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# Linear Control of Electro-hydraulic Injection Moulding Machine

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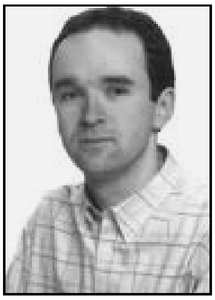
Absolwent (2000) Wydziału Mechatroniki Politechniki Warszawskiej. Do 2007 r. zatrudniony jako asystent w Zakładzie Urządzeń Wykonawczych Automatyki i Robotyki. W pracy naukowo-badawczej zajmuje się zagadnieniami algorytmów sterowania, budową i diagnostyką płynowych urządzeń wykonawczych.



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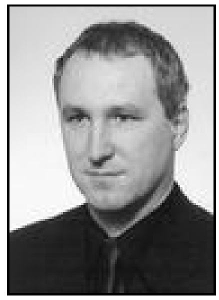
W działalności naukowej zajmuje się głównie modelowaniem dynamiki układów, sterowaniem zaawansowanym oraz optymalizacją wielokryterialną przy wykorzystaniu algorytmów inteligencji masowej. Jeden z twórców opracowywanych w instytucie pakietów: identyfikacji MITforRD oraz modelowania PExSim.



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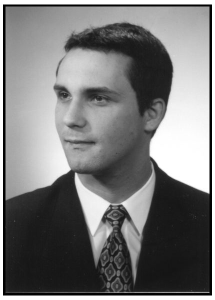

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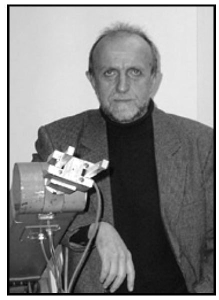

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**Abstract**

This paper presents the idea of a linear control strategy, simulation and experimental results represented by graphs. The results from the implementation of the proposed control algorithm with the use of a real machine are also shown.

**Keywords**: Electro-hydraulic control system, ICON-HISIM, Injection Machines.

## Sterowanie liniowe elektrohydraulicznego napędu maszyny wtryskowej

**Streszczenie**

W artykule przedstawiono: sposób działania liniowego algorytmu sterującego, wyniki symulacji i eksperymentów zostały przedstawione w postaci wykresów. Znajdują się tu również wyniki uzyskane w wyniki implementacji opracowanego algorytmu na rzeczywistej maszynie wtryskowej.

**Słowa kluczowe**: Elektrohydrauliczny układ sterowania, ICON-HISIM, maszyna wtryskowa.

## 1. Introduction

Modern hydraulic systems for High – Speed Injection Machines are based on servovalve – controlled electrohydraulic actuators, connected to a common pressure rail, with pressure kept at a fairly constant level. Such physical configuration of the machine and it's actuators leads to energy losses. Based on research results of project Brite/EuRam BE-97 5089, a new configuration of hydraulic system with a fixed – displacement hydraulic pump connected to electric servomotor was proposed. Such solution was not yet available on the market, and there is no standard in the control of these modules.

**I**ntelligent **Con**trols for **Hi**gh-**S**peed **I**njection **M**oulding Machines (ICON-HISIM) was an international project that started in October 2004 and finished in 2008. The consortium consists of 8 partners from 4 European countries. It includes 3 SMEs and 3 research institutes. The general objective of the package that was prepared by the Institute of Automatic Control and Robotic team was to develop an advanced control system for a clamping unit. The aims of the control were as follows: the lowest action time, real-time adaptation on the machine parameters changes, as well as the noise, power consumption and vibrations reduction.

## 2. Model of Clamping Unit of the Injection Machine

Model of a clamping unit of the injection machine was created by *Institut für Fluidtechnik* TU Dresden (TUD). ITI SimulationX was used for this assignment. Mechanic diagram of this part of the machine is shown in the Fig. 1.

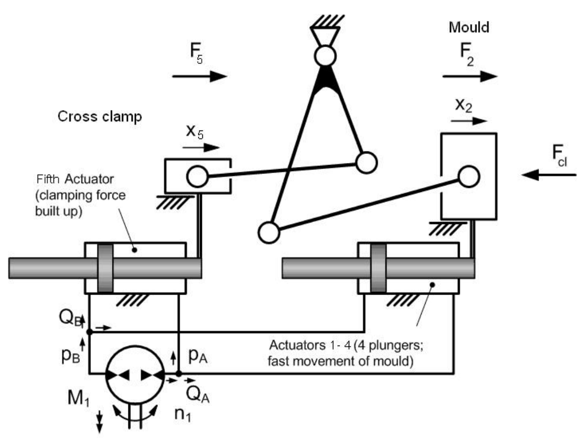



Fig. 1. Diagram of the clamping unit of the injection machine
Rys. 1. Schemat mechanizmu zamykającego formę maszyny wtryskowej

It has parallel with the model which is shown in the Fig. 2. There are three sections in this model:

- Clamping unit,
- Electrical motor and
- Controller.

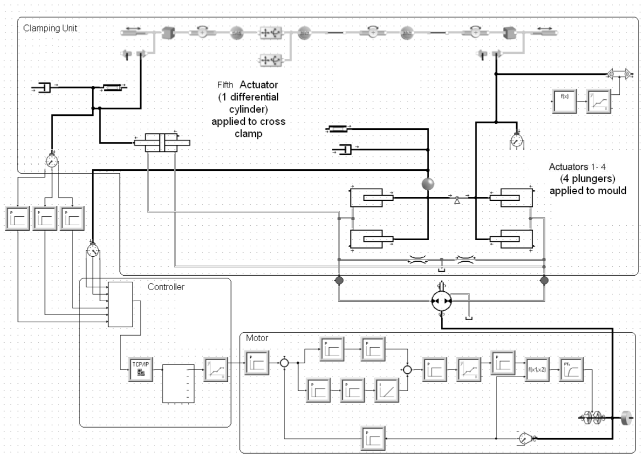



Fig. 2. Model of clamping unit of injection machine in ITI SimulationX
Rys. 2. Model mechanizmu zamykającego formę maszyny wtryskowej (w oprogramowaniu ITI SimulationX)

## 3. Linear Control Strategy for Clamping Unit

Because the new type of clamping unit has a strong nonlinearity (Fig. 3.), especially in the last phase of the movement (closing) and the gains in the system are changing about 1000 times, we can suspect that the classic linear approach will not work correctly in such a system.

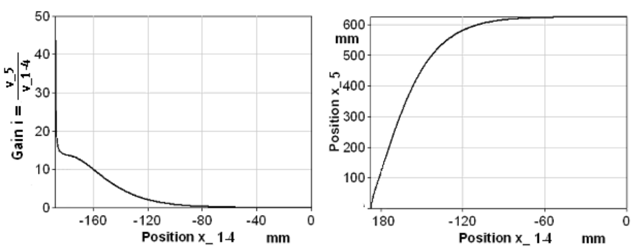



Fig. 3. Relationship between movement of closing pistons x_1-4 and locking piston x_5
Rys. 3. Zależność pomiędzy przemieszczeniami siłowników zamykających x_1_4 I siłownikiem blokującym x_5

**Conception and implementation**

That's why we have proposed the linear controller consisting of two parts:

- Partially open-loop control,
- State space controller (with modifications) for the final movement.

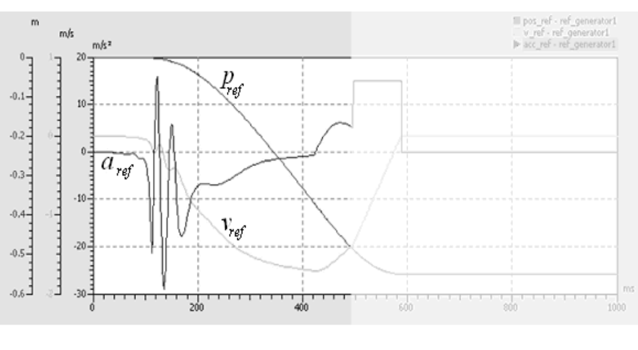



Fig. 4. First phase of control – move with the maximal speed
Rys. 4. Pierwsza faza sterowania – ruch z maksymalną prędkością

At the beginning of each phase (opening and closing form) the controller sets the CV (control value) – speed of clumping unit to the maximum possible value – the machine moves as fast as it can. It sets the maximum possible velocity for the motor/pump unit.

During this fast phase it is necessary to observe the position and keep the pump velocity with reasonable limits to fulfill limitations on the pressure and acceleration values. If the current position is close enough to the final position, the state-space controller should start to brake the form. That means the control will turn on the state space controller. This phase is denoted with weak contours in the above picture.

"Close enough" means that the following relation is true

$$p_{final} - p_{current} < \frac{v_{current}^2}{2*a} \quad (1)$$

where:

$p_{final}$ - final position,
$p_{current}$ - instant position currently measured, close to the braking phase,
$v_{current}$ - instant velocity currently measured,
$a$ - acceptable deceleration

During this phase of control, the State Space Controller (SSC) generates three reference signals: position, velocity and acceleration.

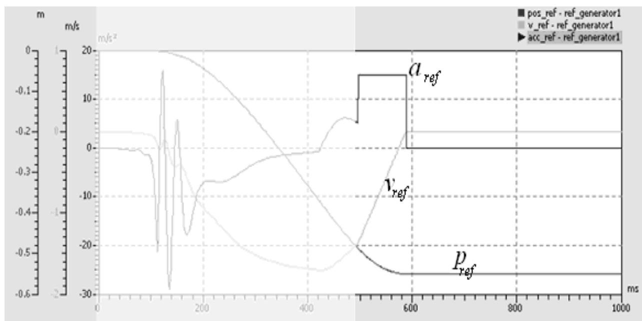



Fig. 5. Second phase of control – move with an acceptable deceleration
Rys. 5. Druga faza sterowania – ruch z dopuszczalnym opóźnieniem

The controller keeps the acceleration reference constant up to the final position.

The state space controller needs to have a feedback from the position, velocity and acceleration.

Because the system may be not asymptotically stable, there was a need to compensate this – an additional component to the control value was added. It was based on an assumption that the velocity of the form is proportional to the velocity of the pump.

The final form of the space state controller was:

$$cv = k_{shift} + k_{ref} v_{ref} + k_p\left(p_{curr} - p_{ref}\right) + k_v\left(v_{curr} - v_{ref}\right) + k_a\left(a_{curr} - a_{ref}\right) \quad (2)$$

where:

$cv$ - the controller output for the motor rotational speed and hydraulic pomp,
$k_{shift}$ - shift parameters of the control value
$k_{ref}$ - reference velocity coefficient
$k_p$, $k_v$, $k_a$ - position / velocity / acceleration - gain coefficients,
$p_{ref}$, $v_{ref}$, $a_{ref}$ - reference values of position / velocity / acceleration,
$p_{curr}$, $v_{curr}$, $a_{curr}$ - measured values of position / velocity / acceleration.

The following picture shows the interface of the controller program. It allows us to modify all parameters of the controller. The controller has different parameters for each phase of the clamping cycle (opening and closing).

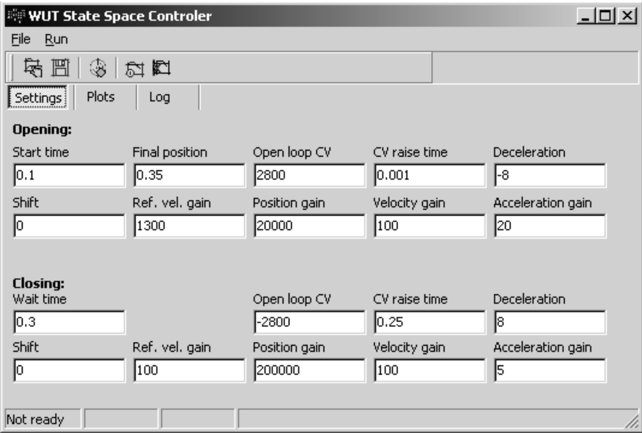



Fig. 6. Interface of the controller program
Rys. 6. Interfejs programu sterującego

**Opening:**

*Start time* – delay of the move start [s],
*Final position* – stroke of mould and plunger cylinders 1-4 at the opening [m],
*Open loop CV* – maximal velocity of the motor-pomp set [rpm],
*CV raise time* – interval for the speed increase [s],
*Deceleration* – maximal deceleration of the mould during the opening (final phase) [m/s$^2$],
*Shift* – shift parameters of the control value $k_{shift}$ (equation 2) [rpm],
*Ref. vel. gain* – velocity coefficient $k_{ref}$ (equation 2) [1],
*Position gain* – $k_p$ (equation 2) [1/s],
*Velocity gain* – $k_v$ (equation 2) [1],
*Acceleration gain* – $k_a$ (equation 2) [s],

**Closing:**

*Wait time* – delay of the move start [s]
*Open loop CV* – maximal velocity of the motor-pomp set [rpm],
*CV raise time* – interval for the speed increase [s],
*Deceleration* – maximal deceleration of the mould during the opening (final phase) [m/s$^2$],
*Shift* – shift parameters of the control value $k_{shift}$ (equation 2) [rpm],
*Ref. vel. gain* – velocity coefficient $k_{ref}$ (equation 2) [1],
*Position gain* – $k_p$ (equation 2) [1/s],
*Velocity gain* – $k_v$ (equation 2) [1],
*Acceleration gain* – $k_a$ (equation 2) [s],

These parameters are also described in the following diagrams, Figs. 7 and 8.

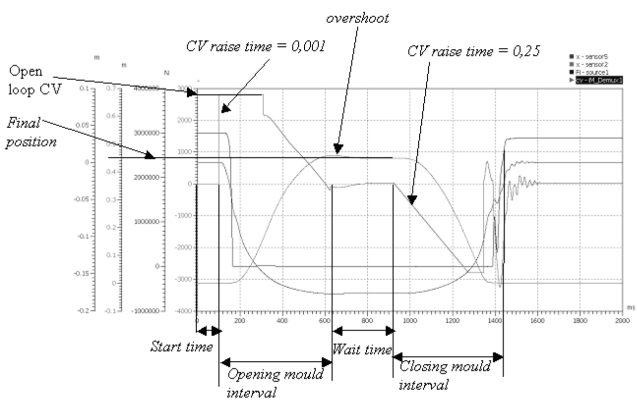



Fig. 7. Position of piston 5 (red), position of the form (green), clamping force (blue), CV - speed value (grey)
Rys. 7. Położenie siłownika 5 (czerwony), położenie formy (zielony), siła zamknięcia (niebieski), wartość prędkości (szary)

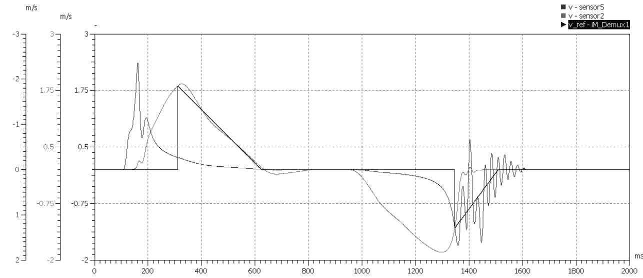


Fig. 8. Velocity of piston 5 – *sensor 5*(red), velocity of the form – *sensor 2* (green), reference velocity for control - from controller (blue)
Rys. 8. Prędkość siłownika 5 –sensor 5 (czerwony). prędkość formy – sensor 2 (zielony), sygnał prędkości zadanej ze sterownika niebieski)

During the mould opening, the controller sets the velocity (and position) of the mould *sensor_2* – pistons 1-4. During the closing, the velocity (and position) of the fifth piston are controlled.

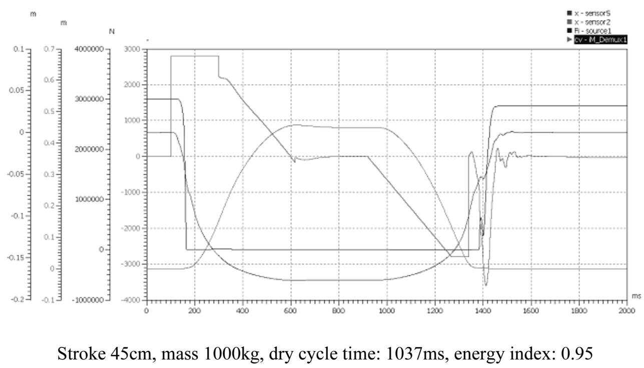
## 4. Simulation Test Results

Following diagrams for the mould control were obtained for different mould masses and strokes. The Figures present basic values: position of piston 5 (sensor 5), position of the mould (sensor 2), Clamping force (Fi source) and the control value. All transients were obtained for the same controller parameters.

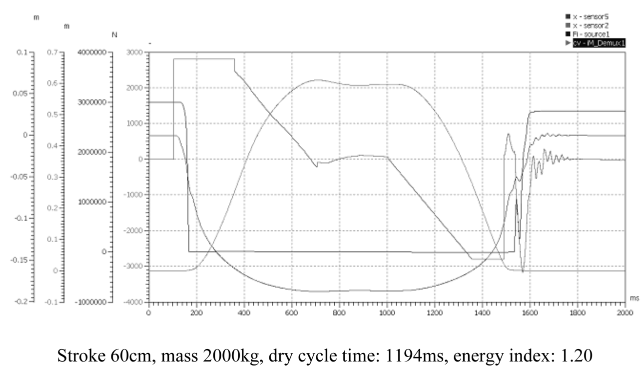
For better visualization, values of sensor 5 are presented with a reversed sign. A dry cycle time was determined as the control interval with subtraction of a quiet phase time (in the middle of each plot), and given in seconds at the bottom of each picture. Moreover, there a factor called the energy index is presented (3), that was used for comparison of the energy consumption in each cycle (with the constant value of $k_1 = 10{\cdot}e^6$) where $T$ (at the closing of the form) was determined as a time of the clamping force reaching 90% of required of its maximum value).

$$E_1 = \frac{\int_0^T M \cdot \omega \cdot dt}{k_1} \tag{3}$$

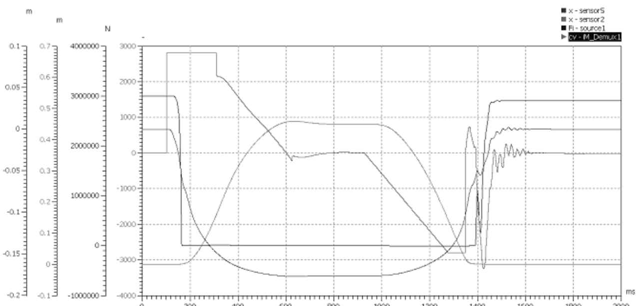
where: $M$ – is the torque, $\omega$ - is the rotation speed.



Stroke 45cm, mass 1000kg, dry cycle time: 1037ms, energy index: 0.95



Stroke 60cm, mass 2000kg, dry cycle time: 1194ms, energy index: 1.20



Stroke 45cm, mass 2000kg, friction +30%, dry cycle time: 1048ms, energy index: 1.10

For better comparison of the control effects, some indices were calculated and presented in the plots, that integrate control quality in each case. Tab.1 contains these indices taken from the above-shown diagrams.

The *dry cycle time* is the necessary time for opening and closing (see Fig. 7.).

*Velocity of the plunger actuators* is the velocity of the form at the moment when the clamping force reaches 90% of its maximum value.

*Maximum position of the form* is the position that is reached during the opening of the form (usually it has some overshoot).

*Energy index* was already defined above.

Measurements of the dry cycle time, deviation of the plunger actuators / form position, velocity of the plunger actuators / form and energy index were calculated until the moment when the clamping force reaches 90% of its rated value.

The control system operates properly for different position jumps and for different masses of the form, see Table 1. The quality of the form positioning during the closing was quite good and independent on the stroke, mass of the form and even the friction force.

During the form opening, some overshoot was observed (6 to 13 mm). This overshoot depends on the mass (a bigger mass has induced a bigger overshoot), and on the friction force (a bigger friction has induced a smaller overshoot).

Tab. 1. Combination of different strokes, mass of the form, and friction coefficients
Tab. 1. Kombinacja różnych wartości skoku, masy formy i współczynnika tarcia

| Calculated parameters | dry cycle time | velocity of plunger actuators | maximum position of form | Energy index |
|---|---|---|---|---|
| stroke, mass, shift of friction | [ms] | [m/s] | [cm] | [ ] |
| 30cm, 2000kg | 891 | -0.016 | 30.79 | 0.90 |
| 45cm, 2000kg | 1045 | -0.014 | 45.92 | 1.09 |
| 60cm, 2000kg | 1194 | -0.010 | 60.99 | 1.20 |
| 45cm, 1000kg | 1037 | -0.011 | 45.70 | 0.95 |
| 45cm, 3000kg | 1067 | -0.013 | 46.14 | 1.24 |
| 45cm, 2000kg, friction -30% | 1051 | -0.017 | 45.86 | 1.10 |
| 45cm, 2000kg, friction +30% | 1048 | -0.016 | 45.92 | 1.10 |

## 5. Experimental Results

The simplest way to test the algorithm on a real machine, was to use a machine owned by TU Dresden – one of the ICON project partners. Thanks to this co-operation, tests of control algorithms were implemented on a machine similar to the prototype. Investigated machine consisted of: constant displacement pump driven by an asynchronous electric motor, hydraulic actuator (differential cylinder), toggle mechanism and mould (Fig. 9). The algorithms were implemented in the real time processor card DS1104.

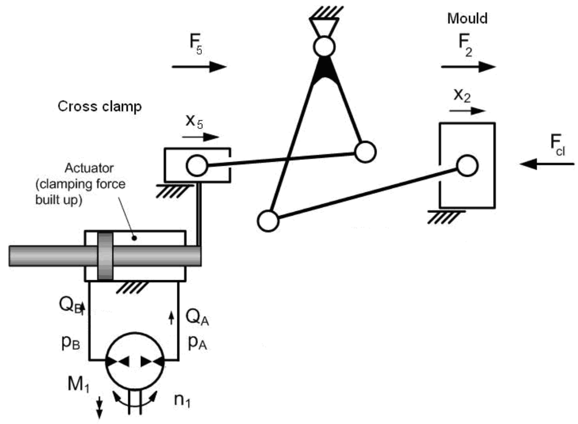
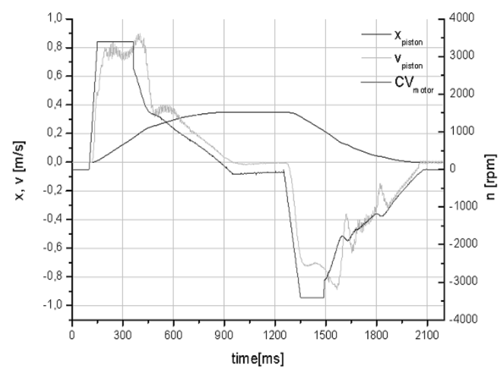



Fig. 9. Diagram of the clamping unit of the tested injection machine
Rys. 9. Schemat mechanizmu zamykającego formę testowanej maszyny wtryskowej

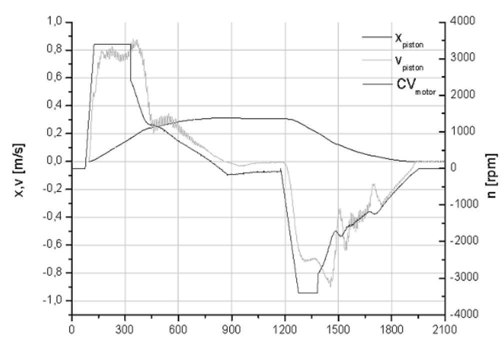
Following measurements were made with the use of a linear controller with a constant parameters algorithm parameters (as in the simulation tests), for the following displacements: 25, 30 and 35 cm.

During the investigation with the use of a real machine, a proper work (smooth and precise) of designed algorithms was proved. The dry cycle time was min. 5% shorter than the one implemented in the previous version (state space control), with less energy consumption.

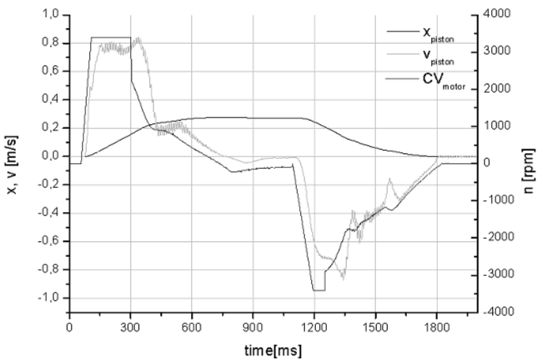
Presented results were achieved after a very short start-up time, thanks to the applied fast prototyping technique. Prepared models (using Simulation X and MatLab) were precise enough to investigate and calibrate designed algorithms before their implementation with the use of a real machine.




Stroke: 35cm, dry cycle time: 1684ms, overshoot (opening) 8 mm




Stroke: 30cm, dry cycle time: 1571ms, overshoot (opening) 10 mm




Stroke: 25 cm, dry cycle time: 2720ms, overshoot (opening) 25 mm

In general, the control algorithm works properly for different strokes of a mould. Quality of positioning of the form during the closing and opening cycle is good (see Table 2).

Tab. 2. Comparison of different strokes
Tab. 2. Porównanie parametrów pracy dla różnych skoków

| Stroke | Dry cycle time | Overshoot |
|---|---|---|
| [cm] | [ms] | [mm] |
| 25 | 1471 | 25 |
| 30 | 1571 | 10 |
| 35 | 1684 | 8 |

During opening of the form, some overshoot was observed (2 to 25 mm).

Increasing mould stroke resulted in increasing a dry cycle time – and reducing a specific dry cycle time (dry cycle time divided by the mould stroke).

## 6. Summary

A general objective for the above described project was to develop an advanced, linear control algorithms for a clamping unit. The aims of the control were: dry cycle time had to be as short as possible, real-time adaptation to the machine parameters changes was expected, and the noise, power consumption and vibrations had to be reduced.

To achieve the aims, fast – prototyping technique was applied. The first mathematical models of the investigated prototype were prepared (by TU Dresden team). Then these models were used as a basis for the design and tests of control algorithms. At last, the developed algorithms were implemented in a real time processor card DS1104 so as to control the real machine.

Developed algorithms were precisely described and implemented in C++ code with clear and ready to use (ready to load into an industrial controller) operator's interfaces. Both: simulation and real tests were conducted.

*Artykuł recenzowany*