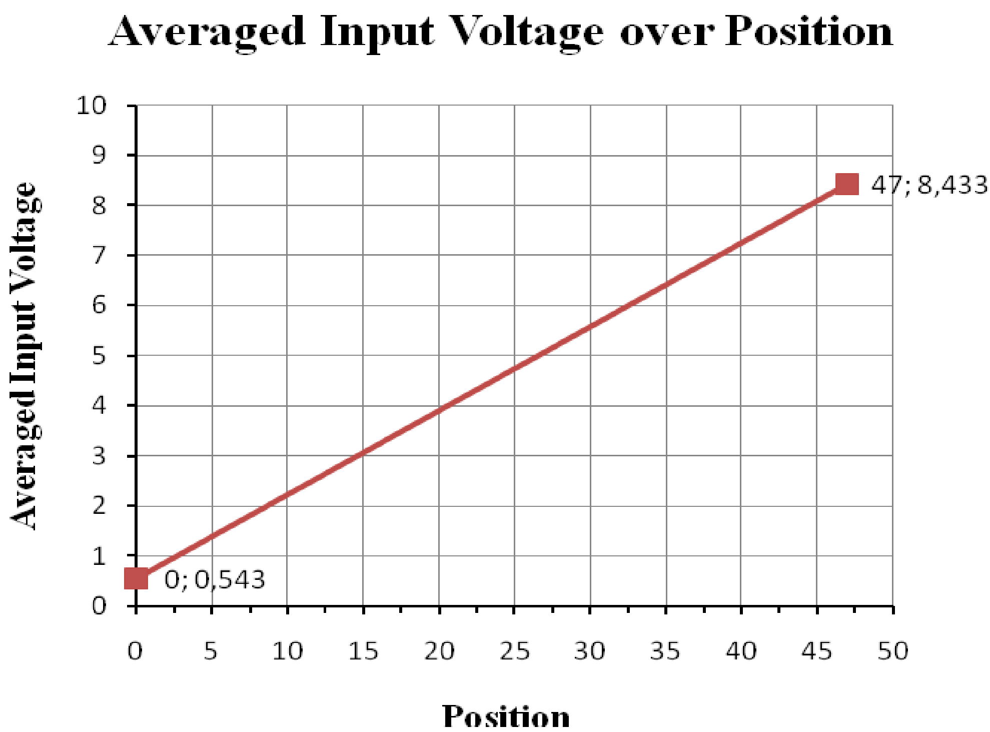


Figure 8.26 *Averaged input voltage over position.*

Considering the strain gauge measurements, a MMC 16 A makes them suitable for the LabView software and the hand drive display. It balances the Wheatstone bridge configurations and it is in charge of the strain gauge approximations. These approximations are based on the results obtained when the Wheatstone bridge is subjected to the test values set by the amplifier card. For instance, if the test value is 50 $\mu\varepsilon$ the output voltage from the amplifier will be 2.5 V. The hand drive display related to stress measurement and the LabView code designed for this purpose are configured by using the ratio obtained from these tests and equations 8.5 and 8.6. Their combination allows the operator to know the stress value in the particular points in which the strain gauges have been assembled.

Regarding the LabView software, its approximation is based on the values displayed in the hand drive and in the MMC 16 A amplifier. Therefore the LabView software is programmed so that their virtual indicators and graphs display the same values as the hand drive ones do. As a consequence the LabView code is configured to remove the voltage losses related to the wire connections.

8.5. Verification of the measurement system approximation

The verification of the approximation obtained (chapter 8.4) tests the precision, repeatability and reproducibility of the measurements. The procedure followed consists of taking three measurement series for each sensor. The series compares the same points.

In case of force sensors, a hydraulic cylinder (ENERPAC RSM-50) is used to provide the necessary force in order to test them. It subjects the sensors to pressure. Therefore with a known cylinder effective area (5.067 cm^2) these pressure values are converted into force values. Six measurements are taken in ascending and descending order from 0 N (0 Kp/cm^2) to 12421.7505 N (250 Kp/cm^2) and vice versa. The obtained values are shown in Table 9.

Table 9 *Values used to test the pushing plate force sensor approximation.*

Pressure (kp/cm^2)	Force (N)	Force Measurement (N)	Error (%)
0	0	0	
50	2484,350	2494	0,387
100	4968,700	4980	0,227
150	7453,050	7450	0,041
200	9937,400	10050	1,120
250	12421,751	12518	0,769
200	9937,400	11312	12,152
150	7453,050	8822	15,517
100	4968,700	6116	18,759
50	2484,350	3298	24,671
0	0	74	

Based on Table 9 and Figure 8.27, the behavior of the pushing plate force sensor is closed to the expected one with increasing forces. The measurement errors during this process are lower than 1.2 % and the slope of the straight line obtained from the force measurements over applied force (Figure 8.27 green line) is similar to the ideal one (Figure 8.27 red line). In addition to this, the behavior with decreasing forces is different in comparison with the expected one. The friction forces occurred between the assembled components such us guides, plates, etc. affect the process and produce the hysteresis effect in the measurements. It is shown in Figure 8.27 (blue line).

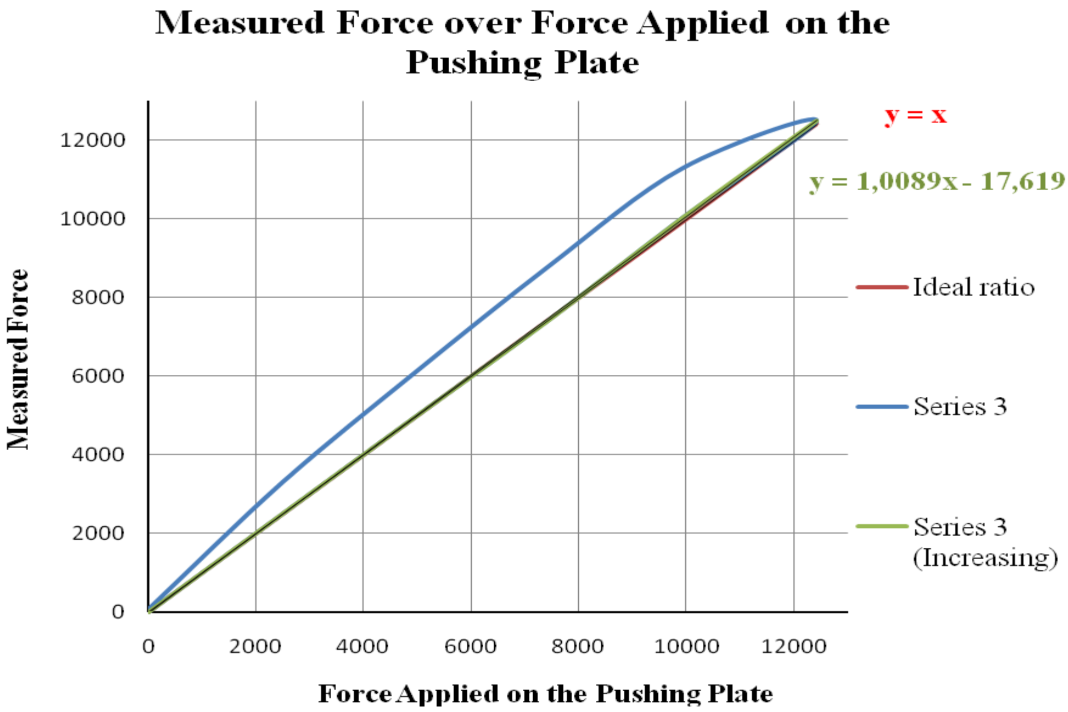


Figure 8.27 *Measured force over force applied on the pushing plate.*

Reproducibility is the variability of measurements system caused by differences in operator behavior. Its relative error is calculated in equation 8.9 (ISO 376:2004)

$$b = \left| \frac{X_{\max} - X_{\min}}{X_r} \right| x100 \tag{8.9}$$

where b is the relative reproducibility error, $X_{\max}$ is the maximum measured value, $X_{\min}$ is the minimum measured value and X_r is the average of the measured values. Repeatability is the variation of the measurements obtained by one person while measuring the same item repeatedly. Its relative error is calculated in equation 8.10 (ISO 376:2004)

$$b' = \left| \frac{X_3 - X_2}{X_{wr}} \right| x100 \tag{8.10}$$

where b' is the relative repeatability error, X_2 and X_3 are the same measurement point in different series and X_{wr} is the average of the measured values. The reproducibility and repeatability of the pushing plate force sensor is shown in Table 10. Their values are lower than 1 % with increasing values. The errors with decreasing values are higher than the previous ones due to the action of friction forces.

Table 10 *Relative reproducibility and repeatability error of the pushing plate force sensor.*

Froce (N)	Relative reproducibility error (%) (Series 1,2 3)	Relative repeatability error (%) (Series 2, 3)
0		
2484,350	0,798	0,719
4968,350	0,564	0,564
7453,050	0,988	0,988
9937,400	0,759	0,299
12421,751	0,479	0,415
9937,400	0,495	0,212
7453,050	1,395	1,140
4968,350	1,749	1,052
2484,350	2,583	1,651
0	5,217	5,263

In the same way as the pushing plate force sensor, the approximation of the stop plate force sensor is verified. Its results are considered similar in comparison with the previous analysis. The most important difference between them is the behavior of both sensors in the last tested value. Whereas the pushing plate force sensor behaves linearly in comparison with the applied values, the stop plate force sensor varies its slope moving away from the ideal behavior. Its analysis is shown in Figure 8.28.

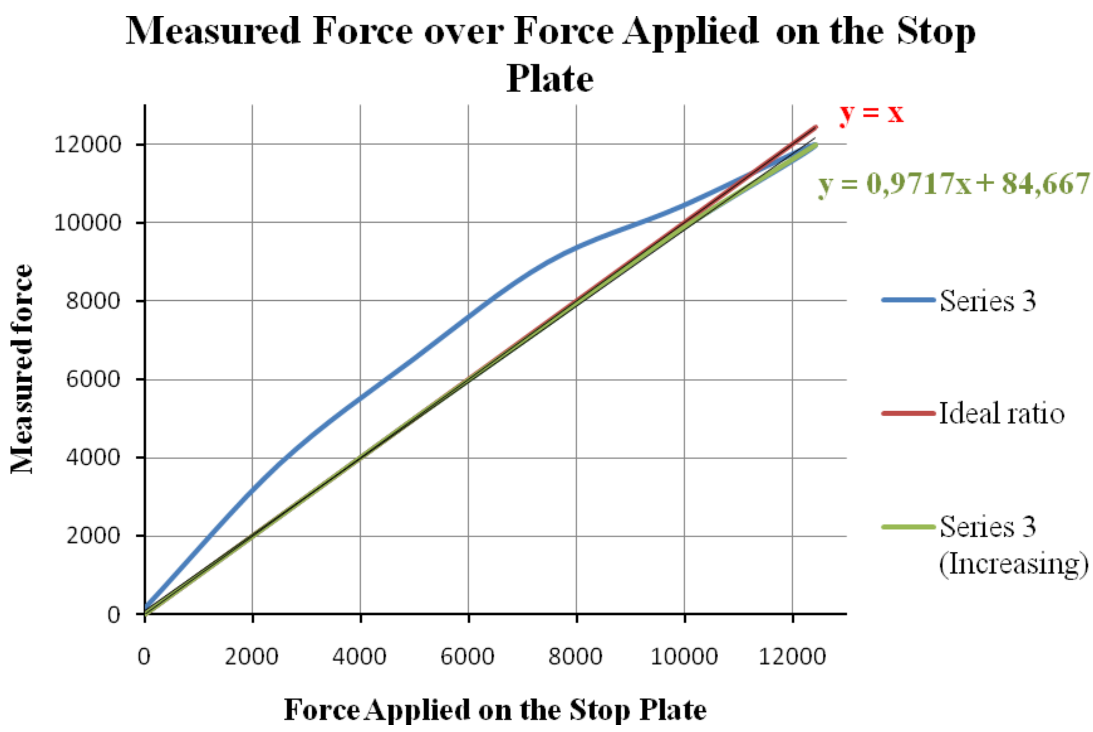


Figure 8.28 *Measured force over force applied on the stop plate.*

In case of the position sensor, a vernier caliper is used to provide the necessary position points in order to test it. Ten measurements are taken in ascending from 0 cm to 45 cm. The obtained values during one series are shown in Table 11. The verification is not needed in descending order because there is no hysteresis in this type of sensors.

Table 11 *Values used to test the pushing position sensor approximation.*

Position (cm)	Position (cm)	Error (%)
0	0	
5	5	0
10	10,1	0,990
15	15,1	0,662
20	20,1	0,498
25	25,1	0,398
30	30,1	0,332
35	35,1	0,285
40	40	0
45	45,1	0,222

Based on Table 11 and Figure 8.29, the behavior of the position sensor is closed to the expected one. The measurement errors during this process are lower than 1 % and the slope of the straight line obtained from the force measurements over applied force is similar to the ideal one (Figure 8.29) (its slope value is 1.001 which is closed to 1).

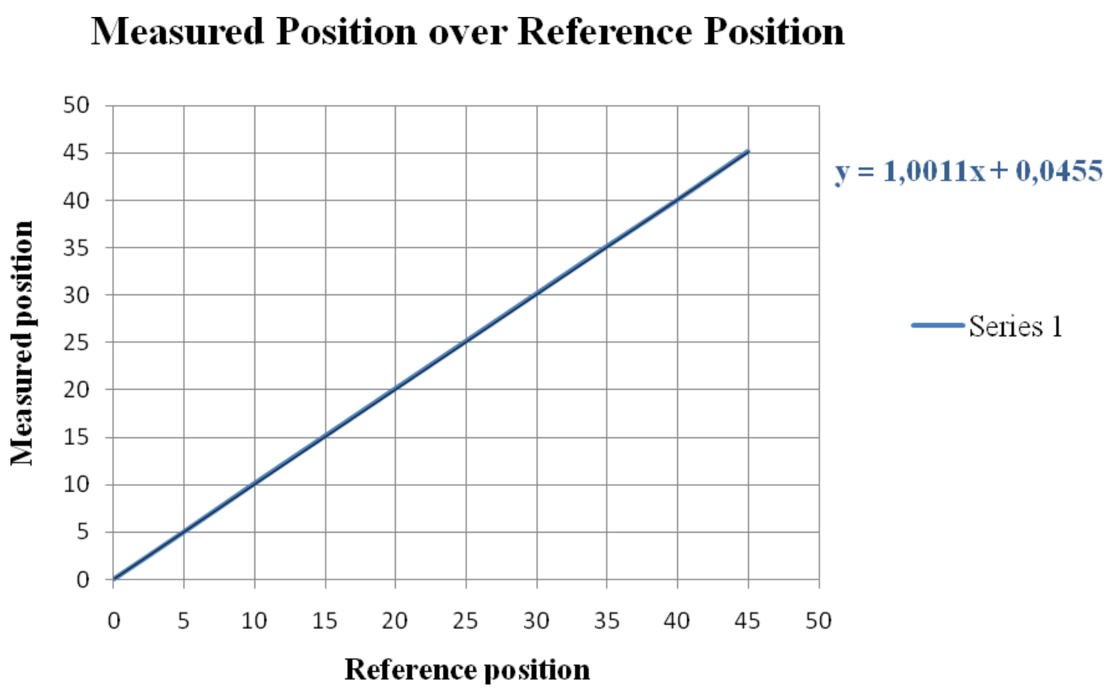


Figure 8.29 *Measured position over reference position.*

The relative reproducibility and repeatability error of the position sensor is shown in Table 12. Although the second test point (5 cm) reports high relative reproducibility error, their values are lower than 1 % in the rest of the cases with increasing values. In addition to this, the relative repeatability error is zero in most cases.

Table 12 *Relative reproducibility and repeatability error of the position sensor.*

Position (cm)	Relative reproducibility error (%) (Series 1,2 3)	Relative repeatability error (%) (Series 2, 3)
0		
5	1,974	0
10	0	0
15	0,659	0
20	0	0
25	0	0
30	0,331	0
35	0,284	0
40	0,250	0,250
45	0,222	0

In case of the strain gauges, a MMC 16 A subjects the Wheatstone bridge to the test values set by the amplifier card. These test values are 0.50 and 100 με. As a result, the verification of the strain gauges approximation is carried out by taking three series of measurements related to these test values in each strain gauge. Subsequently the relative reproducibility and repeatability error of the measurements are calculated. Considering the strain gauge A located in the upper guiding wall, their results are shown by Table 13.

Table 13 *Relative reproducibility and repeatability error of strain gauge A located on the upper plate.*

Strain (με)	Relative reproducibility error (%) (Series 1,2 3)	Relative repeatability error (%) (Series 2, 3)
0	0,214	6,061
50	0,003	0,078
100	0,003	0,099

The rest of the strain gauges follow the same behavior shown in Table 13. Although the first test point (0 με) reports high relative repeatability error, their values are close to 0 % in the other test points. This high error is obtained because a small variation in the output voltage between two series is divided by a number closed to 0. In addition, the relative reproducibility error is close to 0 % taking 50 and 100 με tests into consideration.

Regarding the LabView software, its approximation is verified visually. It consists of a comparison between the values displayed by both the hand drive and the MMC 16 A amplifier and the ones displayed by the LabView virtual indicators. The values in both cases have to be the same.

The verification of each sensor approximation has been carried out under the same conditions and using the laboratory sources.

8.6. Verification of the control system

The LabView control system is verified in order to check if it is working properly. The verification of the control system tests if it switches off the compressing unit when a particular controlled variable exceed its established limits (Chapter 8.3). These tests are carried out under real conditions. Firstly, the limits of the pushing plate position are checked. For this purpose it is driven to the maximum position value and when it matches up with the current pushing plate position the compressing unit has to stop working. In the same way as the maximum value, the minimum one is tested. In addition, the reset button has to drive the cylinder to a particular established start position. Consequently, it is tested in order to verify that it stops the pushing plate in its reference position.

From this point, the following tests are carried out using wooden logs whose length and diameter were 0.29 m and 0.045 m. In order to check the proper running of the control system related to the force and stress variables, lower limit values are used. For instance, whereas the limit of the force applied on the pushing plate is modified in the LabView code the other variable limits are kept in their established values. Therefore this variable will exceed its limits before the others. As it is done with the force applied on the pushing plate, the one applied on the stop plated and the stress related to the strain gauge measurements are tested.

The emergency lights are also tested during these verification processes. Therefore, when a particular variable limit is exceeded the general emergency light has to be switched on. In addition, the light related to this variable has also to be switched on in order to facilitate the location of the variable which is being dangerous for the compressing unit.

Finally, these tests allow the designer to check the interaction between the control and measurement system and the compressing unit. The action on the relays is verified and consequently, the proper running of both the hand drive buttons and the LabView virtual controllers. The measurement system is also tested under real working conditions.

9. RESEARCH RESULTS

The verification of the measurement system approximation explained in chapter 8.5 analyzes not only the behavior but also the reproducibility and the repeatability of the measurements. These results show that the force sensors behave in a similar way in comparison with their ideal cases (Figure 8.27 and 8.28). In case of the stop plate force sensor, its behavior varies moving away from the ideal one with high force values, for instance 12421.751 N which is the last force value tested (Figure 8.28). The assembly between the force sensor and the stop plate may produce this difference from the ideal results. In addition, the reproducibility and repeatability values obtained from these verifications satisfied this Master Thesis’s requirements. Whereas these values are lower than 1 % with increasing force values, they show higher results with decreasing ones. It is caused by the friction forces. In case of the position sensor, its behavior is similar compared with the ideal one and its reproducibility and repeatability satisfied this Master Thesis’s requirements. Regarding the verification of the strain gauges measurement system, the reproducibility and the repeatability were checked. Although the first test point (0 $\mu\varepsilon$) reports high relative repeatability error, their results were reasonable.

The verification of the measurement system approximation was carried out using the laboratory sources. The use of standard patterns would have led to the calibration of the whole system (compressing unit, components connection, hardware, and software) and the verification would have been more accurate. In addition, the approximation results of the compressing measurement system have been affected by the tools used for this purpose such as the hydraulic cylinder, the vernier caliper and the test values set by the amplifier card.

The control system behaved correctly and it avoided dangerous situations for both the compressing unit and the control and measurement components. It was verified following the procedure explained in chapter 8.6. The interaction between the LabView software, the hand drive, where the relays are installed, and the compressing unit were tested and its result satisfied the initial requisites. The emergency lights programmed in the LabView software worked properly when they were tested. In addition, the cylinder was driven by both hand drive and computer. Whereas the relays response was almost immediately when they were operated by hand drive, their response takes more than one second in case the compressing unit was driven by computer. It could be due to the bit rate that the computer was able to reach in its USB connection.

10. FUTURE RESEARCH

This research work has developed a control and measurement system for a compressing unit. It collects the necessary information to understand the logs behavior during a compression process. This research work suggests the study of the variables which have an effect on this compression process. It will lead to the improvement of the control and measurement system. For this purpose, the on/off valve can be replaced with servo valve. In addition, a PDI controller can be developed based on the theories explained in chapters 5.2 and 5.3. This Master Thesis recommends the analysis of the different types of control methods which can be used to achieve this goal. They are described in chapters 5.5 and they are based on the position, force or pressure control. On the other hand, a pulsewidth modulation (PWM) technique can be developed in order to obtain an accurate position control system by using on/off valves (van Varseveld 1997).

This research work recommends the study of the indirect variables influence (chapter 7.3.3) during the compressing process. In case their values affect the proper running system, it is suggested to control and measure them. Furthermore, the study of the future variables described in chapter 7.3.4 is also proposed.

In conclusion, this Master Thesis recommends further studies related to the compressing unit in order to improve the accuracy of the control and measurement system.

11. CONCLUSION

The aim of this Master Thesis was to develop a control and measurement system for a log batch compressing unit. The study of the variables involved in the process and the interaction between control and measurement theories concluded in the development of this research work.

The analysis of the sub-processes involved in the logs compression led to a control and measurement method based on combinational logic control theories. On the basis of this method, a computer and a hand drive interface were developed. They were able to drive the compressing unit, measure the most important parameters involved in the sub-processes and avoid dangerous situations for the system (compressing unit, components connection, hardware, and software). Furthermore an approximation was carried out in order to configure the control and measurement system. Finally a verification of the research work tested if it worked properly according to the initial requirements of the Master Thesis.

The research results concluded that the control and measurement system satisfied the requisites needed to develop future researches related to this compressing unit. The values displayed during the tests were similar to the theoretical ones and the control system avoided dangerous situations for the system when it was needed. In conclusion, the research results show that the control and measurement system worked properly.

Finally, future investigations are recommended in order to understand the wooden logs behavior during the compression carried out in pulp manufacturing. This Master Thesis suggests the development of either a PDI controller or a PWM technique suitable for this unit in order to obtain an accurate compression process. The outcome of this will be the improvement of the grinding machines' efficiency and consequently, the papermaking process.

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