MEDIÇÃO DE TEMPERATURA NOS PONTOS CRÍTICOS DA TRANSMISSÃO ELETRO-HIDRÁULICA DE MODO DUPLO COM O CONTROLE DE VELOCIDADE COMBINADO

TEMPERATURE MEASUREMENTS AT CRITICAL POINTS OF DUAL-MODE ELECTRO-HYDRAULIC ACTUATOR WITH COMBINED RATE CONTROL

ИЗМЕРЕНИЕ ТЕМПЕРАТУРЫ В КРИТИЧЕСКИХ ТОЧКАХ ДВУХРЕЖИМНОГО ЭЛЕКТРОГИДРАВЛИЧЕСКОГО ПРИВОДА С КОМБИНИРОВАННЫМ РЕГУЛИРОВАНИЕМ СКОРОСТИ

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Received 06 June 2018; received in revised form 15 November 2018; accepted 04 December 2018

RESUMO

A transmissão eletro-hidráulica de modo duplo com o controle de velocidade combinado é projetada para controlar as superfícies de controle da aeronave com um alto nível de eletrificação dos sistemas de bordo. Tal transmissão é capaz de funcionar tanto a partir do sistema hidráulico centralizado a bordo quanto do sistema elétrico de potência da aeronave. O artigo discute a determinação experimental de temperatura em pontos críticos de uma transmissão eletro-hidráulica de modo duplo com o controle de velocidade combinado ao operar sob carga para vários modos de controle da transmissão. Foi estabelecido que a transmissão com controle de velocidade combinado possui alta eficiência energética, enquanto suas características dinâmicas na região de pequenas amplitudes de deslocamento do link de saída são próximas àquelas de transmissões com controle de estrangulamento de velocidade.

Palavras-chave: *transmissão eletro-hidráulica, controle de velocidade combinado, características dinâmicas, energia térmica.*

ABSTRACT

Dual-mode electro-hydraulic actuator with combined rate control is designed to control the steering surfaces of the aircraft with an increased level of electrification of onboard systems (More Electric Aircraft). This actuator is able to operate from the onboard centralized hydraulic system, and from the electrical power system of the aircraft. The paper deals with the experimental determination of temperature at critical points of a dual-mode electrohydraulic actuator with combined rate control when it is operating under load for different control modes. It is found that the actuator with combined rate control has a high energy efficiency, while its dynamic characteristics in the area of small amplitudes of the output link movement are close to the characteristics of actuators with servovalve speed control.

Keywords: *electro-hydraulic actuator, combined rate control, dynamic performances, thermal energy.*

DOI: 10.52571/PTQ.SI1.2018.407_PeriodicoES.pdf

АННОТАЦИЯ

Двухрежимный электрогидравлический рулевой привод с комбинированным регулированием скорости предназначен для управления рулевыми поверхностями самолёта с повышенным уровнем электрификации бортовых систем. Такой привод способен работать как от бортовой централизованной гидросистемы, так и от силовой электросистемы самолёта. В работе рассматривается экспериментальное определение температуры в критических точках двухрежимного электрогидравлического привода с комбинированным контролем скорости при работе под нагрузкой для различных режимов управления приводом. Установлено, что привод с комбинированным регулированием скорости обладает высокой энергетической эффективностью, при этом его динамические характеристики в области малых амплитуд перемещения выходного звена близки к характеристикам приводов с дроссельным регулированием скорости.

Ключевые слова: *электрогидравлический привод, комбинированное регулирование скорости, динамические характеристики, тепловая энергия.*

INTRODUCTION

Dual-mode electro-hydraulic actuators (hereinafter referred to DEHAs) are playing an increasingly pivotal role in the promotion of the "more electric aircraft" concept (Alekseenkov, 2014; Redko *et al.*; Bildstein, 2002; Van Den Bossche, 2006; Evolution of Powered…, 2012). Dual-mode actuators can operate the aircraft control surfaces, while being powered both by onboard centralized hydraulic system and by the electrical power system. From the point of construction view, a distinctive features of DEHA are in using of a single hydraulic cylinder and an built-in autonomous (i.e. independent from the centralized hydraulic system (Gamynin, 2012; Aleksenkov *et al.*, 2011; Redko and Selivanov, 2005)) hydraulic power source that consists of an electric motor with power and control unit, hydraulic pump, a hydraulic accumulator, and other hydraulic components (Le Tron, 2007; Mare and Fu, 2017). The inclusion of a local autonomous power source into the construction of a DEHA means that the efficient dissipation of thermal energy and the overall energy efficiency of the actuator are as topical an issues as the requirements to the provision of high performance quality in question (Ermakov *et al.*, 2005).

In terms of design solutions and control algorithms there is a number of essential differences between DEHAs that were manufactured in Russia and those produced abroad, e.g. Liebherr's EBHA (Bildstein, 2012; Van Den Bossche, 2006). Those differences are described in (Selivanov, 2011; Selivanov, 2010). It is worth noticing that open-access sources contain no publications that allows to made an assessment of the power efficiency of EBHA, however, the implementation of DEHAs onboard of the Airbus A-380 (Goodrich, 2008; Van Den Bossche, 2001) may indicate that such research were done (Alekseenkov, 2014; Rongjie *et al.*, 2009).

This article presents the results of the experimental research of a Russian-made DEHA with Combined Rate Control (Alekseenkov, 2014; Khomutov, 2008; Selivanov *et al.*). The main aim of the research was in optimization and estimation the modified control algorithms of a DEHA with Combined Rate Control (hereinafter referred to as DEHA-CRC (Redko *et al.*)), and the detection of critical temperature points of the actuator in terms of their heating.

MATERIALS AND METHODS

The subject of the tests, as was said previously, was the prototype of DEHA-CRC that was named “DRP-1”. A prototype of DEHA-CRC (Ogoltsov, 2014) (including the actuator configuration, its circuits, functional mechanization, and control algorithms) were designed by the Department 702 team of Moscow Aviation Institute under the supervision of A. M. Selivanov and manufactured by Rassvet Moscow Machine-Building Plant as a part of cooperation between State Research Institute of Aviation Systems (GosNII AS) and MAI.

The main aim of creation of “DRP-1” was the cutting-edge research into dual-mode electro-hydraulic actuators with combined rate control, the optimization of the control laws and pinpointing its dynamic characteristics. Those fact was substantially determined the appearance of the "DRP-1": the actuator contains non specialized hydraulic components, besides, the original design did not involve heat extraction from assemblies and units.

Please refer to Figure 1 below to see a dual-mode electro-hydraulic actuators with combined rate control "DRP-1" that was positioned on a test rig. Resting on a stationary metal base (4) that was built into the floor is an "DRP-1" (1) and its pneumatic loading mechanism (2). These two actuators are coupled by the kinematical link – a moving arm (3). The arm was designed so as to place the rod of pneumatic loading mechanism in perpendicular to the arm rotation axis in its neutral state. This fact means that practically the whole force (torque) that was generated by the loading mechanism (except for friction) was imparted to the tested actuator during it works at the area of a low amplitude of input signals (when deviations of the actuator rod from neutral state were small).

The value of the force in the pneumatic cylinder was adjusted before each tests. It necessity to refer that the force that was generated by the pneumatic cylinder had a constant sign.

RESULTS AND DISCUSSION:

It was mentioned earlier that the design of a DRP-1 consists of two actuators: one of them is typical electro-hydraulic servovalve actuator (EHSA), other is an autonomous electro-hydraulic actuator with combined rate control (EHSA-CRC). In terms of the actuator design, this means that most of the hydraulic components like the hydraulic cylinder, the hydraulic block, the control valves etc are operated when actuator is powered both by centralized hydraulic system and electrical power system. Based on the above, the operation mode when "DRP-1" is powered by the centralized hydraulic system was selected as the reference operation mode to which temperature values measured at the actuator's critical points.

Temperature measurements were taken by Dallas Semiconductor DS18B20 external temperature sensors installed at "DRP-1" in control points, as shown on Figure 2 below. The signals were received and processed by means of an Arduino Nano V3 module-based control breadboard with DS3231 modules connected, and an SD Card data saving module.

Figure 3 shows temperature curves at the control points of an "DRP-1" when it is powered by the external hydraulic system. Actuator worked at idle. For all the Figures, the control points where the temperature sensors are located are the same as those on Figure 2. The temperature curves suggest that the heating of "DRP-1" at idle does not exceed 3..5 degrees Celsius when it was powered by the external hydraulic system.

For estimation of actuator energy efficiency in autonomous mode at idle the temperature was measured for two cases: when the actuator worked with a constant initial pressure Ps=5MPa at the output of it's pump (Figure 4) and when the actuator worked with adaptive pressure regulation, that was depended on the external load (Figure 5) . Please refer to (Alekseenkov, 2014) for a detailed description of the operation modes in question.

Idle run has been chosen because all the known foreign electrohydrostatic actuators (EHAs) or dual-mode electrohydrostatic actuators (EBHAs) when it is powered by the electrical power system, use electric motor rate control that has high energy efficiency, while the "DRP-1" uses combined rate control that is less energy efficient within the range of low amplitudes of the rod travel and when the actuator runs idle.

The curves on Figure 4 suggest that hydraulic pump supply and return lines, the housing of the pump, the reverse valve, and BLDC motor have maximum heating when the actuator works in combined rate control mode at idle. However, the temperature of the units never grows more than 10 ^{O}C within 30 minutes of idle run, with the actuator receiving no forced cooling. The heating of the supply and the return hydraulic lines is also caused by switches-on the interline bypass valve with additional hydraulic resistance done to reduce the rate of growing of supply pressure on the pump.

Compared to control mode with constant initial output pressure (Figure 4), actuator control mode with adaptive adjustment of pressure differential on the reverse valve causes less intense heating of the actuator assemblies when it is at idle, which can be seen from the curves on Figure 5. E.g., the temperatures at the critical points only grow by 5 ^{O}C within 35 minutes of operation.

The temperature curves for the critical points of the "DRP-1" operating in autonomous mode under load are of special interest. Figure 6 shows temperature change curves for the control points of the actuator when it processes input harmonic signals at the frequency of 1 Hz and at an amplitude that corresponds to the actuator rod shift by 1 mm, the external load being 2,300 daN, which is 60% of the maximum force that the actuator can produce when it operates in autonomous mode. The curves suggest that the supply and return hydraulic lines of the pump (due to the switch-on of the bypass valve with additional hydraulic resistance), as well as the housing of the pump are the most prone to heating.

It is worth noticing that the temperature of the pump's supply hydraulic line grew from 48 ^{O}C to 76 ^{O}C, the temperature growth rate being 0.036 ^{O}C/sec throughout the actuator operation time (from second 0 to 780, see Figure 6). At 780 second, the loading mechanism was switched off while the law of control imparted to the actuator input was remained. After that the pump's supply hydraulic line temperature dropped to 40 ^{O}C in 480 sec; thus the temperature decrease rate was 0.075 ^{O}C/sec, which was approximately twice the temperature growth rate. Similar results could be observed for the pump's return hydraulic line and the housing of the pump. The results showed that actuator had a good heat exchange between the pump housing design and the environment.

Besides, the temperature curves suggested that the BLDC motor was not a critical unit from the heating point of view when actuator worked at low amplitudes of input signals. As according to the combined rate control algorithm, the principal task of the actuator motor at low amplitudes of input signals was to generate a supply pressure, with its shaft rotation rate changing only slightly.

None of the above operation modes involved forced actuator cooling. From the point of view of dynamic performances, the adaptive adjustment of pressure differential on the reverse valve was limited to 5 MPa additional pressure and worked at the area of 0 to 1150 daN. As shown on Figure 7, the adaptive adjustment improves actuator dynamic performances during operation under the load of 1000 daN, but is not effective when the value of the load increases to 2300 daN.

CONCLUSIONS:

The estimated temperature parameters for the principal units and assemblies of a dual-mode electro-hydraulic actuator with combined rate control have been found through research. The results suggest that despite design features inherent in all dual-mode actuators (including a built-in hydraulic power source that makes a built-in local hydraulic system), a dual-mode actuator with combined rate control has rather a high energy efficiency when running idle in autonomous operation mode.

At the area of a low input control signals (low amplitudes of rod travel) the characteristics of actuator with combined rate control in general are the same to the characteristics of electro-hydraulic servovalve actuator with volumic (the pump operating volume that depends of output pressure) regulation. At the area of a medium or a high input control signals (more than 10% from maximum rod travel) the characteristics of actuator with combined rate control are the same to the characteristics of electro-hydrostatic actuator.

The actuator control algorithms with adaptive output pressure adjustment allowed to enhance the energy efficiency of the actuator whenever necessary by reducing the region of predominant flow restrictor control, thus being similar to EHA-type actuators in terms of energy efficiency.

The temperature curves for the actuator operation under load (Figure 6) suggested that the temperatures at the critical points would not exceed the maximum allowable temperatures for actuator units and assemblies when actuator works in a mixed operation cycles with various amplitudes of rod travel under the action of loads that vary in sign and value.

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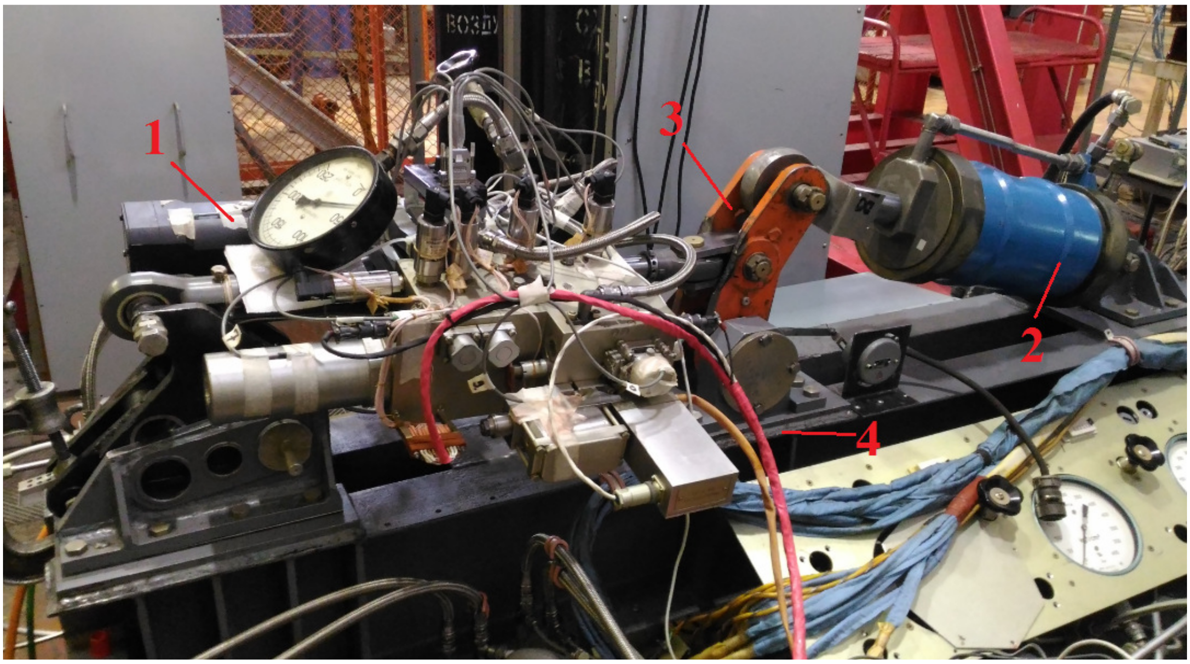

Figure 1. *The test rig*

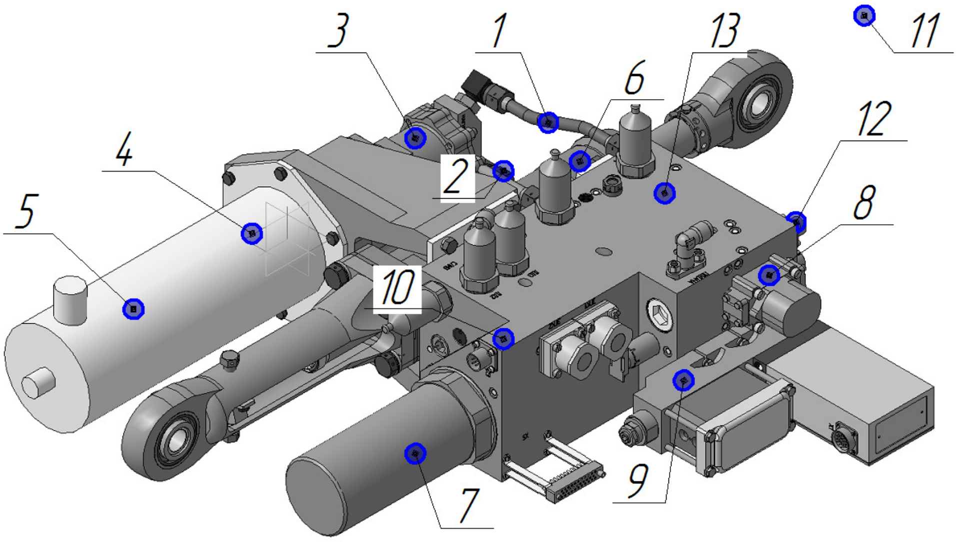

Figure 2. *The locations of temperature sensors on a "DRP -1". The units shown on the Figure are as follows:* ***1*** *– The temperature sensor on the pump's supply hydraulic line,* ***2*** *– The temperature sensor on the pump's return hydraulic line,* ***3*** *– the temperature sensor on the pump's housing,* ***4****, and* ***5*** *– the temperature sensors on the Brushless DC motor's housing,* ***6*** *– the temperature sensor on the hydraulic cylinder's housing,* ***7*** *– the hydraulic accumulator's temperature sensor,* ***8*** *– EHSV temperature sensor,* ***9*** *– the reverse valve's temperature sensor,* ***10*** *– the housing temperature sensor at point I,* ***11*** *– the ambient air temperature sensor,* ***12*** *– the active mode valve temperature sensor,* ***13*** *– the temperature sensor at point II*

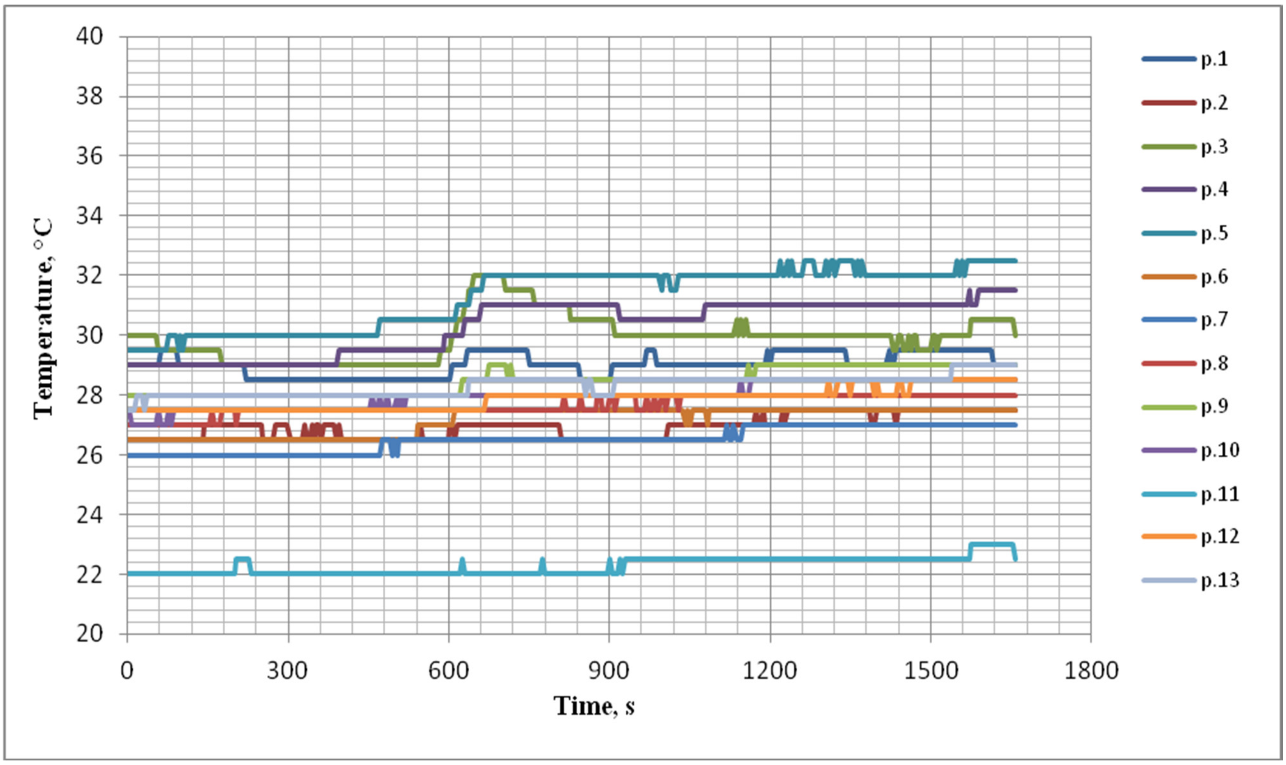

Figure 3. *Temperatures at the control points of the "DRP -1" powered by the external hydraulic system at idle*

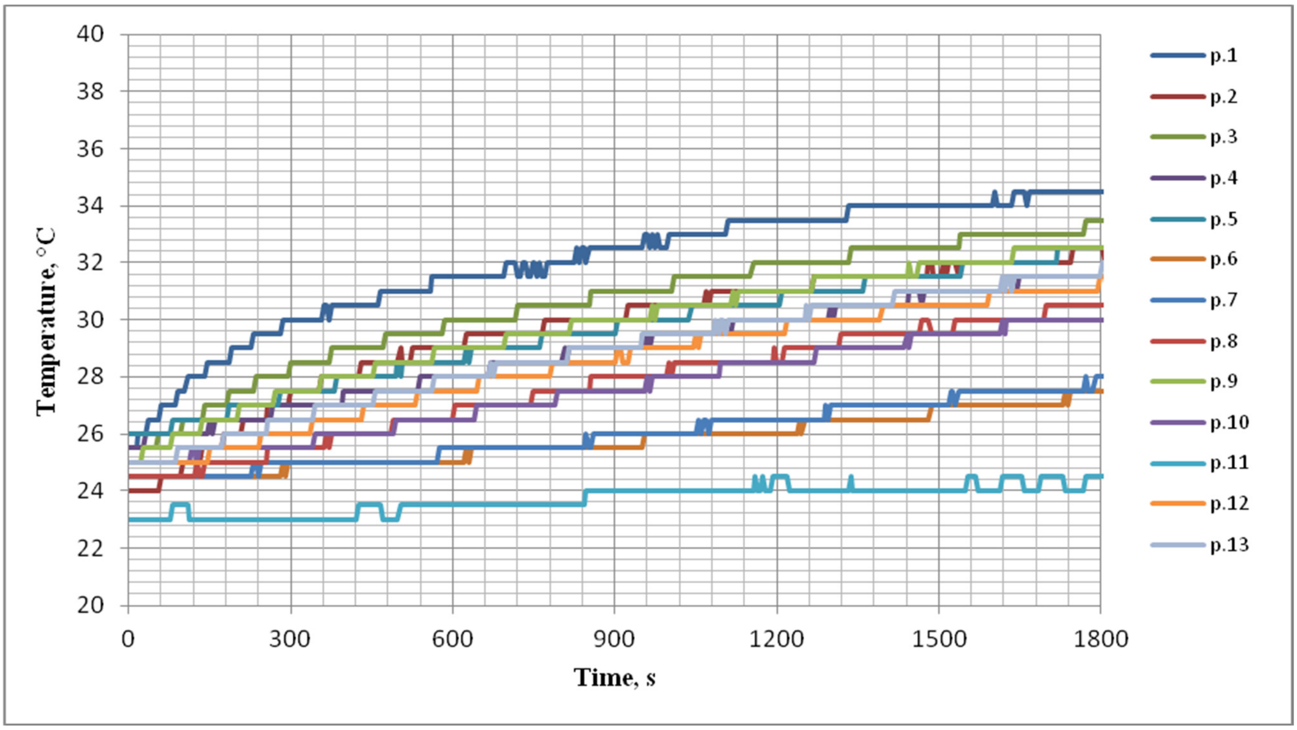

Figure 4. *Temperatures at control points of the "DRP -1" in autonomous operation mode at a constant initial output pressure Ps for actuator idle run*

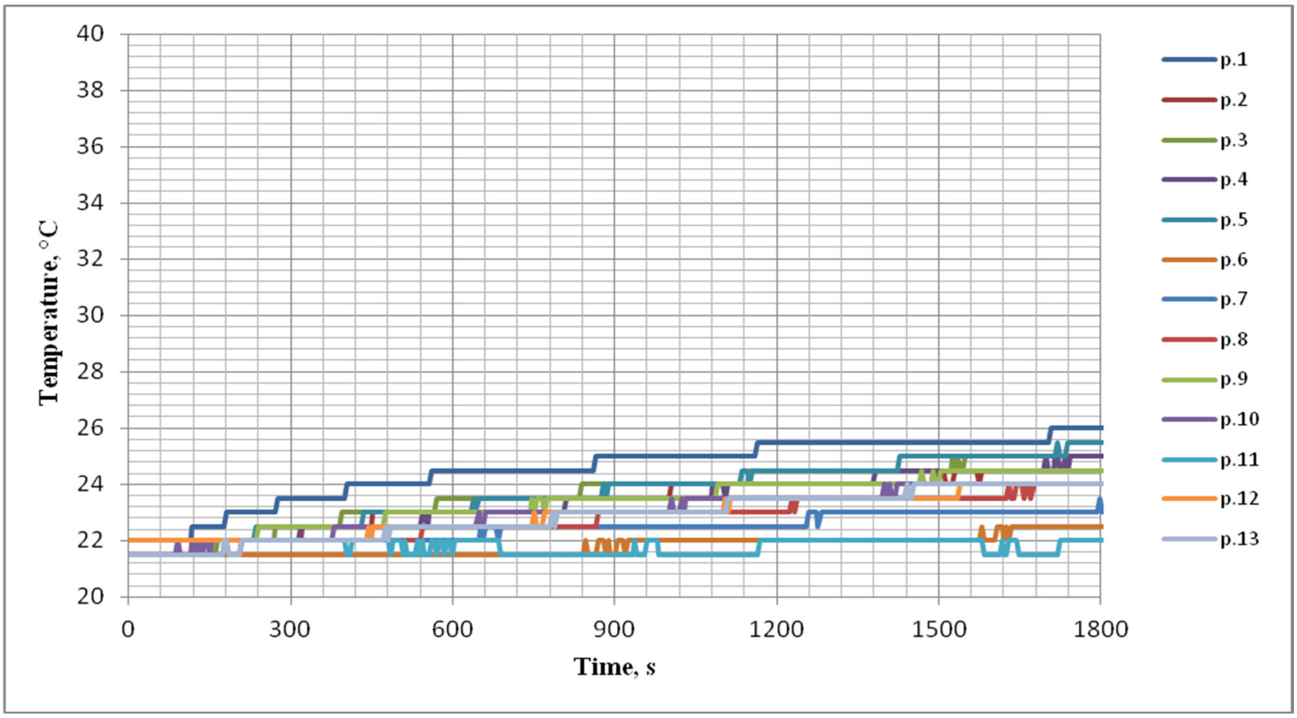

Figure 5. *Temperatures at the critical points of the "DRP -1" in autonomous operation mode with addition adaptive correction that is based on proportional (to the output load) maintaining a value of differential pressure on the reverse valve for actuator idle run*

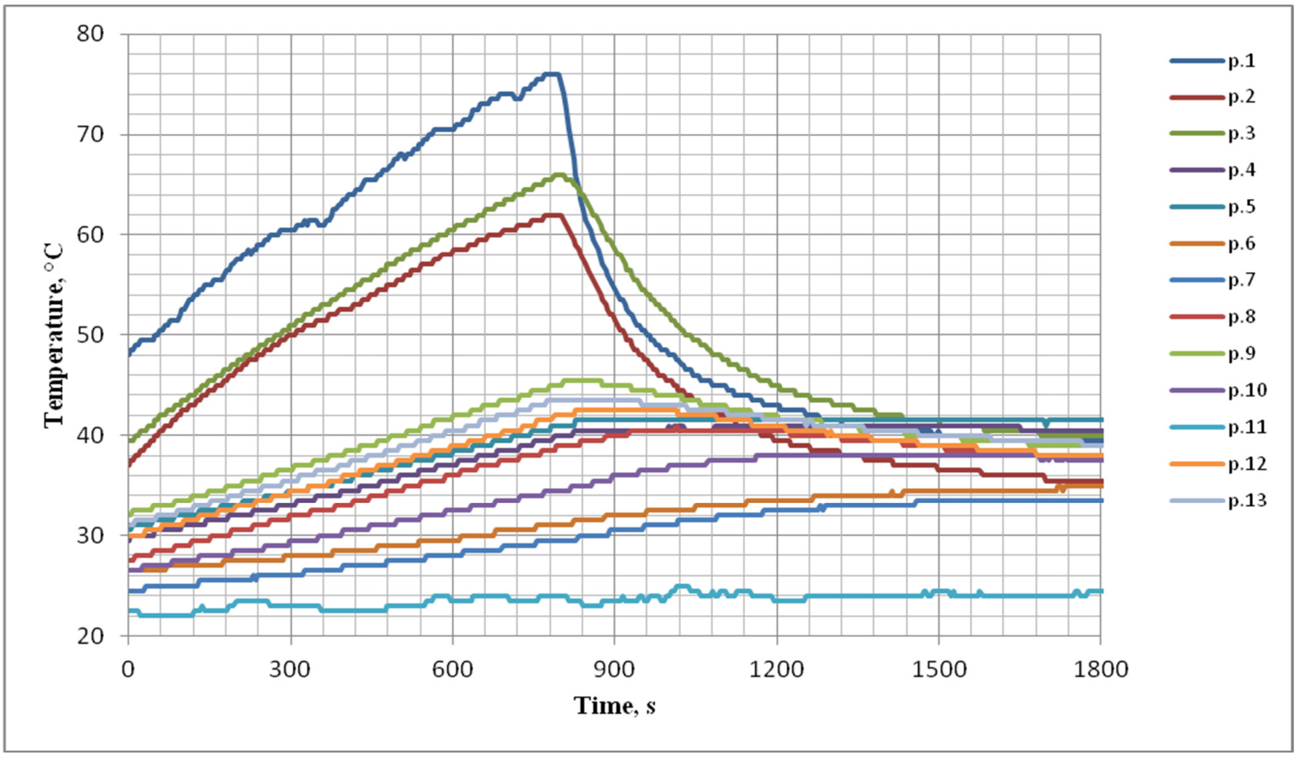

Figure 6. *The temperatures at the critical points of the "DRP-1" in autonomous operation mode within the processing cycle of harmonic signals under load*

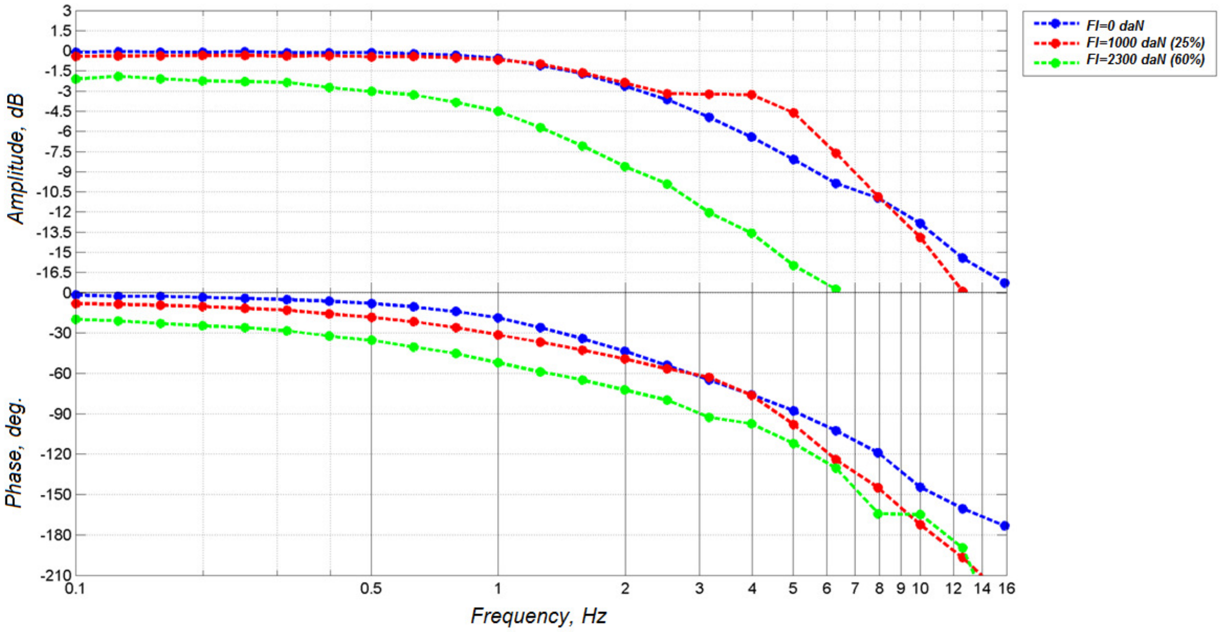

Figure 7. *The experimental dynamic performances of the "DRP-1" in autonomous operation mode under load at 1 mm amplitude of rod travel*