Journal of Machine
Construction
and Maintenance
PROBLEMY EKSPLOATACJI
QUARTERLY
ISSN 1232-9312 3/2017 (106)

p. 67–73

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A CONTROL SYSTEM FOR STAND FOR MEASURING THE BURN RATE OF SOLID ROCKET PROPELLANTS USING CRAWFORD'S METHOD

Key words: propellant burn rate, Crawford burner, measurement automation, hierarchical control system.

Abstract: Measuring the burning rate for solid rocket propellants by using resistor wires threaded through the sample enclosed in a high pressure chamber, called the Crawford bomb, is the oldest method of measuring this important fuel parameter. Many measuring stands that use the Crawford method do not meet standards of modern automation solutions. The control system for the stand described in this paper eliminates the disadvantages of the existing designs and facilitates their upgrade. The presented model of a pressure stand provides a way to design a correct controller and to conduct its simulation research. The hierarchical structure of the system ensuring, e.g., the recording and analysis of the measurement data, improves research quality. The upgrade can be carried out without changing the essential elements of the stand.

System sterowania stanowiskiem do pomiarów szybkości spalania stałych paliw rakietowych metodą Crawforda

Słowa kluczowe: szybkość spalania paliw rakietowych, bomba Crawforda, automatyzacja pomiarów, hierarchiczny system sterowania.

Streszczenie: Pomiar szybkości spalania stałych paliw rakietowych przy użyciu drutów oporowych przewleczonych przez próbkę zamkniętą w komorze wysokociśnieniowej, zwaną bombą Crawforda, jest najstarszą metodą pomiaru tego istnego parametru paliwa. Wiele stanowisk pomiarowych realizujących metodę Crawforda nie odpowiada poziomowi współczesnych rozwiązań automatyki. Opisany w artykule system sterowania stanowiskiem eliminuje wady istniejących konstrukcji i umożliwia przeprowadzenie ich modernizacji. Przedstawiony model instalacji ciśnieniowej stanowiska umożliwia zaprojektowanie właściwego regulatora i przeprowadzenie jego badań symulacyjnych. Zastosowana hierarchiczna struktura systemu, zapewniająca m.in. zapis i analizę danych pomiarowych, podnosi jakość prowadzonych prac. Modernizacja może być przeprowadzona bez zmiany zasadniczych elementów wykonawczych stanowiska.

Introduction

The burn rate is one of the basic parameters characterizing propellants. Measuring this value for solid fuels can be performed by three basic methods, using sealed pressure chambers called Crawford burners, small scale rocket engines, or the actual engines equipped with appropriate measuring devices [1, 2, 3, 4].

For sealed pressure chambers, also known as Crawford bombs, the burn rate can be measured by several methods, using, e.g., pressure increase during burning, ultrasonic techniques, microwave techniques, x-rays, changing the sample capacity, or optical techniques [5]. The oldest method, described in the MIL-STD-286C standard [6], consists in measuring the time between the burning through of the wires threaded through the propellant sample. The sample is placed in a cylindrical chamber filled with nitrogen and in controlled conditions of pressure and temperature, while its ignition is electrically initiated. The sample has an elongated shape and is covered with a combustion inhibitor, so that burning runs along the sample at the surface of its head.

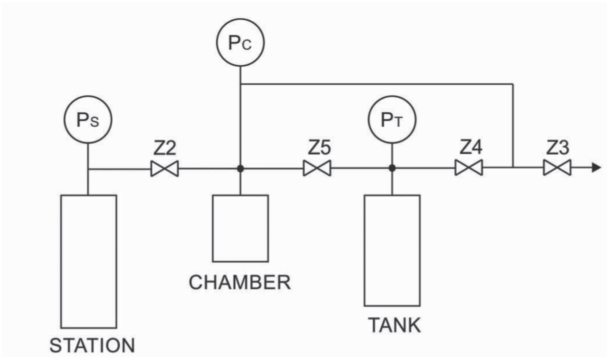

Fig. 1. A schematic diagram of the pressure system in a Crawford burner stand STATION – nitrogen tank, CHAMBER – Crawford bomb with a filter for combustion products, TANK – a tank for pressure increase compensation during propellant burning

In a typical measuring stand, the measuring of burning time is performed for various values of pressure, and is determined using 4 high pressure valves (Fig. 1). The source of pressure is a station with nitrogen bottles (*STATION*) with a P_s pressure of up to 20 MPa. The opening of the *Z2, Z5,* and *Z4* valves, while *Z3* is closed, results in the bomb with the filter system (*CHAMBER*) being filled. The *TANK* container acts as a battery for pressure increase, which occurs during the burning of the test material.

The method was developed by Crawford in 1947 [7], and since then many measuring stands with varying degrees of automation have been developed. Continuous development of engineering control systems and industrial automation provides for their modernisation and elimination of common defects, such as the following:

– Low quality pressure regulation, reflected in the extended time necessary to obtain a given value, high overshoots, high process gas consumption;
– Low accuracy in pressure measurements in all measuring points of the stand's pressure system;
– A lack of a suitable visualization for the operator of the time measured between moments of burning through of the measuring wires that were threaded through the propellant sample; and,
– The inability to record measured parameters.

The most important problems in the development of a new control system for the stand are related to the following:

– The need to regulate pressure using on-off valves with long time action delays;
– Pressure adjustment with the possibility of leaks and various degrees of filter contamination built into the installation, which changes the parameters of the object adjustment; and,
– Fluctuations in the supply of pressure (P_s).

The classic solution for gas pressure regulation is the use of a proportional valve. This solution, used in particular in pneumatic positioning systems, deals well with adjustable pressure, for example, through the use of a Linear-Quadratic-Gaussian (LQG) regulator [8], but its disadvantage is high cost of the valve [9]. The cheaper hardware solutions with on-off valves use neural networks [9] or sliding mode regulators [10, 11]. The actuators of these regulators are various types of pneumatic valves operating at pressures typical for pneumatic systems - up to about 0.7 MPa. The stand for measuring the burning rate of solid rocket propellants is supplied with the pressure of 20 MPa, and for these values and in chemically aggressive environments, high pressure valves are used, controlled by a pneumat-ic system, consisting of a low pressure diaphragm element and a high pressure valve. The valve's operating frequency is low, and action delay is about 150 ms (valves 20-12LF4, Hipco).

The Crawford bomb is closed on both sides with threaded covers with sealing polymer O-rings. The gases formed in the combustion process contain corrosive vapours that damage the seals. In addition, the seals are usually loosely fitted to make it easier for the operator to place samples inside the bomb. Valves and pressure sensors are protected against the undesirable effects of propellant combustion products, by ceramic filters, which, as a result of subsequent measurements, become contaminated and produce changes in the operating conditions of the pressure regulator.

The pressure system of the developed stand has an input gas storage tank (typically 99.9% nitrogen) and a compressor with a regulator that provides a constant pressure at the inlet to the system. The simplified version of the stand (Fig. 1) does not have a compressor. The system is powered by one or more industrial bottles, where the pressure can drop significantly during the subsequent measurements.

1. The block structure of the control system

The control system structure is a typical multilayer configuration (also called hierarchical) [12] (Fig. 2). The test ring is controlled by means of Programmable Logic Controller (PLC) type TM241CE40R manufactured by Schneider Electric company.

The pressure regulators implemented in the process receive processed (filtered, calibrated, transformed into electric current form) pressure measurement signals in the station system. The measurements are encoded and transmitted by means of 4–20 mA DC current loops. standards. For measuring P_S, P_C, and P_T pressures, the PAS-GEE6S4NS00 (Kobold) sensors were used with accuracy of ± 0.075% and a measuring range of 25 MPa. The other input and output signals of the controller are binary and analogue too. Binary signals are assigned to binary sensors of the object (e.g., compressed air sensor, the status of measuring wires detector), and they control high pressure valves and the transformer of the ignition initiation system. The signals from K-type thermocouples designed to measure the temperature at two points of the installation.

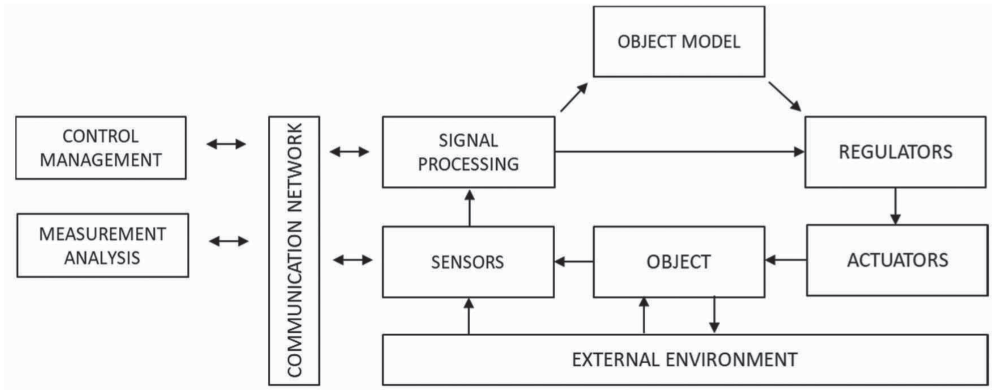

Fig. 2. The structure of the control system for a stand measuring the burn rate of solid rocket propellant

The controller is connected via an Ethernet network with a supervisor computer (type WLP-7920-15, Wincomm). It is a fanless PC with a touch screen as an operator panel. It can also be used to perform measurement data analysis; however, in order to improve the functionality of the stand, a separate computer is used for data analysis tasks. This provides for data analysis without blocking access to measuring tasks.

The structure of the system also reflects the main stages of system design, including the development, based on sensor signals, of an object model that allows the design of a pressure regulator in a stand system.

2. Pressure control system

2.1. A model of a pressure system for a measuring stand for burning rate of high energy materials

The pressure system model (Fig. 3) was developed using MATLAB with a Simscape add-on. The following containers: *Station*, *Chamber*, *Tank* are represented by the *Constant Volume Pneumatic Chamber* element of the program. It is described by the law of the conservation of mass:

$$G = \frac{V}{RT}\left(\frac{dp}{dt} - \frac{p}{T}\frac{dT}{dt}\right) \tag{1}$$

where G – is flow velocity at the tank inlet, V – tank volume, p – tank pressure, R – gas constant, T – tank gas temperature, t – time, and the law of conservation of energy:

$$q = \frac{C_v V}{R}\frac{dp}{dt} - q_w \tag{2}$$

where q – is heat flow due to gas entering the tank, q_w – heat flow through the tank walls, C_V – specific heat at constant volume. Connections between tanks are carried out by *Pipe* and *Orifice*. The *Pipe* element is also modelled using the *Constant Volume Pneumatic*

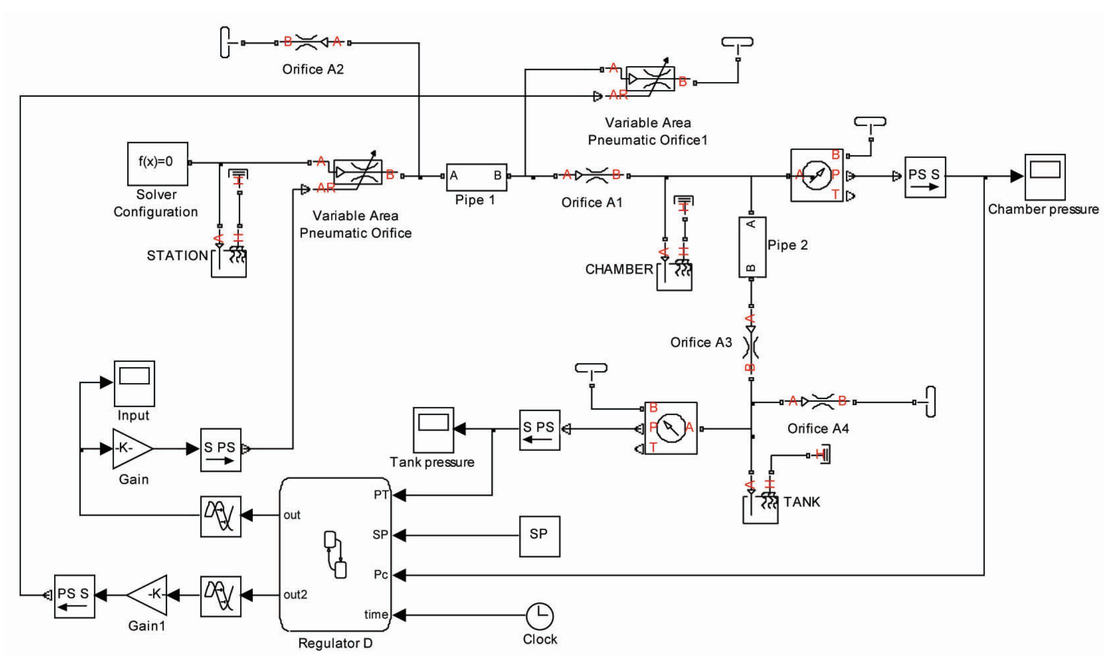

Fig. 3. A diagram of a pressurized stand system with the Crawford bomb

Chamber, supplemented by the convection heat transfer mechanisms between the gas in the pipe and its wall, and the pipe wall and it environment.

The leakage in the system is represented by the *Orifice A2*, and it is described by the following relation:

$$G = C_d\, A\, p_i \sqrt{\frac{2\gamma}{\gamma-1}\frac{1}{R\,T_i}\left[\left(\frac{p_0}{p_i}\right)^{\frac{2}{\gamma}} - \left(\frac{p_0}{p_i}\right)^{\frac{\gamma+1}{\gamma}}\right]} \qquad (3)$$

where G – is mass flow rate, C_d – expansion coefficient, A – the area of the cross-section, p_i, p_0 – inlet and outlet pressure, γ – the ratio of specific heat at constant pressure and specific heat at constant volume. The remaining *Orifice* narrowings are simulated by the filters protecting the system from contamination with combustion products.

3.2. Pressure regulator in the combustion chamber

Due to large delay of the pressure valves, the natural type of regulator is a binary controller with hysteresis. It is possible to use a regulator with feedback from state variables: P_C, P_T, or one that can be switched between them.

The regulator with feedback to the value of the P_C state variable requires a relatively long time to reach a repeatable phase of repeatable regulation in which the Z_2 valve is switched on at regular intervals (repeatable regulating). This is because of the (1) relationship, particularly for the considerable difference in capacity of the *Chamber* and *Tank* volumes and the conditions in which the *Tank* is emptied. The *Tank* is used for the accumulation of pressure increase that occurs during propellant burning. Its volume is over six times greater than the *Chamber*. As a result, for a controller with feedback from the $P_{C,}$ filling the small volume tank occurs with a significant outflow of gas into the high volume tank.

For a regulator with feedback to the value of the P_T state variable, the time to reach repeatable regulating phase becomes shorter; however, in its initial phase, there is a large distortion of overshoot for the P_C variable. Measurement of combustion is carried out in the repeatable control phase, and the operator wants to achieve the given P_C pressure value quickly. The initial overshoot does not introduce risks to the measurements.

In the target regulator – with switchable feedback – in the first phase of regulation, the feedback from P_T is used, and then, after the pressure has stabilized around the set value, the feedback is switched to the P_C variable (Fig. 4a). The regulator has an additional track, which includes *Orifice 1* valve that allows gas venting from the system. It is used when the system is fully sealed. After finding that there is no drop of pressure in P_C within a given time (up to 150 s, Fig. 4b), *Orifice 1* valve is open until reaching the P_r value = P_{CSP} *(1-k)*, where P_{CSP} is the required pressure and k is an experimentally selected coefficient.

Simulation test results also indicate that the controller is resistant to changes in leakage and filter throughput in the stand installation (Fig. 5).

Reducing leakage by half (by reducing the diameter of the *Orifice A2* and *Orifice A4*) extends the operation of the pressure regulator P_T and increases the P_C overshoot, which decreases with decreasing pressure of P_S. While increasing the leakage causes analogous changes of an opposite nature. The changes in the system leakage, and likewise in the throughput of the filters, do not interfere with the controller algorithm.

The regulator implemented in the PLC and tuned (in terms of the selection of time delays) has regulating accuracy at 0.1 MPa (Fig. 6). The required, normative

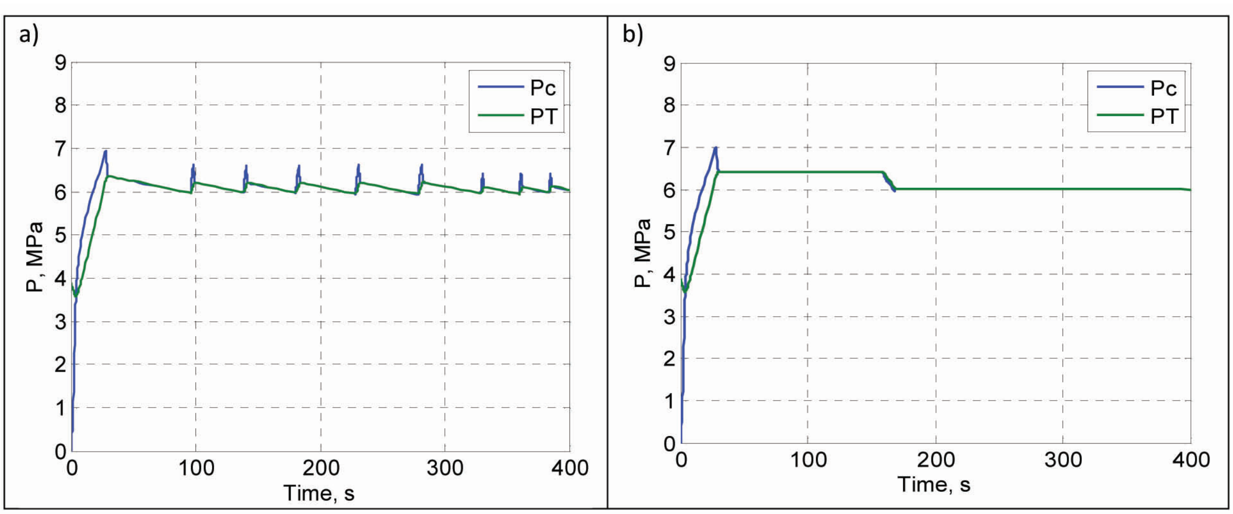

Fig. 4. The course for a regulator with switchover coupling, with a given leakage (a) and with no leakage (b). Initial conditions: PS = 20 MPa, PC = 0.1 MPa, PT = 4 MPa, PC SP = 6 MPa

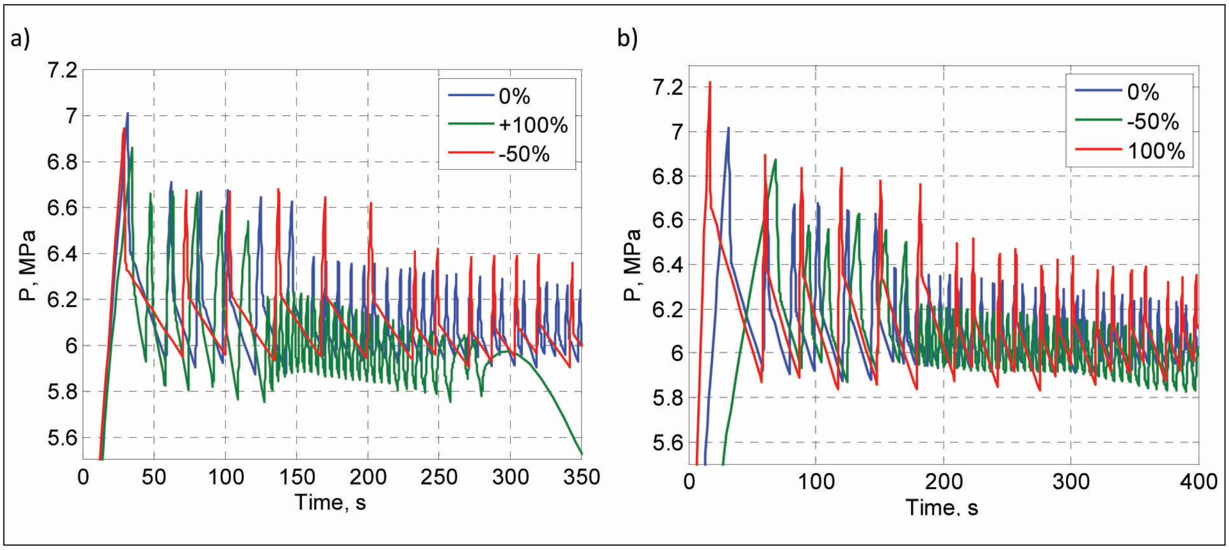

Fig. 5. The impact of the leakage (a) and filter throughput (b) on the controller action. Indications: 0% – nominal value, adopted after the verification of the model, +100% – double increase, and -50% – a reduction by half

accuracy (resolution) of pressure measurement is 10 psi (0.689 MPa) [6]. The differences between the simulated and real course result from the inaccuracies in the model. The simulation model is a structural model [13], which represents the phenomena occurring in the process, and not the quantitative relationships between the inputs and outputs of the process.

The model captures only the nature of the changes in the regulated pressure, which allow the evaluation of the behaviour of regulators that are constructed in different ways. An exact model of the system is difficult to develop because of the changeability of the parameters describing the condition of the filters and leakages in the system.

3. Supervisory control

Supervisory control is carried out by the central control computer software (Fig. 7). Functions of the program can be divided into four main groups: monitoring the process and the stand, measuring support, measurement data recording, and the analysis of the measurement data.

Monitoring the process and the stand consist in graphics (animations and graphs) and numerical imaging of the status of all controlled elements of the stand and the process variables. The user can also select the type of signal filtration of P_C pressure (Fig. 8a) that is a filter with a moving average (number of observations N = 40)

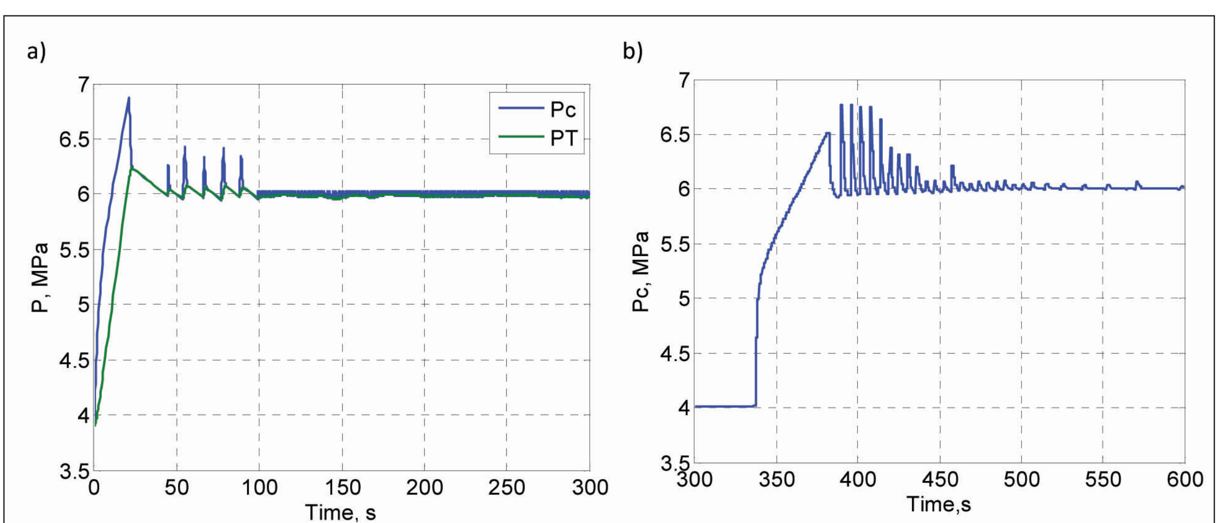

Fig. 6. The course of the pressure PC regulation for the model (a), and for a real system (b). Initial conditions: PS = 20 MPa, PC = 0.1 MPa, PT = 4 MPa, PC SP = 6 MPa

Fig. 7. The view of the operator panel (a) and the stand construction (b) for measuring burning rate for solid rocket propellants

or a low-pass filter (a filter with Butterworth topology and frequency limit 0.03 Hz).

An additional monitoring element is the status window and the valve control window (Fig. 8b) used mainly for maintenance purposes. It allows manual enabling and disabling of the valve while viewing pressures in the stand.

Measurement control allows an automatically performed measurement procedure including the verification of the performance conditions including safety conditions.

The recorded measurement data allows generating a report from a single measurement. The data in the report form is placed automatically. The user can optionally place their own description of the sample (Fig. 8c). An analysis of the measurement data consists in comparing previously recorded measurements performed at different P_C pressures. The results of single measurements are saved in an MS Excel spread sheet (Fig. 8d). The *.xlsx file generated in the supervisor computer can be stored directly in the data analysis computer. The prepared spread sheet template allows the user to add or delete selected graph points.

As a result, information is obtained about the possible need to repeat or supplement measurements for specific P_C pressure values. This also makes it easier to describe the burn rate relationship with the following equation:

$$r = aP_c^n \qquad (4)$$

where r – is burning rate, a – empirical constant, temperature coefficient, P_c – chamber pressure, n – burn index (Fig. 8d).

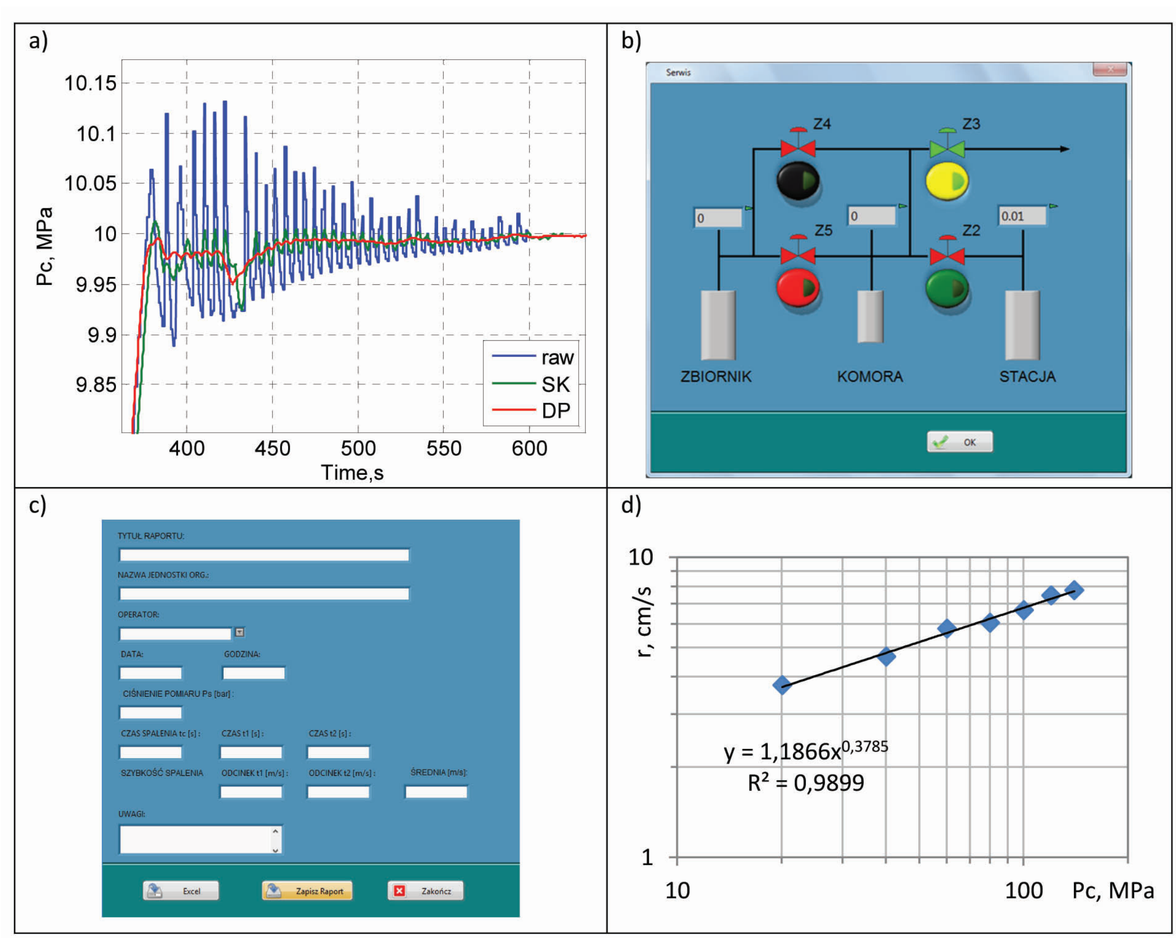

Fig. 8. A diagram for PC signal filters: raw – non-filtered signal, SK – filter with rolling average, DP – low-pass filter (a), status window and valve control system (b), report generation window for combustion rate measurements (c), sample graph for measurement results in MS Excel template (d)

For several measurements of burn rate recorded for the same pressure, the user may enter the average of these measurements in the graph.

Conclusions

The presented control system for a stand for measuring the burning rate of solid rocket propellant eliminates the typical weakness of many devices built in the past, and it enables them to be upgraded. The developed model of pressure station for the stand allows for the selection and validation of the pressure regulator inside the measuring chamber characterized by sufficient accuracy, while maintaining conditions of rapid attainment of a given value and low consumption of gas filling the chamber. The performed simulated tests confirmed the robustness of the regulator to the changes in the parameters of the installation of the stand. This facilitates performing both accurate measurements in quality control as well as in quick, engineering measurements for evaluating and designing new rocket propellant materials.

The use of the hierarchical architecture of the control system greatly facilitates the operation of the stand, mainly through clear visualization of the measurement course, the presentation of their results, and the separation of the supervisory section of the control system and the section that performs the measurement data analysis. The use of Ethernet connections in the control system makes an easy further integration with external systems, including, for example, laboratories management systems.

References

1. Sutton G.P., Biblarz O.: Rocket Propulsion Elements. 7th ed., John Wiley & Sons, New York 2001, pp. 419-473; ISBN 0-471-32642-9.
2. Bajkowski J., Szlitkus P., Wolszakiewicz T., Zalewski R.: Modelowanie i badania właściwości stałych paliw rakietowych. IPBM PW, ITeE – PIB, Warszawa – Radom 2012, pp. 203-218, ISBN 978-83-7789-090-5.
3. Wolszakiewicz T.: Badania balistyczne i wytrzymałościowe stałych paliw rakietowych w aspekcie prawidłowości ich zapłonu oraz możliwości wystąpienia sytuacji awaryjnych pracy silników rakietowych. Instytut Przemysłu Organicznego, Warszawa, 2013, pp. 9–34, ISBN 978-83-914922-2-2.
4. Atwood A.I., Ford K.P., Wheeler C.J.: High-pressure burning rate studies of solid rocket propellants. Progress in Propulsion Physics, 2013, 4, pp. 3–14.
5. Gupta G., Jawale L., Mehilal, Bhattacharya B.: Various Methods for the Determination of the Burning Rates of Solid Propellants – An Overview. Cent. Eur. J. Energ. Mater. 2015, 12 (3): 593–620.
6. Military Standard. Propellants, Solid: Sampling, Examination and Testing. MIL-STD-286C w/ CHANGE 2, 2010.
7. Crawford B.L., Hugget C., Daniels F., Wilfong R.E.: Direct Determination of Burning Rates of Propellant Powders. Anal. Chem. 1947, 19 (19): 630–633.
8. Wang X.-S., Cheng Y.-H., Peng, G.-Z.: Modeling and Self-Tuning Pressure Regulator Design for Pneumatic-Pressure–Load Systems. Control Engineering Practice. 2007, 15: 1161–1168.
9. Ahn K., Yokota S.: Intelligent Switching Control of Pneumatic Actuator Using On/O Solenoid Valves. Mechatronics. 2005, 15: 683–702.
10. Gulati N., Barth E.J.: Pressure Observer Based Servo Control of Pneumatic Actuators. Proceedings of the 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, 2005.
11. Shen X., Zhang J., Barth E.J., Goldfarb M.: Nonlinear Model-Based Control of Pulse Width Modulated Pneumatic Servo System. Journal of Dynamic Systems, Measurement, and Control. 2006, vol. 128: 663–669.
12. Samad T., McLaughlin P., Lu J.: System architecture for process automation: Review and trends. Journal of Process Control. 2007, 17: 191–201.
13. Grega W.: Metody i algorytmy sterowania cyfrowego w układach scentralizowanych i rozproszonych. Wydawnictwa AGH, Kraków 2004, pp. 168–216, ISBN 83-89388-78-2.