INTERNATIONAL JOURNAL OF SYSTEMS APPLICATIONS, ENGINEERING & DEVELOPMENT
Issue 1, Volume 2, 2008

Embedded processor control of a lime machine

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***Abstract*—**The development of real-time control systems requires effective hardware and software systems and design tools. This paper presents the design and implementation of a microprocessor-based embedded control system for a lime slurry delivery machine, intended for lime production plants. The main goal in this approach was to ensure high performance, as provided by a special-purpose design, with minimum electronic hardware cost. VHDL models simulations were executed to verify the controller's design. Validation of the designed system was accomplished through real-time implementation tests. The simulation results were satisfactory close to those derived by further experimental investigation. The proposed control system was experimentally verified and evaluated upon a specific prototype of a lime slurry storage and delivery machine. The control system is based upon the Intel 80C188EB microprocessor.

***Keywords*—**Embedded control, microprocessor control, modeling, simulation.

I. INTRODUCTION

DISTRIBUTED control systems with embedded devices are used for the real time control of industrial processes and other systems [1]. Hydraulic actuators are widely used in a variety of industrial applications and systems for a number of decades now [2], [3]. In most cases, applications of hydraulic actuators require only periodic on-off control. Commonly found applications are those in systems that deliver some kind of fluid using precise fluid flow control [4]. In order for a control method to be effective, the response of the hydraulic valve and actuator needs to be sufficient so that to not affect the whole system performance. However, the nonlinearities associated with the compressibility of lime and the friction forces in hydraulic actuators make the precise flow control usually difficult [5]. Standard solutions offer little or no variation in the feature set for the end user.

In this research, the implementation of a microprocessor-based control system is presented for flow control of a stationary lime slurry slaking and delivery machine. The machine system under control and investigation is a prototype designed and constructed within an industrial company (Adam Machines Constructions Company, Volos, Greece). Although such mechatronic systems are not commonly found, however, to some extend the methods and control techniques of hydraulic motion have already been studied and applied in similar other cases [6], [7], [8]. In general, computer-based systems have improved the functionality of the conventional plant monitoring and control facilities in several cases. Modelling and simulation techniques have also play an important role in such systems optimization [9].

The control system implemented is based on Intel 80C188EB microprocessor [10]. This controller has embedded all the required architecture to perform the task of control. For connecting parts of distributed control system we selected CAN bus (Controller Area Network). CAN bus is given international standard ISO11898 which uses the first two layers of ISO/OSI model. This distributed control system was found to be quite useful in assisting the real-time control and operation of the machine. The actual system under control is a lime slaking silo and rotary agitation unit driven by a gear transmission mechanism and electric motor. Lime slaking is the process of mixing quicklime (calcium oxide, CaO) with water to form hydrated lime (calcium hydroxide, CaOH2). Although calcium hydroxide is only slightly soluble in water, by using excess of water lime slurry is finally produced. The system is designed to provide a continuous flow of lime.

Simulation is an important tool used to evaluate the design of control systems [11]. Simulations were carried out by using the LabVIEW (National Instruments) graphical programming environment. For this reason, a real-time interactive user interface was designed and implemented for investigating the functionality of the controller. The LabVIEW tool provides a large amount of ready-to-use control functions. Furthermore, an experimental setup was used to examine in practice the overall control system. Simulation and experimental results are presented validating the design and the model.

The remainder of this paper is organized as follows. Section 2 provides a brief description of the machine system under

Manuscript received Jan. 12, 2008. This work was supported in part by the Greek Department of Development under Grant No 4.3.6.1g 219-G (GR-CZ project 2005-07, by the GSRT of the Hellenic Republic). Revised Febr.21, 2008

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control. Section 3 describes the methodology used in designing the controller. Section 4 provides details of the implementation process. In section 5 and 6 the design simulations, and the experimental results obtained from real tests are presented respectively. Conclusions and related future research are given in Section 7.

II. THE MACHINE SYSTEM UNDER CONTROL

Industrial applications use a variety of devices, many of which have their own unique specifications and requirements during the control operation. The overall machine system in this work is basically consisted of the lime slaking and decantation silo, the controller unit (80C188EB- based) and an operator's manual control panel. The machine under control (Fig. 1) is a system that stores and delivers lime slurry with accuracy and satisfactory speed. The lime storage tank is a cylindrical silo (10m^3, ~3tons) equipped with an agitation and scrapping system for delivery of lime slurry. The lime is discharged out of the silo while being continuously mixed.

Fig. 1 the lime slaking and delivery machine under control

Lime agitation and delivery is based on a rotational mechanical system of horizontal shaft driven by a gear pump and cogs system (a gear wheel mechanism). The rotational speed of the cogs system plays an important role in determining the capacity of the lime slurry output. The shaft’s torque and the hydraulic pressure combine into a resultant driving force that produces a helical motion of rotation. Shaft’s rotation generates a relative velocity between the shaft scrappers (paddles) and the cylinder silo. This rotating motion yields a helical motion of the shaft which forces the lime slurry to be delivered at the outlets.

The machine is equipped with five electro-hydraulic valves (Duplomatic, Pmax 320Bar, 24VDC) that control the flow of the hydraulic fluid (pump-driven by an ac 15HP motor). The proportional control valves can adjust flow rate from -500 to 500 l/min according to the input voltage (0-10V) by changing the spool position. The flow of lime slurry is measured using an electronic measurement unit (Danfoss Magflo MAG3500 electromagnetic flow-meter).

III. CONTROL METHODOLOGY

The operation of the machine is based on a hydraulic pump system (driven by an ac motor). The hydraulic system drives a hydraulic motor (via electro-hydraulic valves), which in turn drives a gear wheel mechanism that regulates the speed (rotation) of the single-shaft agitation system that controls the actual flow of the lime slurry out of the silo (tank). In other words, the system converts hydraulic power into rotational mechanical power, which is applied to the load (lime slurry).

A. *Tank Mathematical Model*

The mathematical model of the tank [12] could be obtained by the following equation:

$$q_{in} - q_{out} = a\frac{dl_o}{dt} \tag{1}$$

where q_{in} is the inlet flow, q_{out} the outlet flow, a is the cross-sectional area of the tank and lo the lime slurry level. If we consider that the outlet flow q_{out} is a linear function of the lime slurry level height l_o and a constant parameter K_f that depends on the viscosity and velocity of the lime flow, then (1) could be expressed as follows:

$$t_c\dot{l}_o + l_o(t) = K_f q_{in}(t) \tag{2}$$

where $t_c = aK_f$ is the hydraulic time constant of the tank. This is a first-order differential equation that describes the mathematical model of the tank. The transfer function of the tank is obtained by taking the Laplace transformation of the above (2) as follows:

$$\frac{L_o(s)}{Q_{in}(s)} = \frac{K_f}{t_c s + 1} \tag{3}$$

A block diagram of the tank control system is shown in Fig. 2.

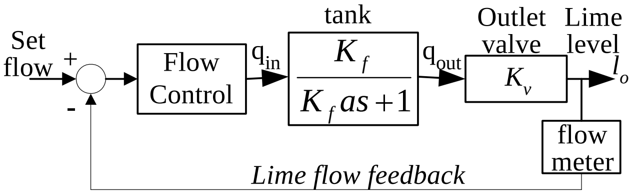

Fig. 2 block diagram of the tank (lime silo) controller

The outlet volumetric flow rate Q_{out} of the lime slurry is proportional to the speed $\dot{p}_{cog}$ of the gear shaft according to the following equation:

$$Q_{out} = K\dot{p}_{cog} \tag{4}$$

where K is lime constant.

B. *The Rotary Agitation System*

Rotation of the paddles agitation system is achieved with a cogs system (driven by a hydraulic motor) coupled to the paddles shaft (see Fig. 3). The design of the paddles in combination with the rotating motion (x_{rot}) of the shaft yields a helical motion (x_{hel}). In this way, each particle in the lime slurry mixture is moved forward (x_{ax}) towards the delivery outlets based on the force produced by the resultant helical motion. Due to this clockwise helical motion the lime flows out from the outlets.

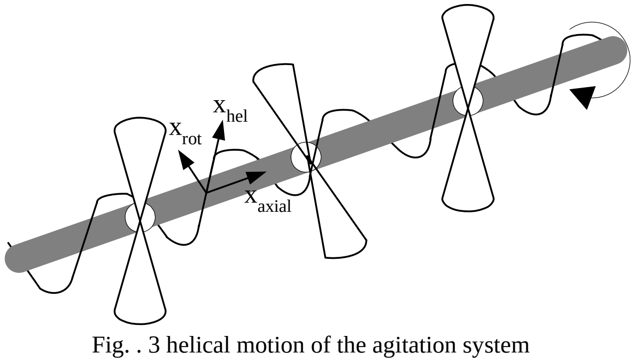

Fig. . 3 helical motion of the agitation system

To eliminate the dependency between x_{rot}, x_{ax}, and x_{hel} in the state-space equation we set the following relation:

$$x_{hel} = \sqrt{x_{rot}^2 + x_{ax}^2} \tag{5}$$

C. The Control System

The main control variable is the speed of the paddles shaft. The input variable is the shaft's rotational speed and the output variable is the actual angular (rotational) speed of the shaft, which forces the lime to flow out of the silo. The block diagram of the system is shown in Fig. 4, where ω is the reference angular (rotational) speed of the paddles shaft, K_{pv} is the controller proportional gain, V_{sv} is the electro-hydraulic valve-control voltage, d_{sv} is the electro-hydraulic valve-spool displacement, p_{cog} is the gear system rotational position, p_ω is the shaft rotational position proportional to p_{cog}, and $\dot{p}_\omega$ is the actual shaft angular (rotational) speed. The position d_{sv} of the valve spool controls the flow rate Q of the hydraulic fluid in the hydraulic motor which forces the gear wheel mechanism to rotate. The proportional valves system convert analog electrical input signal into appropriate cross-sectional opening. The differential pressure in the hydraulic motor (actuator) is directly controlled by the flow rate in valves.

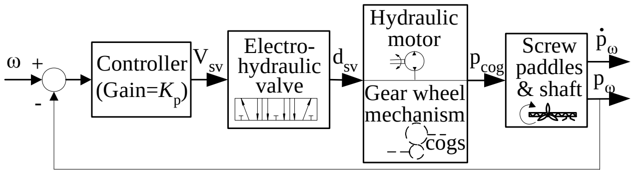

Fig. 4 schematic diagram of the overall control

The gear wheel system is the actual mechanism that rotates the paddles shaft agitation system. The viscosity and density of the lime slurry is such that this mechanism is essential for the mixture to be rotated and forced to the outlets. This is because viscosity may be regarded as friction that is internal to the liquid. Since the lime slurry liquid is nearly incompressible its density is constant. The flow of a viscous liquid like lime slurry is found to be laminar based on the following equation (the Reynolds number):

$$N_r = \frac{v\rho D}{\eta} \tag{6}$$

where v is the fluid velocity, ρ the density, D the outlet pipe diameter and η the viscosity.

Taking an average velocity of about 100cm/s, a density of 2.24g/cm^3, viscosity of 0.2 and pipe diameter 20cm, the above equation gives a value which is nearly 2000. Rotating the shaft a relative velocity $\dot{p}_\omega$ is generated (between the shaft paddles and the silo's wall) that regulates the lime flow. A 4 x 4 state-space model of the system can be formed:

$$\left[p_1\, p_2\, p_3\, p_4\right] = \left\lfloor p_{cog}\; p_\omega\; \dot{p}_\omega\; P \right\rfloor \tag{7}$$

where P is the pressure of the load (lime volume).

Upon this system state-space model, computer simulations were executed in order to verify the design of the controller.

IV. THE CONTROLLER

The machine controller is based on an 80C188EB microprocessor that communicates with a host computer in order to acquire the initial working data. The architecture of these microprocessors family was optimised for applications in industrial controllers. The use of the single-chip microprocessor reduces the amount of elements required and subsequently the board's dimensions, simplifying the design process and increasing the systems' perspectives.

Although the capabilities of this control system are not very enhanced, however are sufficient for this specific application of automation, and with minimum electronic hardware cost (even the cost for the fabrication of the controller's physical layout was low). For this reason, a standard programmable device was not chosen. A simplified block diagram of the 80C188EB microprocessor-based machine controller is given in Fig. 5.

As a means of communication and control of the 80C188EB microprocessor-based controller, an application control program in Intel 80x86 family assembly language was developed. The software module implemented in the controller was used to generate the triggering signals to the motor driver relays and the actual electro-hydraulic valves of the system.

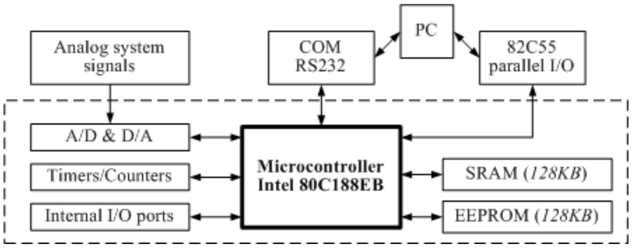

Fig. 5 block diagram of the controller

The control software for the realisation of system's functionality was written in assembly language using the 80x86 family MASM Assembler. The code was optimised in order to use efficiently the available memory and reduce compilation time and execution speed. An indicative fragment of this control software module is given below:

```
80x86 MASM Assembler Page 0001
.186   ; generate code for 80186/80C188
org 01FF0h    ; location in ROM
port equ 40h   ; assign port A of PPI
; poweron segment at 0FFFFh
power_on:
mov dx, offset pos
mov ax, eprom_start + 31h
out dx, al
jmp far ptr start
```

The above software control system provides all the required control facilities for the machine's operation, through a low-level programming interface. The application code was developed on a desktop host PC, before being downloaded (the executable) onto the target board, via a serial link (RS-232). Once the development was complete, the executable code was programmed in the onboard EPROM for standalone operation.

In addition to the above control software, further work is currently under progress towards the creation of a high-level programming interface using Visual C/C++. The application program in C/C++ would provide a graphical interface communication module that would establish all the appropriate communication parameters between the user operator and the machine's controller (80C188EB microprocessor). In general, it would interpret high-level motion commands (e.g. *start()*, *stop()*) and invoke the corresponding functions to process and execute the user task requests. The combination of low and high level programming languages in a graphical front-end would assist further the machine operator in real-time interactive control.

Modern manufacturing always involves some kind of intelligent automation based on computers [13]. Microprocessor-based controllers are widely used in industrial applications due to their flexibility in programming functionality, speed and accuracy [14], [15] [16]. Although for this implementation work a standard programmable device could have easily been chosen, however due to research and investigation reasons, the decision was for an in-house developed microprocessor-based product. As a result, the control system designed was based on 80C188EB Intel microprocessor (25 MHz, 20bits address bus, 1M address space, 8 bits data bus, 16 I/O pins, 3 timers/counters, 5V).
The single board controller basically contains four 62256 (32K x 8) RAMS that compose an 128K x 8 bit memory, two 27C512 (64K x 8) EPROMs that compose a 128K x 8-bit memory, two RS232 (PC) communication ports and a programmable peripheral interface circuit that directly connects to the equipment (electro-valves and motor relays).

The development of the controller's physical layout design was implemented using OrCAD Capture software (*Cadence Design Systems, Inc.*). The controller basically consists of the 80C188EB Intel microprocessor unit, memory modules and the 82C55 programmable peripheral interface (PPI) unit. This controller has embedded all the required architecture to perform the task of control. One of the advantages of this control board is the low power consumption (5-volt circuit supply), favourable in a variety of applications. A fragment of the controller's design is shown in Fig. 6.

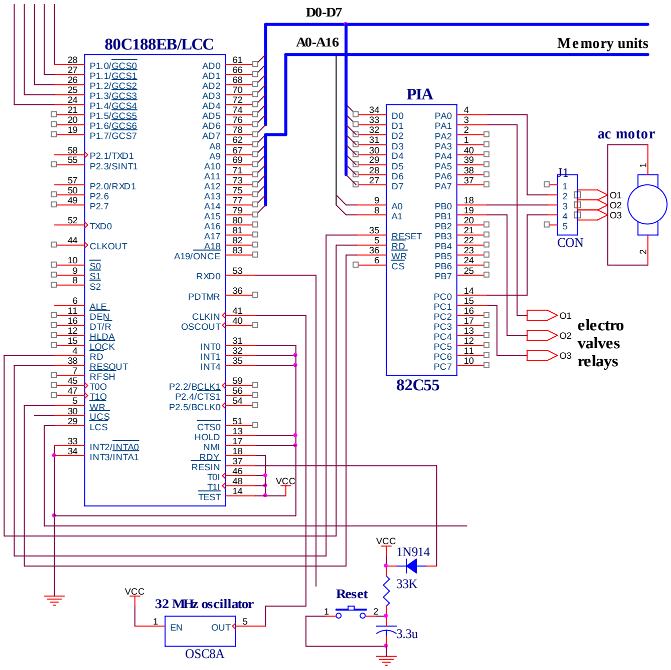

Fig. 6 basic design of the microprocessor-based controller

In Fig. 7 is shown a part of the memory control unit design. The system's synchronisation is accomplished through an external crystal-based (quartz-oscillator) pulse generator (32MHz), in order to ensure high accuracy and TTL level signal required. The 74HC573 circuit (Latch) buffers the addresses from the microprocessor towards the EPROMs and SRAMs memory units

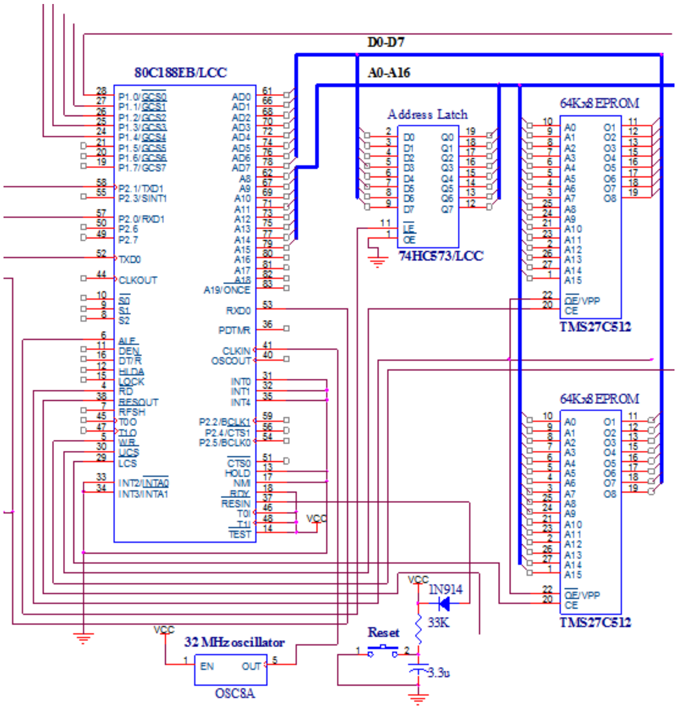

Fig. 7 the controller memory units

The performance of the 80C188EB-based controller was evaluated based on simulations and analysis performed with ModelSim software package (ModelSim SE Plus 5.7d, Model Technology – *Mentor Graphics Corporation*). This software enables automatic target CPU code generation. Through this feature it is effective to replace modelled physical and link layers with CAN bus handle routines integrated right in the microprocessor.

The VHDL code produced was divided into a series of process statements according to the described architecture. The architecture of the simulated controller with all-important signals is visible in the VHDL simulator. The whole length of the simulation model code used in system's functionality verification is not presented due to its substantial length. A fragment of the simulated code of the controller's behavioural description follows below:

```
LIBRARY IEEE; USE IEEE.std_logic_1164.all;
ENTITY CONTROLLER IS PORT 9O1:OUT
 std_logic;O2:OUT std_logic;O3:OUT std_logic);
END CONTROLLER;
ARCHITECTURE STRUCTURE OF CONTROLLER IS
COMPONENT \82C55\
PORT(
VCC: IN std_logic; GND: IN std_logic;
RESET: IN std_logic; \C\\S\\\: IN std_logic;
\R\\D\\\:IN std_logic;\W\\R\\\:IN std_logic;
A0, A1: IN std_logic;
PA0: INOUT std_logic; ... PA7: INOUT std_logic;
PB0: INOUT std_logic; ... PB7: INOUT std_logic;
PC0: INOUT std_logic; ... PC7: INOUT std_logic;
); END COMPONENT;
```

A sample timing diagram of output waveforms of controller simulation is shown in Fig. 8. This figure illustrates an interface connection to the output device under control (motor driver switches), indicating the bus cycles required to fetch vector information (through PB0, PC0) from the peripheral device.

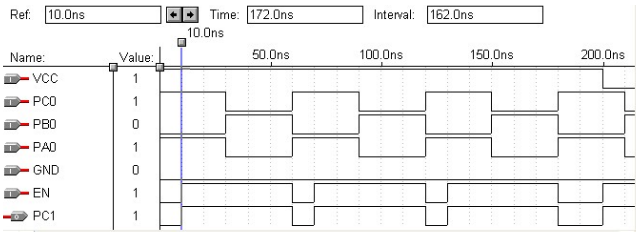

Fig. 8 timing diagram of the controller output (via PIA)

The performance of the designed control system was evaluated under real-time operating conditions (certain tests and measurements have been performed) and was compared to the specifications established during the initial design stages. During the real test procedures several system internal data were collected and analysed for testing system's efficiency and accuracy. All the tests and measurements have been carried out based on constant delivery of lime slurry, as well as other specific manufacturing factors. In most of the cases the completion of machine's operation was optimal.

V. SIMULATIONS

Simulations of the designed system are crucial to understand and verify its performance and functionality. The model for the above system was developed with reference to the control methodology described in Section 3.

The block diagram (see Fig. 9) of the actual executable model is constructed in LabVIEW graphical programming language G as a modular program. Appropriate components and structures are used to indicate the flow of lime in the output terminal. The entry and exit ports in the block diagram are analogous to the statements examined earlier in the state space model of the lime slurry tank (silo). Formula nodes are used for evaluating the mathematical expressions in the mathematical tank model examined earlier. The front panel of the LabVIEW created is an interactive interface that simulates the flow of lime slurry out of the tank and provides waveforms of output results that allows us to investigate the rate of lime flow.

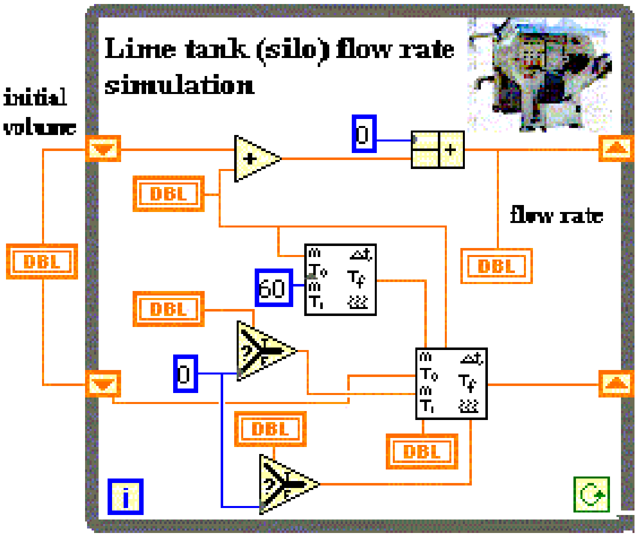

Fig. 9 the LabVIEW model design of the controller

VI. RESULTS VERIFICATION

The performance of the control system was evaluated using on-machine tests and compared with the simulation results. The effectiveness of the designed control system was evaluated in practice. Fig. 10 depicts the schematic diagram of the experimental system used in the real-time tests.

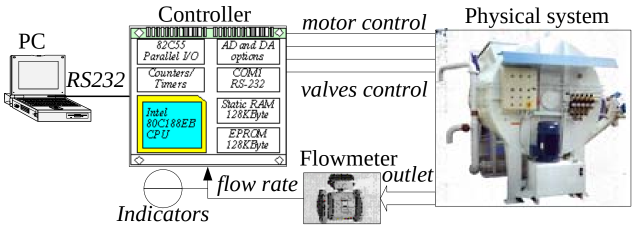

Fig. 10 schematic view of the experimental test system

The experimental system consists of the actual machine, a flow-meter, the control board, indicators and a personal computer for data acquisition and monitoring purposes. The settings of flow-meters calibration, required for accurate flow rate measurements, are shown in Table I.

Table I
Flow-meter calibration settings

MAG 3100 flow-meter features	Calibration settings
Pressure [bar]	Max 40
Supply frequency	50 Hz
Temperature [^{o}C]	-20 to 180
Nominal diameter	125 mm
Flow span	1500 l/m
Meter uncertainty	±5%
Frequency	1pulse/unit (per liter)
Pulse width	20 msec

Validation tests indicated that the simulation model as well as the implemented system seemed to perform normally. Even in some cases, the simulation model could predict the output lime flow with sufficient accuracy. This is measured using the electromagnetic flow-meter. In the case of the cylindrical silo, the lime volume is known accurately. The motor speed (that drives the hydraulic pump) was set to a constant value during each test run. Fig. 11 shows a comparison of the estimated output flow Fest = 1450 l/min with the actual flow Fact ≈ 1350 l/min as measured with the flow-meter. It can be seen that the simulation tracks the actual flow value quite closely.

It was also observed that if rotations increase, shaft velocity is increased, and lime pressure and rate of flow is increased too.

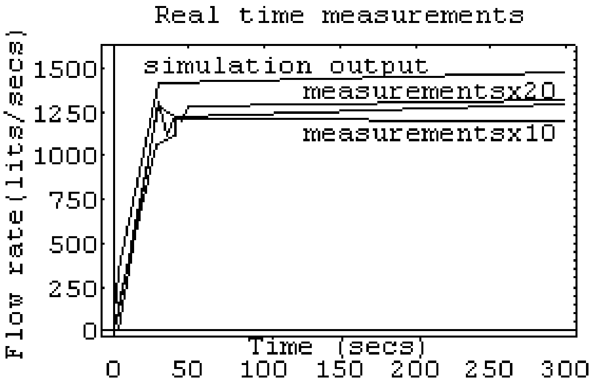

Fig. 11 comparison of simulation and test results on flow control

Further tests were conducted in an experimental setup comprising of a linear potentiometer for shaft's position feedback and a data acquisition and control board (National Instruments PCI-MIO-16E4) to acquire the electrical signals related to the position of the gear system and regulate accordingly the valves voltage input.

VII. CONCLUSION

An accurate flow controller is essential for fluid delivery machines (lime slurry in our case). This paper presents an applied method of designing a flow controller for lime slurry delivery machines. The controller is capable of achieving accurate flow control as measured by flow-meter, regardless the variation of lime viscosity (however, within an optimal working range).

The performance of the controller was simulated using a LabVIEW model and tested in the actual machine. The simulation results were validated with both off-line and on-line tests. The results from simulation analysis and machine tests indicated that the simulation model could predict the actual flow and machine performance reasonably well. The validity of the proposed system is evaluated through experiments. From the results of evaluation experiments it was confirmed that the proposed controller could realise efficient control and successfully regulate the lime flow rate

ACKNOWLEDGMENT

The authors would like to thank the *Adam Machines Constructions Company*, in Volos, Greece, for providing access to the industrial platform for this research, as well as the Technological Educational Institute of Larissa, Greece, for providing access to its facilities.

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