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STUDY ON ELECTROMECHANICAL DRIVES USED IN VENTILATION AND SMOKE EXTRACTION SYSTEMS

BADANIA NAPĘDÓW ELEKTROMECHANICZNYCH STOSOWANYCH W SYSTEMACH ODDYMIANIA I WENTYLACJI*

The paper presents experimental tests for electromechanical drives for use in ventilation and smoke extraction systems of buildings. The determined characteristics (force, shift, current and voltage as a function of time) enable the assessment of applicability of these drives as the drives of flaps and windows in fire protection systems. The study was conducted using a developed test stand facilitating the determination of characteristics of work of linear and rotary drives in changeable temperatures.

Keywords: *test system, electromechanical drive, smoke extraction and ventilation, fire protection system.*

W artykule przedstawiono badania eksperymentalne napędów elektromechanicznych pod kątem zastosowania w systemach wentylacji i oddymiania budynków. Wyznaczone charakterystyki (siła, przemieszczenie, prąd i napięcie zasilania w funkcji czasu) pozwalają na dokonanie oceny możliwości ich zastosowania do napędu klap i okien w systemach przeciwpożarowych. W badaniach wykorzystano opracowane stanowisko umożliwiające wyznaczanie charakterystyk pracy napędów liniowych i obrotowych w zmiennych warunkach temperatury.

Słowa kluczowe: *system badań, napęd elektromechaniczny, oddymianie, wentylacja, system ppoż.*

1. Introduction

Electromechanical actuators (EMAs) are much more commonly used in industrial applications, where there is a must for multiple forces and loads to be reliably exerted. The purpose of electromechanical solutions is to convert electrical energy into mechanical energy of the actuator.

The dynamic development of EMAs stems from their growing popularity in the most demanding sectors of modern technology. Due to the risk and criticality of functions executed in actuators in applications concerning human and technical object safety, EMAs used must meet the highest durability and reliability requirements. For that purpose, it is necessary to conduct detailed tests enabling the determination of operating characteristics of EMAs working under different conditions of force and environmental excitations. Laboratory tests performed in a relevant environment resembling real-life operating conditions are the foundation for the acquisition of specialised knowledge about the correct operation and durability of EMAs. The work parameters recorded during the tests enable the development of modern diagnostic systems which are an essential element of safe control systems. The information from the investigations provides valuable data sets used in the diagnosis and operating capacity prediction models. Improving test methods, the reliability of recreated operating conditions, and the accuracy of recorded work parameters of EMAs are the basic conditions for ensuring a high level of technical safety.

2. Application of electromechanical actuators

EMAs are finding increasing use in new areas of application in the aviation (both civil and military), aerospace and military industry. As for the construction of aircrafts, electric actuators are responsible for the positioning of the elements of a tailplane, i.e. ailerons, flaps, spoilers, or aerodynamic brakes. In the case of spacecrafts, electric actuators are used for the positioning of antennas and robotic arms, but there are also plans for such actuators to be used for the construction of rockets and their thrust vector control [25]. R&D works aimed at the application of EMAs for the positioning of rudders of ships and submarines are also conducted [20, 38].

In latest aircrafts (i.e. Boeing 787 or Airbus 380), EMAs operate landing gear breaks, and in the case of military aircrafts (i.e. F-35 Joint Strike Fighter), they are used for the positioning of weapons [1]. The nearest future will see the intensification of R&D aimed at the construction of aircrafts in which electric systems will entirely replace hydraulic systems [2]. The elimination of the central hydraulic system will reduce the weight of an aircraft, which in turn will lead to the decrease in the power consumption.

EMAs are, however, far more complicated than hydraulic actuators, which stems from the necessity to integrate in one module numerous precise components including i.e. electric motors (usually two), differential gears, reduction gears, screw mechanisms and built-in control system elements [25]. Despite the high level of complexity, these systems have to comply with severe and restrictive requirements, stating that the faults may not occur more often than $1x10^5$ (strike-fighter aircraft F/A 18) or even $18x10^6$ (fighter F-35 AB) flight hours [6].

Taking into consideration the issues of safety, actuators are the critical components of an aircraft system (fig. 1).

Even a small, undetected fault can lead to very serious consequences. This is confirmed by results of aircraft accidents, in which such failures as e.g. the failure of the actuator of the horizontal rudder, turned out to be the cause of the crash. Cases in which excessive, uncontrolled wear of servomotors stood behind the grounding of the entire fleet are also recorded. Therefore, actuators used in aviation undergo detailed functional tests, whose results enable the develop-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Fig. 1. Actuators with screw gear controlling the positioning of the flaps in the IL-76 transport aircraft

ment of reliable structures and support better understanding of various causes of defects of complex structures of EMAs.

Collecting knowledge from the experiments enables fast and reliable detection and identification of faults, in which such additional methods as FMEA and FTA supporting the design of suitable algorithms tailored to specific actuators, are used [14]. The developed actuator fault prediction methods are an essential element of contemporary monitoring systems that use artificial intelligence, fuzzy logic and neural networks. The analysis of possible faults allows the selection of detection algorithms - heuristic methods, model-based methods and experimental data sets [13, 17]. They provide early detection of small defects, and enable the monitoring of gradual degradations.

The developed diagnostic systems for EMAs support proper planning of renovations. The traditional approach of overhaul after given hourly service is an unsatisfactory solution. The observed wear, especially in the case of military aircrafts, depends on the individual style of piloting and the operating environment. The reasons for the occurrence of dangerous situations lie in the wear which, due to the unique style of piloting under e.g. battlefield conditions, is a much quicker phenomenon than anticipated. [17]. Therefore, it is reasonable to replace periodic maintenance with the strategy to carry out repairs based on the current assessment of the technical condition of the object, conducted using an intelligent system forecasting further operating capacity. Systems for the diagnosis of actuators will enable the elimination of redundant systems, typical for aircraft structures, which in turn will contribute to a significant reduction in their weight and the reduction in the overall dimensions of new aircrafts and other systems responsible for technical safety [13].

Due to the responsibility of the tasks performed, the accurately archived set of many years of experience, and the high implementation potential, studies on actuators used in aerospace set the standard for tests for these devices also in other fields of their application, like mechanical engineering, shipbuilding and construction industries, for instance.

3. Actuator tests

Study on EMAs enables the development of safe systems with damage tolerance, the self-diagnosis, the early detection and localisation of defects, and the assessment of the degree of degradation of devices and actuators. The development of the advanced research on EMAs is mainly driven by the needs of the aerospace industry. For this purpose, extensive field and laboratory tests are conducted, and their results are the basic information used in the developed diagnostic and monitoring systems.

The first experiments were carried out on real objects, in which the hydraulic actuators were replaced with an electromechanical system. Such tests were performed under the Electrically Powered Actuation Design (EPAD) programme executed in cooperation with the U.S. Air Force, the U.S. Navy and NASA. In the study, an EMA was installed in the F/A-18B fighter to control the left aileron. The tests conducted during 22 flights for the total of 25 hours allowed the registration of work parameters of the actuator, and enabled the comparison with the operation of the typically used hydraulic system located in the right wing [12]. The main problems detected concerned the overheating of the engine, the inefficient energy dissipation during braking, and the low durability of the casing of the ball screw nut.

So as to enable the execution of cheaper laboratory tests resembling real operation conditions, a mobile test stand, making the tests to be performed in the flight mode, on board of an aircraft, was developed. The stand was developed in collaboration with the NASA Prognostic Center of Excellence and the California Polytechnic State University [3, 16, 27]. The installation of the developed stand does not require any modifications in the design of the aircraft structure. The operation on board of an aircraft makes it possible to perform tests under the influence of real loads exerted by varied values of vectors of velocities and accelerations occurring during the flight. The stand comprises three actuators: two tested actuators and a load exertion actuator. One of the tested actuators is in working order, whereas an intentional defined damage is caused to the other. The actuators which are being tested are, by means of magnetic coupling, connected to the load system. The types of faults caused concern the damage to the screw mechanism (loss of threading, deformation of balls, return channel ball jam, excessive backlash), the electric motor (overheating, vibration), and the sensors (indication error or signal loss). [5] The sensor system of the test stand enables the recording of the following parameters: the amplitude and frequency of vibrations of a tested actuator, the value of the load set, the temperature, the voltage and current of power, and the length and angular position of the screw. The characteristics are correlated in time with the information recorded by the on-board flight data recording system.

The tests enable the recording of the characteristics of the monitored parameters during the occurrence of the determined faults, and their comparison with the model derived from a working motor. The test system is designed to work with the Boeing C-17 Globemaster military transport aircraft and the UH60 Blackhawk helicopter. The stand can also be used for the testing of diagnostic systems monitoring the work of the tested actuators. The device became widely used as a test platform that allows the testing of diagnostic and control systems operating in conditions where the fault occurred. The stand was used for numerous investigations and verification tests for diagnostic and prognosis systems based on models, experimental data, and hybrid solutions combining analytical models with functions defined experimentally [4, 15, 25].

An alternative to mobile test systems are stationary stands enabling the performance of tests on actuators of larger size and load capacity. Tests on the Moog MaxForce 833-023 actuator presented in [1] were performed using a hydraulic system. The tested actuator was connected to a hydraulic load actuator by means of a rotating robotic arm. The stand enables the three directional measurement of accelerations impacting the actuator, the registration of the temperature of the stator, the determination of the position of the tip of the piston rod, and the two directional measurement of the force on the piston rod. The control system enables different levels, types and profiles of loads to be set for a tested actuator.

Another stationary test stand built in cooperation between the Impact Technologies and the NASA Ames Research Center is used for the experimental study on diagnosis and prognosis methods for EMAs with screw gear [1]. The dynamic loads are set using a large Mogg 866 EMA enabling the generation of longitudinal force of up to 50 000 N. The control system ensures the possibility of varied shaping of the load profile. The load can be exerted in a rectangular, trapezoidal, sinusoidal and triangular manner. The structure of the stand enables the performance of long-term tests with data recording at up to 64 kHz.

A simplified version of the stand is a solution using a pneumatic actuator to exert a load on the piston rod of the tested EMA [1]. Using a pneumatic system, it is possible to set loads which do not exceed the value of 4500 N. The system is equipped with three independent controllers. Two of them work in a subordinate system and control the operation of the proportional air pressure regulator and the servo motor, and cooperate with the master PXI controller.

A slightly different concept of EMA tests was used in the method using Hall sensors for the diagnosis of the technical state of screw gears. The non-contact measurement technique facilitates the monitoring of the wear of an actuator based on the detected defects of balls in the screw mechanism [9]. The Hall sensor installed on the nut makes it possible to generate a sinusoidal signal, proportional to the distance of the ball from the sensor surface. In the case of detection of a defective ball, the signal is distorted and has smaller amplitude. The study was conducted on the stand in which the gear was driven by a 30 kW electric motor. The axial load of a tested mechanism was set using a hydraulic actuator connected with the front of the screw. The level of the load dependent on pressure in the actuator controls the controller of the proportional valve.

Tests on EMAs using stepper motors can be performed on a test stand developed at the Micromechanics and Photonics Institute at the Warsaw University of Technology. The stand is intended for the determination of operating characteristics for precise, linear, high resolution actuators, and their positioning precision [43]. The determination of border movement characteristics is performed using feed impulses of known frequency, through the loading of the pusher with defined force, and the precise detection of the pusher's movement. The stand has two load exertion fields: the control field and the actuator load field, and two measurement fields for the measurement of the load force and the shift of the pusher. The tested actuator is loaded using a DC motor with electronic commutation, coupled with the pusher by means of a tension roller mechanism with a built-in force strain gauge sensor. The border start characteristics are determined through the programmed loading of the actuator with the predefined force, and the search for the maximum beat frequency at which the actuator will work in a stable manner. The measure for actuator's stable operation is the linear shift of the pusher stemming from the set number of control impulses.

Apart from tests performed by R&D organisations, studies on EMAs are also conducted by industrial R&D centers, in which case the results of such investigations are confidential and unavailable in print. The example of industrial tests on EMAs are experiments conducted by the Honeywell International Inc. on linear EMAs used i.e. in aviation, transport, process control [28]. The tests are conducted in dynamic load conditions reflecting the character of the actuator's operation resulting from the moving of masses or the presence of different load forces, in order to determine the inertia and delay the reaction of the actuator.

Control over technological processes involving the transmission of gases and liquids (chemical, mining, refining industry) requires the use of remotely controlled valves driven by rotary actuators. The manufacturers of industrial automation including valve actuators developed stationary (PV 1405 AUMA) and mobile (PV 1236 AUMA) test devices equipped with an integrated diagnosis system allowing the verification of operating parameters of rotary actuators in a wide range of loads (up to 6 000 Nm).

Stands for testing rotary actuators used in rail transport were also developed by the Kyalsi Engineering Inc.

4. Study on electromechanical actuators in ventilation systems of buildings

Out of the technical areas in which EMAs are broadly applied, the ones of great importance are construction and fire protection. Reliability of EMAs is also directly related to the issues of fire safety, particularly fires safety of public buildings.

In order for rescue operations to be carried out effectively, the area where the fire broke out needs to be cut off, and the smoke removed from the fire exit route [24] The closing of the fire screen bulkhead, the opening of smoke vents or ventilation windows is performed using EMAs [21, 22, 32, 42]. The screw, chain and spindle mechanisms used in actuators allow effective and fast positioning of the effector (flaps or windows) so as to transfer the smoke and hot air outside a burning building (Fig. 2).

Fig. 2. Linear EMA with screw gear controlling the opening the smoke extraction flap located on the building's roof

The proper functioning of fire ventilation is a prerequisite for efficient evacuation of a building [10, 30, 31], especially in high-rise buildings, in which it is difficult for rescue actions to be performed from the outside. In the case of floors located over 50 m above the ground, the only chance for rescue is the evacuation through the building's corridors and staircases [11, 13, 18, 19, 37].

EMAs used in modern building automation systems constitute a unique group of electricity receivers operating in fire protection system. Their reliable operation, in the case of fire, is essential for an effective evacuation of people trapped in a burning building.

In automatic flap control systems, the electric current, once transmitted to each object, is distributed via proper installation tailored to the used actuator voltage and current standard. Actuators for smoke extraction systems most commonly use 24V DC [39]. This requires special units equipped with batteries responsible for emergency power backup to be mounted. Reliable and safe transmission of energy from the unit to the receiver requires the construction of an additional electrical installation [35, 36].

The high temperature at the time of fire leads to decreases in the electrical conductivity of wires, which results in lower quality of the supplied power manifesting in the excessive voltage drop and the worsening of fire protection conditions [34, 40]. The low value of voltage results in the decreased torque of the electric motors used in actuators, which can significantly hinder the effectiveness of a rescue operation. Proper cooperation between the power supply system and the actuator is possible only if the required level of electricity consumption is maintained, regardless of the loads and temperature [33] in the building. They have to operate reliably under extreme conditions which occur during a fire.

As the evacuation of people from burning buildings is the most important element of rescue actions, formal requirements for the construction of a building and the electrical appliances installed in it, including EMAs, and working at the time of the fire, are set.

The EN 12101-2 standard [26] specifies the requirements for smoke flaps mounted on the roof and smoke flaps installed in the facade of the building, popularly known as smoke extraction windows.

According to the standard, the window smoke extraction system (window + drive, the so-called Natural Smoke and Heat Exhaust Ventilation – NSHEV) should constitute a complete CE-labeled solution, in accordance with the 93/68/EC Directive.

Due to the direct relationship with the consequences of accidents, technical rescue and fire protection have a particularly important place in a technical safety system. Therefore, the introduction of any new solution must be preceded by a detailed study at the stage of R&D and certification as well.

5 Test methodology

In order to ensure the required reliability associated with the performed functions including the removal of toxic fumes [8, 28], electric drives designed for use in safety systems have to undergo a series of tests [7] which will confirm the required level and stability of relevant operating parameters.

One of the areas of the activity of the Institute for Sustainable Technologies - National Research Institute in Radom includes conducting research related to improving technical object safety [23]. For several years, the Institute has been conducting, in cooperation with the Science and Research Center for Fire Protection - National Research Institute in Józefów, R&D works related to the development of procedures and construction of specialised test and research apparatus supporting the safe operation systems [44], including technical rescue technical [17], and fire protection [29].

The study on ventilation systems performed jointly by the above listed research organizations resulted in the development of a concept of a model test system for EMAs used in fire protection systems.

The developed concept takes into account the directive of the Minister for Internal Affairs and Administration on 20th June 2007, which lists products facilitating public safety, as well as health, life and property protection, and delineates the principles of their release. According to this regulation, the test object is assessed at room temperature. The forced load and the registration of characteristics take place after the natural cooling or heating of the object, previously subjected to thermal risks.

The original test methodology, in contrast to the existing legislation, assumes the on-line registration of the operating characteristics during the impact of the thermal load (Fig. 3). This ensures the assessment of the test object in conditions similar to actual operating conditions. Continuous recording of the basic work parameters of EMAs provides opportunities for extended, in relation to the defined by the existing rules, analysis of the impact of extortions on the behaviour of a tested object.

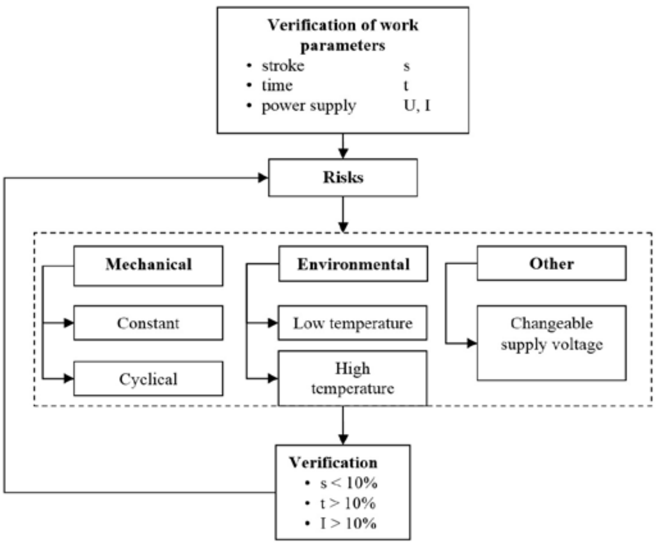

Fig. 3. Draft of selected test procedures for electromechanical drives

The assessment concerns, inter alia, such work parameters as the working stroke, the power consumption and the accompanying time of movement during the opening and closing. The criteria which allow the drive to be used in fire protection systems [7] concern the permissible changes in the following three parameters:

– The time of movement in both directions cannot be changed by more than 10%,
– The stroke cannot change by more than 5%,
– The increase in the power consumption cannot exceed the value of 10% for the two directions of movement.

6. Test stand

The basic element of the developed test system for drives used in smoke extraction and ventilation systems is a test stand, which allows drive tests to be conducted under varying conditions of temperature. Those tests are particularly executed for drives whose actuators perform linear or rotary motion. The developed stand offers a wider range of test possibilities, compared to existing solutions, which is due to the combination of force and thermal excitation systems in one compact unit with an integrated control and data acquisition system.

a) b)

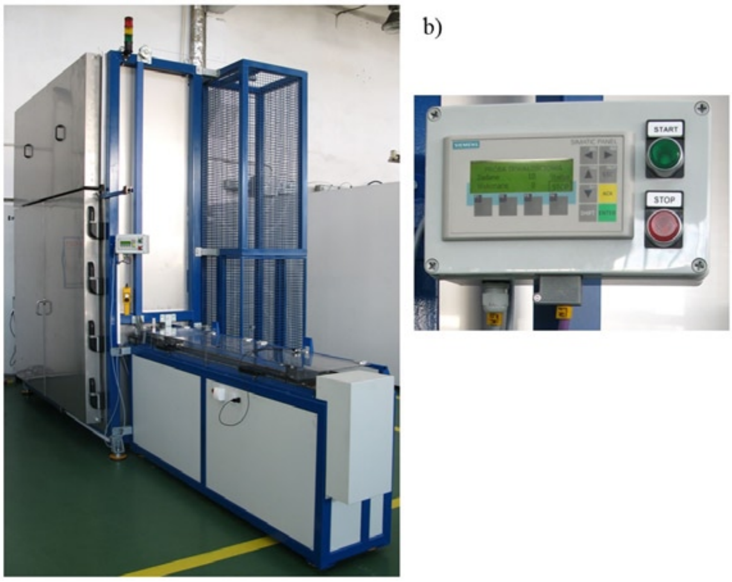

Fig. 4. Actuator test stand: a) general view, b) control panel

The device, designed and developed at the ITeE-PIB (Fig. 4) is composed of a thermal chamber connected to actuators for mechanical excitations. The basic element of the device intended for maintaining stable temperature and humidity conditions at the time of an actuator test, is a thermal chamber equipped with an adjustable, universal system allowing any type of actuator to be mounted.

The developed structural solutions allow the working elements of linear and rotary actuators to be loaded at the time of their movement using gravity or mechatronic load systems. The use of a gravity load system ensures load stability while conducting durability tests, where the required number of cycles can even reach 10 000. The mechatronic system, on the other hand, enables the execution of the endurance tests with predefined dynamics.

The basic parameters of the developed test stand are as follows:

– linear load up to 5 kN
– torque load up to 30 Nm
– shift at the time of:

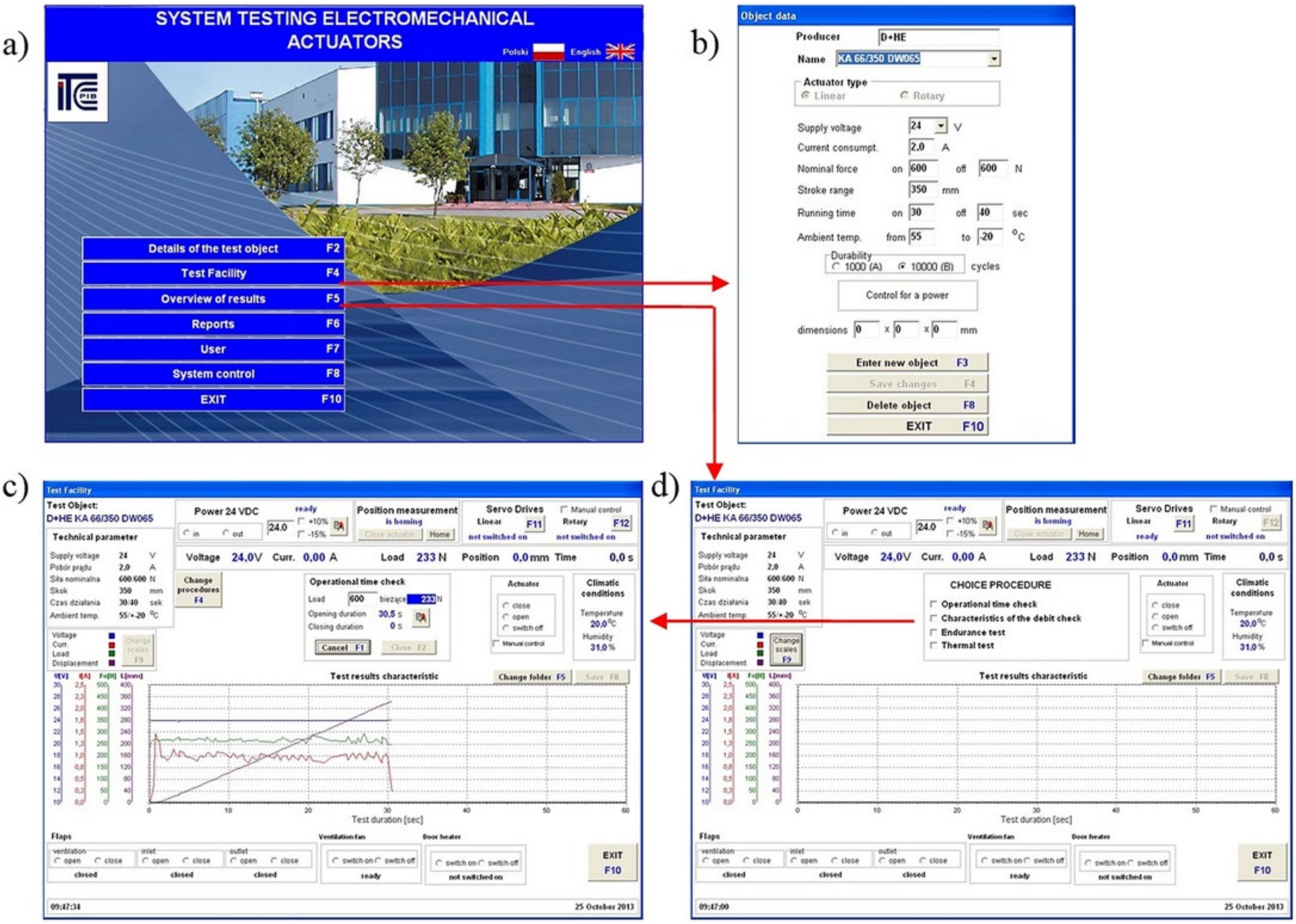

Fig. 5. View of the control system: a) main, b) identification of the object, c) measurements, d) selection of procedures

– linear movement up to 1,2 m
– rotational movement up to 4,7 rad
– test temperature from 243 to 363 K
– actuator supply:

electric actuator 24 V, 230 V AC/DC

pneumatic actuator up to 1 MPa

– measurement and recording: force or moment of force, displacement, temperature, humidity, voltage, current and power.

Selected test procedures and data acquisition are controlled via a control and measurement system with specialised two-layered software. The first of the layers includes a graphic user interface (Fig. 5) communicating with the test system by means of a PC with Windows operating system enabling the identification of a test object, the selection of a test procedure, and the setting of test parameters. The latter layer, on the other hand, concerns the performance of test procedures selected by the user, controlled directly by the PLC.

The stand is particularly intended for the execution of certification tests for EMAs used in fire protection systems, therefore an unambiguous identification of a test actuator during the entire certification procedure is required. For that purpose, a procedure for data input was developed, as it is a prerequisite for the tests to be launched.

Once the user inputs the data into the object, he then can verify and record the basic actuator work parameters which are crucial from the point of view of its future field of application [30,40] (Fig. 5c). These parameters include the following:

– control voltage and current,
– ejection and insertion time,

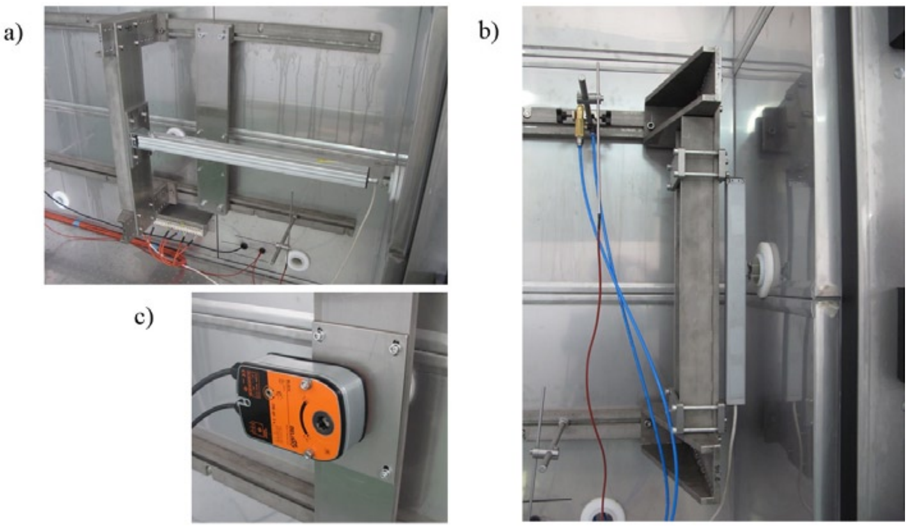

Fig. 6. View of actuators ready to be tested: a) spindle, b) chain, c) rotary

Table 1. Test conditions

Type of a drive	Symbol	Load	Temperature [K]
Spindle	W	460 N	253 ±1 293 ±1 328 ±1
Chain	L	105 N	
Rotary	O	15 Nm	

– stroke,
– nominal force.

The next step in the test process is the selection of a proper test procedure (Fig. 5d). The system generates the parameters of a selected procedure by default, allowing the user to make a final decision concerning their value.

7. Performance of tests

The tests were performed for electromechanical drives of different architecture and purpose. Spindle drives (Fig. 6a) are used for the opening of smoke extraction flaps, façade windows, skylights, glass roof structures, pyramids and roof windows. The structure of these actuators ensures high stability at the time of operation. The actuators' standard equipment includes limit position switches and safety switches in the case of overload. Chain drives (Fig. 6b) are used in the case of façade windows, roof windows and ventilation flaps. They are equipped with limit position switches, closing and opening force controllers, and chain length regulation system. Rotary actuators (Fig. 6c), those with a return spring, enable self execution of the movement of the shutter to the position required by the fire safety system. They are used to adjust the position of air dampers in ventilation and air-conditioning systems.

Table 2. Drive work parameters (temperature: 293 K)

Symbol	Stroke [mm, rad]	Max. power consumption [A]		Time [s]	
		Opening	Closing	Opening	Closing
W	500 ±0.5	0.78 ±0.01	0.20 ±0.01	72.3 ±0.5	59.1 ±0.5
L	346 ±0.5	0.55 ±0.01	0.09 ±0.01	55.8 ±0.5	70.8 ±0.5
O	1.57 ±0.01	0.26 ±0.01	0.03 ±0.01	30.0 ±0.5	20.5 ±0.5

Table 3. Drive work parameters (temperature: 328 K)

Symbol	Stroke [mm, rad]	Max. power consumption [A]		Time [s]	
		Opening	Closing	Opening	Closing
W	500 ±0.5	0.84 ±0.01	0.25 ±0.01	71.1 ±0.5	55.3 ±0.5
L	346 ±0.5	0.42 ±0.01	0.09 ±0.01	53.2 ±0.5	69.1 ±0.5
O	1.57 ±0.01	0.28 ±0.01	0.12 ±0.01	29.5 ±0.5	19.5 ±0.5

Table 4. Drive work parameters (temperature: 253 K)

Symbol	Stroke [mm, rad]	Max. power consumption [A]		Time [s]	
		Opening	Closing	Opening	Closing
W	500 ±0.5	0.85 ±0.01	0.30 ±0.01	78.3 ±0.5	63.2 ±0.5
L	346 ±0.5	0.65 ±0.01	0.15 ±0.01	58.3 ±0.5	72.5 ±0.5
O	1.57 ±0.01	0.26 ±0.01	0.06 ±0.01	31.5 ±0.5	24.8 ±0.5

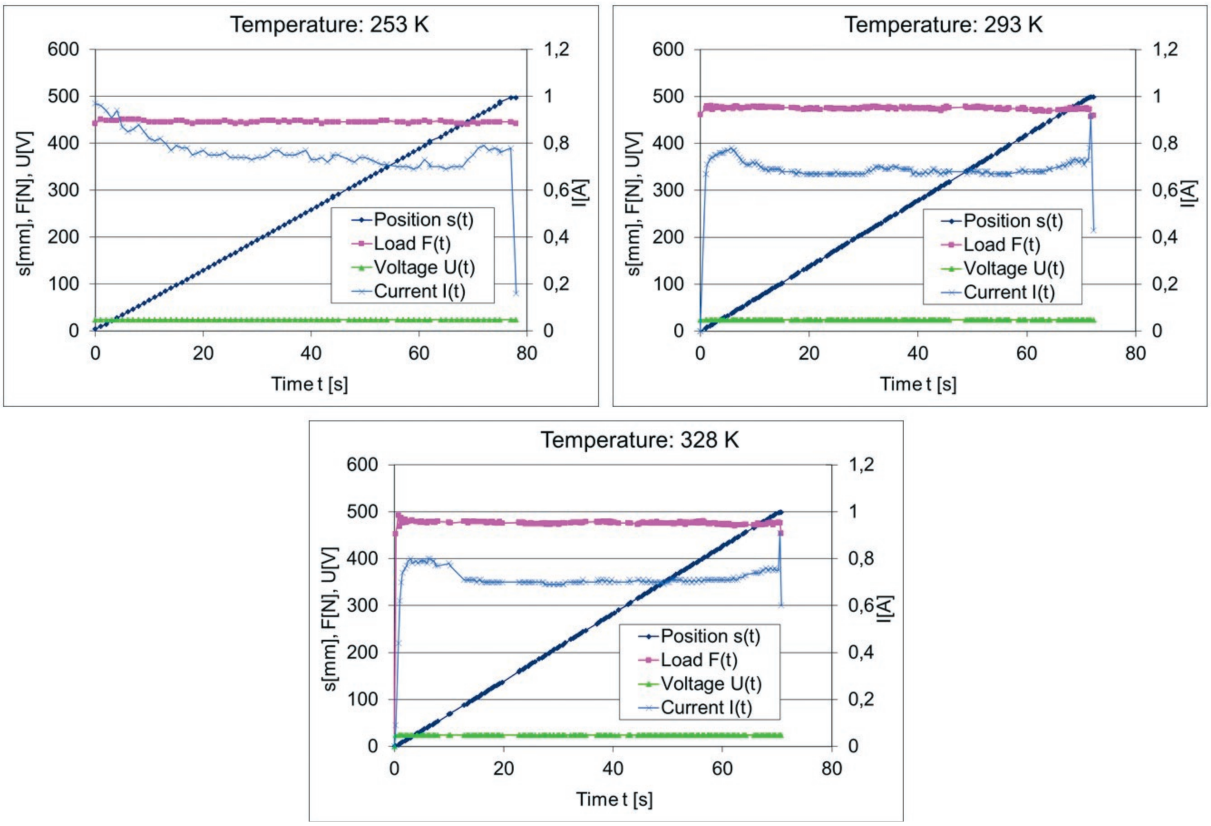

Fig. 7. Sample characteristic of W actuator's work

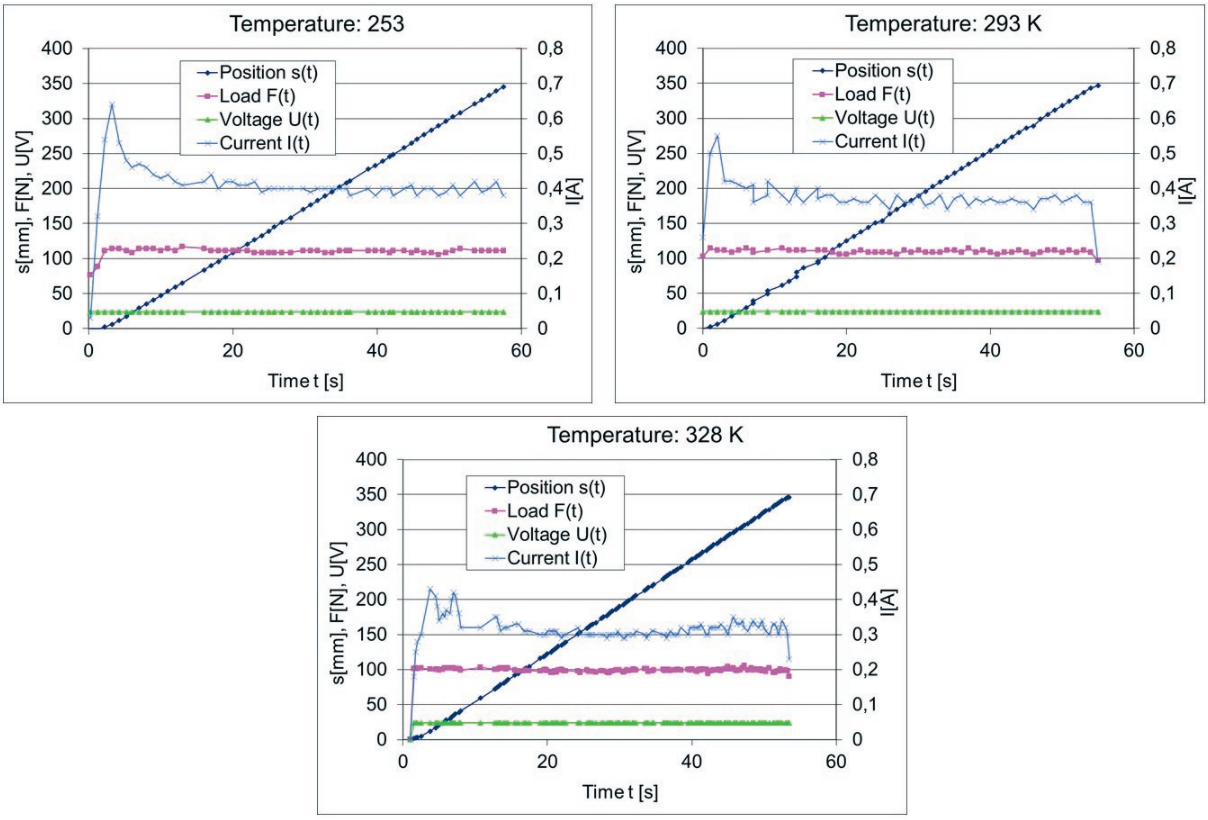

Fig. 8. Sample characteristic of L actuator's work

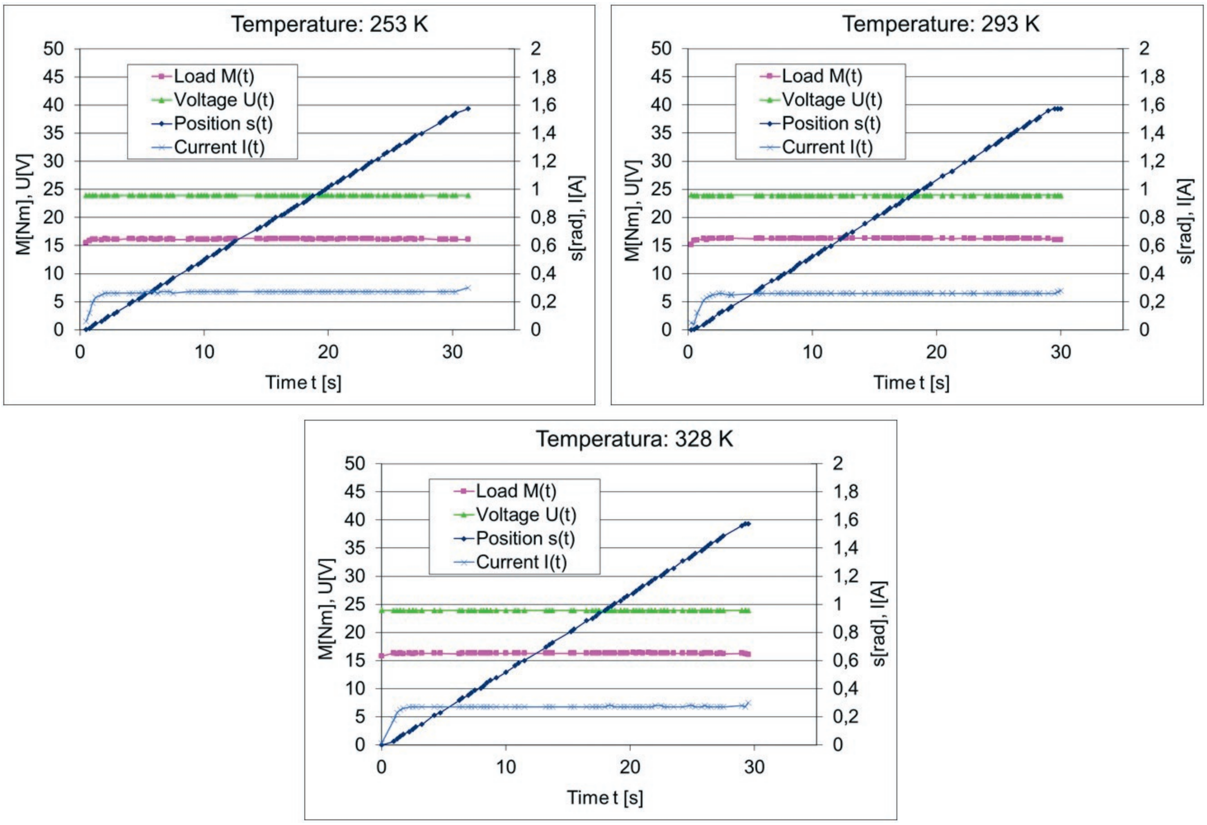

Fig. 9. Sample characteristic of O actuator's work

The way the tested actuator was mounted in the test stand depended on its type and structure, and corresponded to the real character of its work. The temperature of the actuator was set based on the readings from two measuring points located in close proximity to the actuator. The readings were verified using a third sensor placed in the central part of the test zone in the working chamber.

The tests conducted aimed at the determination of the influence of the temperature on the time of movement of a working element of the

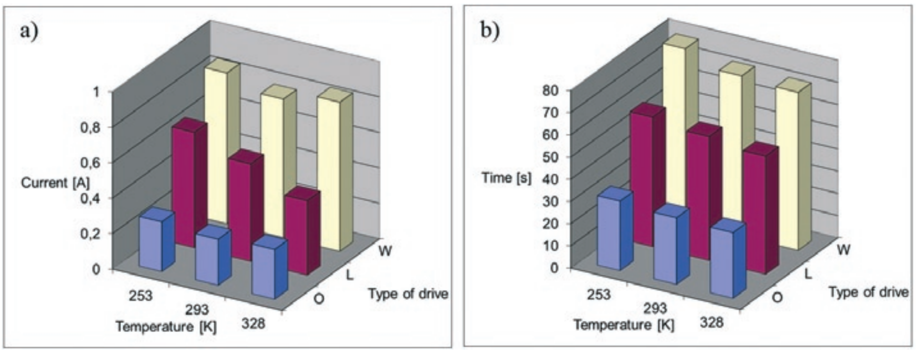

Fig. 10. Comparison between power consumption (a) and time of movement (b) depending on work temperature

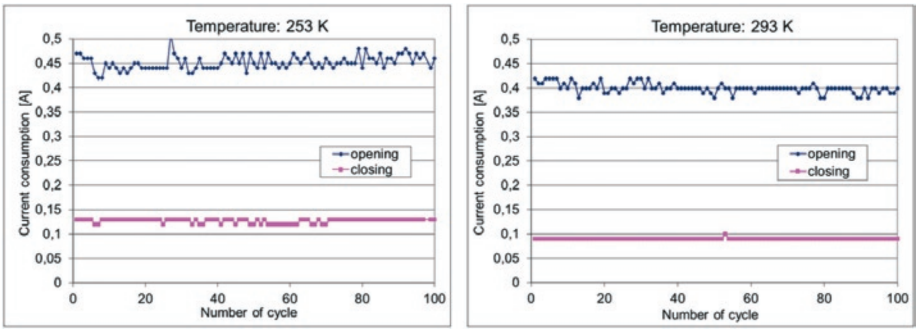

Fig. 11. Comparison of average power consumption for a chain drive in a set movement

drive, and its impact on the power consumption at the time of constant load in changeable temperature conditions (Tab. 1).

The tested actuators were supplied with 24V DC. The tests were conducted at set temperatures after a two hour conditioning period ensuring constant thermal conditions in the entire volume of the object.

8. Test results

During tests, basic parameters deciding on the possibility to use tested actuators in smoke extraction systems were recorded. These parameters included the supply voltage and current, and the shift at the time of loading a working element in the unction of time (Fig. 7, Fig. 8, Fig. 9).

Due to low dynamics of tested actuators, the recording of measurement data was performed in a discrete manner, with the sampling frequency of ca. 2Hz, which was sufficient to conduct a necessary analysis.

The software used in the test system enables the observation of the recorded characteristics in an on-line mode, which allows their current control. The characteristics presented were designed in an external software for the analysis of test results, and developed based on the data archived in *.csv files.

Analysing the changes in recorded work parameters of the actuators, a clear division into three areas can be made. The first area includes the time from the activation to the beginning of the movement of fixed nature; the second – the movement; and the third – the deceleration zone within the internal safety system.

Actuators W and L, during the initial movement, are characterised by increased consumption of power with non-linear waveform. Additionally, the level of value of power consumption depends on the temperature in which the test is conducted. The power features of the actuator O are characterised by a stable waveform over the entire work range of the device. Fluctuations and single peaks visible in the graphs of power characteristics indicate the changeability of internal resistance to movement occurring during the operation of the actuator.

For all tested actuators, the shift is described by linear characteristics, in which the value of the shift is directly proportional to the time of their activation. This means, that the shift of the actuator is of uniform nature, regardless of the momentary changes in resistance to movement.

Constant functions describing the graphs of characteristics of external loads and the supply voltage maintained, unambiguously document the stable conditions of the test process.

In order to increase the readability of the obtained results, based on the recorded characteristics, mean values for individual parameters (Tab. 2, Tab. 3, Tab. 4), deciding on the possibility to use the actuators tested in fire protection systems, were determined.

9. Analysis of the results

According to the test procedure define by the existing regulations [7], the verification of the controlled drive work parameters is performed in conditions corresponding to the temperature of the surrounding. In this case, for all tested objects, no changes exceeding 5% of the initial value (for the temperature of 293K) were recorded. Analysing the results obtained for changeable temperature conditions (in the range specified by the manufacturer) it can however be noticed, that changes in tested values take place at a significantly higher level (Fig. 10)

In the case of spindle and rotary drives, the range of changeability of the maximum power consumption (8.2%), and the time of movement during the opening (7.7%) did not exceed the allowed 10% of the initial value. In the case of chain drives, however, a significant increase in power consumption exceeding 15% was observed for subzero temperatures.

This tendency is confirmed by the analysis of power consumption in the area of operation set at the time of durability tests performed for extreme work temperatures (Fig. 11).

In this case, similar tendencies could be observed as well. At the time of tests conducted at the temperature of 253K, an increase in the mean power consumption was recorded both at the time of opening (12%) and closing (42%).

The tests performed also enabled the assessment of the efficiency of the operation of the overload protection used in the control system of the tested actuators. In some cases, at higher temperatures, the activation of the overload protection was observed, even when there was no increase in load over its nominal value. This constitutes an error, which totally excludes the possibility to use an actuator in applications were higher temperatures may occur as a result of fire.

10. Conclusions

Providing the required level of safety enabling reliable activation of the smoke extraction installation and the evacuation of people is possible thanks to the use of electric actuators characterised by a stable level of electricity consumption, regardless of the temperature of the surrounding. In case of fire, this feature is extremely important particularly due to the fact that together with the increase in temperature, the electrical conductivity of wires decreases, which results in an excessive voltage drop.

The test stand used for the experiment enabled the performance of the tests for typical electric actuators of different architecture in conditions of simultaneous power and thermal exposure. The registered characteristics document the existing differences in work parameters of individual actuators. The induced thermal exposure enabled the determination of the range of parameter changeability, depending on the temperature of the work environment.

The results obtained for the tested drives indicate the lowest power consumption for drives at the temperature of 293 K. When the temperature drops, a significant increase in power consumption can be observed, while at increased temperatures, the power consumption increases slightly only in the case of rotary and spindle drives.

It was noticed, that the time of activation of all tested objects shortens together with the increase in temperature.

The increased power consumption at lower temperatures can be dangerous particularly in the case of multi-storey buildings, when the fire breaks during winter time on its lower levels. In such a situation, cold actuators of smoke extraction flaps located on a building's roof or attic may require such parameters of the electric power, which cannot be provided by the installation, which due to its overheating in the area of fire, is no longer efficient.

Another particularly valuable element of the tests conducted were the results of the effectiveness of work of overload protection. An in-depth verification of this significant parameter can be conducted only in the case of tests performed at increased temperatures.

Based on the tests performed and the results recorded for three, out of many commercially available actuators, it is therefore reasonable to conduct extended certification tests, in which operating characteristics of the actuators are recorded on-line, simultaneously for different temperatures. This constitutes a significant modification to the existing regulation, according to which characteristics are recorded only for the temperature of the surrounding after the heating or cooling of a tested actuator.

The main direction of works necessary for maintaining the reliability of smoke extraction systems is the diagnosis of complete systems in conditions and the scale resembling their real application conditions, which was provided by the developed test stand and methodology.

The test results recorded confirm the possibility of additional application of the stand as a device for verification tests for diagnosis and prognosis systems. The implementation of additional acceleration sensors extending the diagnosis possibilities of the stand will be the scope of further research concerning the development of the scientific works undertaken.

Due to the unique possibilities of reconstructing the changeable conditions of temperature and humidity, the stand can also be used to test actuators used in aviation, maritime and land transport.

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References

1. Balaban E., Bansal P., Stoelting P., Saxena A., Goebel K., Curran S.: A diagnostic approach for electro-mechanical actuators in aerospace systems. Proceedings of the Aerospace conference IEEE, March 2009: 7-14
2. Balaban, E., Saxena, A., Goebel, K., Byington, C., Watson, M., Bharadwaj, S., Amin, S. Experimental data collection and modeling for nominal and fault conditions on electro-mechanical actuators. Proceedings of the Annual Conference of the Prognostics and Health Management Society 2009: 1-15.
3. Balaban, E., Saxena, A., Narasimhan, S., Roychoudhury, I., Goebel, K., & Koopmans, M.: Airborne Electro-Mechanical Actuator Test Stand for Development of Prognostic Health Management Systems. Proceedings of Annual Conference of the PHM Society. October 10-16, 2010: 1-13.
4. Balaban, E., Saxena, A., Narasimhan, S., Roychoudhury, I., Goebel, K. Experimental Validation of a Prognostic Health Management System for Electro-Mechanical Actuators. The American Institute of Aeronautics and Astronautics AIAA Infotech@ Aerospace Conference, 2011: 1-12.
5. Bodden, D., Clements N., Schley B., Jenney G.: Seeded Failure Testing and Analysis of an Electro-Mechanical Actuator. Proceedings of the Aerospace Conference IEEE, March 2007: 1-8.
6. Byington, C., Watson, M., Edwards D.; Stoelting P.: A model-based approach to prognostics and health management for flight control actuators. Proceedings of the IEEE Aerospace Conference, 2004: 3551 -3562.
7. Dziennik Ustaw - rok 2007 nr 143 poz. 1002.
8. Gałaj J., Jaskółowski W., Karpovič Z., Šukys R., Badanie wpływu impregnacji ogniochronnej na skład i ilość produktów toksycznych powstałych podczas spalania drewna sosnowego. Bezpieczeństwo i Technika Pożarnicza 2011; 3: 55-62.
9. Garinei A., Marsili R.: A new Diagnostic Technique for Ball Screw Actuators. Measurement 2012; 45: 819–828.
10. Granovskiy E. A., LyfarI V. A, Vorona A. P., Barbuca M., Jarosz W., Modelowanie ewakuacji podczas pożarów budynków - analiza ryzyka. Bezpieczeństwo i Technika Pożarnicza 2011; 4: 59-63.
11. He Yaping, Wang Jian, Wu Zhenkum, Hu Lu, Xiong Yi, Fan Weicheng: Smoke venting and fire safety in an industrial warehouse. Fire Safety Journal 2002; 37: 191-215.
12. Jensen S., Jenney G., Dawson D.: Flight test experience with an electromechanical actuator on the F-18 Systems Research Aircraf. Digital Avionics Systems Conference DASC, vol. 1, 2000: 1-10.
13. Jie Ji, Kaiyuan Li, Wei Zhong, Ran Huo. Experimental investigation on influence of smoke venting velocity and vent height on mechanical smoke exhaust efficiency. Journal of Hazardous Materials 2010; 177: 209-215.
14. Koopmans M., Hooven R., Tumer I. Reliability based design recommendations for an electromechanical actuator test stand". Annual Conference of the Prognostics and Health Management Society, 2010: 1-15.
15. Koopmans, M. T., Tumer, I. Y. Electromechanical Actuator Test Stand Coupling Design to Support Actuator Prognostic Model Development. Proceedings of the ASME Design Engineering Technical Conferences, 2011: 1285-1296.
16. Koopmans, M. T., Tumer, I. Y. Function-based analysis and redesign of a flyable electromechanical actuator test stand. Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, 2010: 1-12.
17. Kozioł S., Matras E., Zbrowski A.: Modular system for testing the stability and safety of specialised height rescue vehicles. Solid State Phenomena 2013; 199: 55-60.
18. Kozioł S., Zbrowski A.: Metoda poprawy bezpieczeństwa budynków poprzez zastosowanie odzysku ciepła w układach wentylacji pożarowej. Bezpieczeństwo i Technika Pożarnicza 2012; 3: 39-45.
19. Kubicki G.; Wiche J.: Safety Way® – pierwszy inteligentny system ochrony przed zadymieniem dróg ewakuacji. Ochrona Przeciwpożarowa

2010; 3: 24-26.
20. Longoria, R. G., LeSage, J., Shutt W.: Modeling and Requirements Formulation for Submarine Control Surface Actuation Systems. American Society of Naval Engineers Day 2010: 8-9.
21. Matuszewski P, Żybura R.: Testowanie przeciwpożarowych klap odcinających a bezpieczeństwo budynku. Chłodnictwo i Klimatyzacja 2010; 6: 67-68.
22. Mazur D. Elektryczne napędy - nowe możliwości. Świat Szkła 2006; 1: 24-46.
23. Mazurkiewicz A. (kierownik): Projekt Strategiczny POIG.01.01.02-14-03/09 UE/NCBiR „Innowacyjne systemy wspomagania technicznego zrównoważonego rozwoju gospodarki".
24. Mizieliński B. Systemy oddymiania budynków, WNT, Warszawa 1999.
25. Narasimhan S., Roychoudhury I., Balaban E. , Saxena. A.: Combining Model-Based and Feature-Driven Diagnosis Approaches A Case Study on Electromechanical Actuators. 21st International Workshop on Principles of Diagnosis, 2010: 1–8.
26. Norma EN 12101-2: Systemy kontroli rozprzestrzeniania się dymu i ciepła, cz.2: Wymagania techniczne dotyczące klap dymowych.
27. Owens K i inni: Electromechanical Actuator Test Apparatus. US Patent No 7775120B2. 17 Aug, 2010.
28. Półka M., Analiza toksyczności produktów rozkładu termicznego i spalania uzyskanych z wybranych materiałów epoksydowych. Bezpieczeństwo i Technika Pożarnicza, 2010; 3: 73-82.
29. Samborski T., Zbrowski A., Kozioł S.: Modelowy system do badań osłon przeciwwietrznych z czujkami dymu. Technologia i Automatyzacja Montażu 2012; 3: 33-39.
30. Sawicki J. Wytyczne sterowania urządzeniami przeciwpożarowymi. Bezpieczeństwo i Technika Pożarnicza nr 2007; 2: 75-90.
31. SFPE Handbook of Fire Protection Engineering, 2008 Edition.
32. Sitarz G.: Zastosowanie pneumatyki w budownictwie - Klapy Dymowe. Pneumatyka 2013; 1: 26-27.
33. Skiepko E. Ciągłość dostawy energii i przekazu sygnału w instalacjach funkcjonujących w warunkach pożaru. Elektro Info 2012; 10: 12-57.
34. Skiepko E. Instalacje elektryczne funkcjonujące w warunkach pożaru. Elektro Info 2006; 3: 54-57.
35. Skiepko E. Wymagania dla instalacji elektrycznych funkcjonujących w czasie pożaru. Elektro Info 2009; 4: 60-66.
36. Skiepko E. Zasady projektowania sterowań instalacji do odprowadzania dymu i ciepła. Elektro Info 2008; 1-2: 82-88.
37. Sypek G., Wiche J. Temperatura a systemy ochrony przed zadymieniem pionowych dróg ewakuacji. Ochrona Przeciwpożarowa 2009; 12: 39-40.
38. Tesar D., Krishnamoorthy G. Intelligent Electromechanical Actuators to Modernize Ship Operations. Naval Engineers Journal, 2008; 120: 77-88.
39. Wiatr J., Jaskółowski W. Wpływ pożaru na wartość napięcia zasilającego urządzenia elektryczne, które muszą funkcjonować w czasie pożaru. Elektro Info 2012; 1-2: 76-83.
40. Wiatr J., Skiepko E. Zasady doboru przewodów elektrycznych w instalacjach oddymiających. Elektro Info 2011; 3: 80-85.
41. Wiatr J. Wpływ temperatury pożaru na wartość napięcia zasilającego urządzenia elektryczne oraz skuteczność ochrony przeciwporażeniowej urządzeń, które muszą funkcjonować w czasie pożaru. Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska 2012; 2: 37-44.
42. Wicks E. System and method for smoke free elevator shaft. United States Patent 5718627. Feb. 17, 1998.
43. Wierciak, J., Szykiedans, K., Rawski, J., Lisicki J. System pomiarowy do wyznaczania charakterystyk elektrycznych siłowników liniowych. Pomiary Automatyka Kontrola 2007; 9bis: 527-530.
44. Zbrowski A., Samborski T., Kozioł S. Research and test apparatus for certification testing in technical rescue systems. Problemy Eksploatacji 2010; 3: 127-138.

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