Automation of Operation Control of the Human Centrifuge

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Abstract— **Human centrifuge is a motion platform used to artificially achieve transient and sustained G-load intended for physiological pilot training under controlled conditions. This paper presents the successful modernization and upgrade of the control system of the human centrifuge. Due to the need for system redundancy, in addition to the new automatic control system, the previously used manual control system had to be maintained, which is provided by the usage of a switch selector. Human centrifuge speed and positioning control algorithms are based on the implementation of a digital PI and P controller.**

Keywords- human centrifuge; computer control system; G-load control

I. INTRODUCTION

Military pilots are exposed to inertial forces due to acceleration, which follows the maneuvering of the aircraft. Pilots take off and fly at high speeds and perform various maneuvers that expose their body to high accelerations (G-load) up to ten times greater than the Earth's acceleration "g". High G-load effects on pilots and aircraft include G-LOC (G-force induced Loss Of Consciousness), neck injuries, vibration effects, reach envelope reduction, vestibular illusions, etc... Pilots can be trained to adapt to such conditions in a human centrifuge, which provides planetary motion to achieve a high-G load (transient and sustained) [1-4].

In this paper, the modernization and upgrade of a control system for the human centrifuge used for testing and training military pilots at Aero Medical Institute in Belgrade are presented. With the mentioned upgrade, the following was required:

- modernization of the control system, including the development of protocols for all operating modes,
- providing the ability to the operators to predefine the G-force load profiles,
- simplifying the operators' activities while providing safety and reliability in operating.

The paper is divided into four sections. Section 2 provides technical details and required operational characteristics of the presented CMS modernization. The implementation of digital proportional-integral and proportional control for speed and positioning control is presented in section 3. Finally, section 4 presents the appropriate conclusions about the modernized system and the improvements that are obtained.

II. DETAILS OF HUMAN CENTRIFUGE MODERNIZATION

The centrifuge described in this paper is a 1DoF rotating system with a vertically mounted supporting shaft on which a horizontal rotating structure in the shape of a beam is fixed in the middle. The beam rotates in a horizontal plane (planetary motion) with a total length of 18 m, and at both ends, it supports a cockpit in which tests of objects and humans are performed in regard to accelerations achieved due to centrifuge rotation (Fig. 1).

Figure 1. Human centrifuge motion simulator installed at Aero Medical Institute in Belgrade

As a consequence of planetary motion, the centripetal force turns the cockpit for $\pi/2$, and the pilot's G_z axis keeps the direction of centrifugal acceleration. The maximum angular velocity of the vertical output shaft of the centrifuge is n_c=45 rev/min. At this speed, the centrifugal acceleration of the cab and the object in it reaches a value a_c=200 m/s^2, for radius R=9 m. It is common for acceleration to be measured in relative units G, multiples of the acceleration of the earth's gravity g=9.81 m/s^2, which is taken as a unit, and the maximum acceleration of the centrifuge is a_c=20.4G.

A twin DC motor with a power of 450 kW is utilized to actuate the rotation of the system about the vertical axis. The horizontal axis of the twin motor is coupled with the centrifuge planetary axis by means of two-speed reducers: horizontal and vertical, with a total reduction ratio k=12.43. The twin motor that drives the centrifuge is part of the large Ward-Leonard drive system. Motor voltage is provided by a suitable DC generator that is rigid coupling with the medium voltage asynchronous motor. The excitation of the main generator and the regulation of its output voltage level is provided by a special excitation generator G_g, while the constant excitation current of the main motor is provided by another excitation generator G_m (see Fig. 2). The operation of the centrifuge is controlled by acting on the excitation current of the excitation generator via DC converter. The excitation current of the main motor is not regulated; it is practically a constant that is established by another DC converter.

Taking into account the operators' requirements, the technical data on mechanical structure utilized equipment and control elements within the entire human centrifuge system, which was previously controlled manually, novel automatic programmatically (in a sense that it enables operators to control machine by assigning G-Load profiles) control system was adopted and had to be developed. At the same time, the basic requirement to preserve the existing manual control system and to ensure a smooth transition from automatic to manual control had to be met. The choice between automatic or manual control mode is made using the selector switch. The whole system can be differentiated into three segments (see Fig. 2):

- G-load diagram screen,
- controller for automatic control,
- output signal power amplifier.

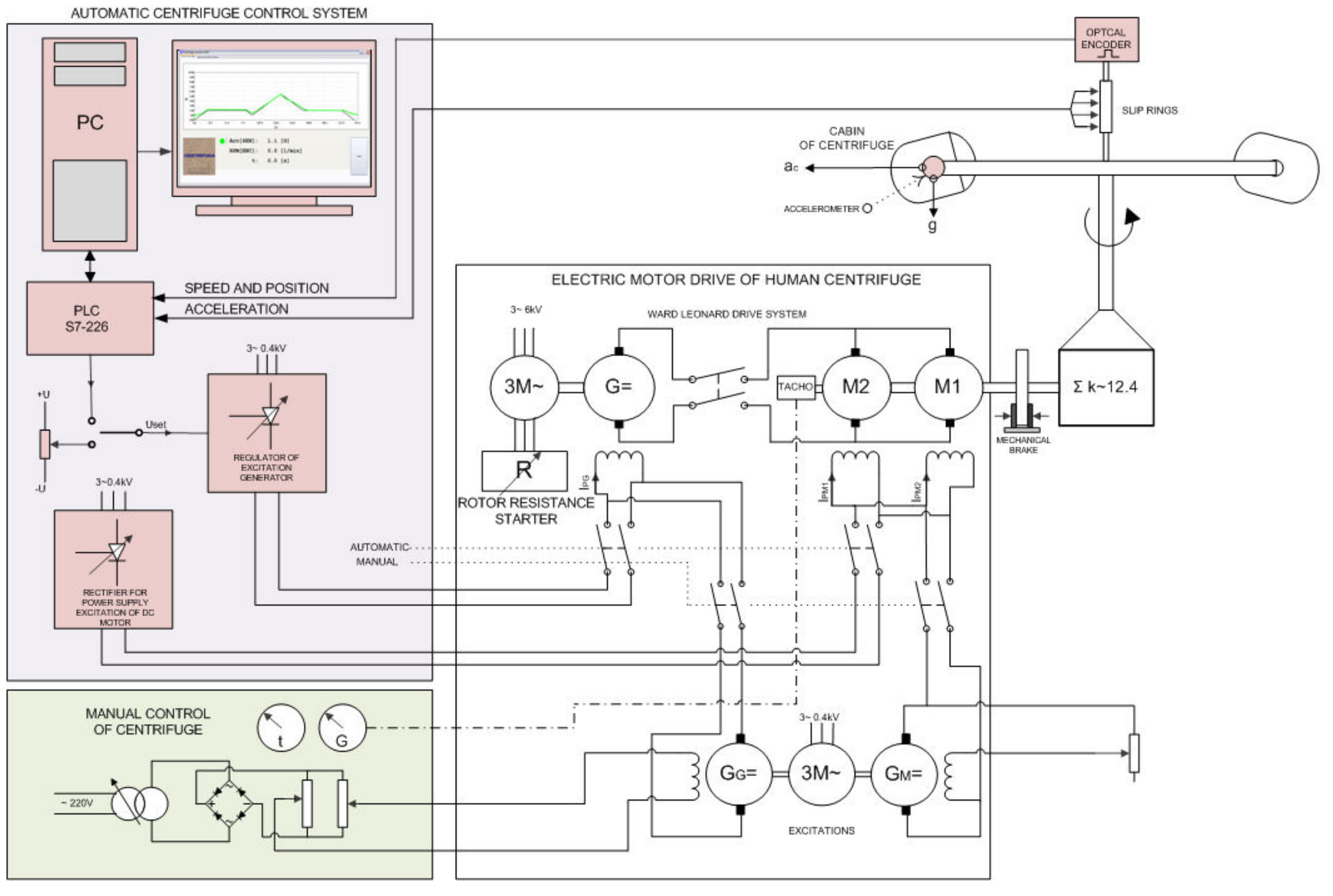

Figure 2. Block diagram of the implemented solution automatic control for human centrifuge

A. G-load diagram screen

The PC graphical user interface, named G-load diagram screen, is intended for operators to create pre-programmed G-load profiles, but also for the display of the measured acceleration values in the centrifuge cabin obtained by the independent accelerometer sensor. The programming of G-load profiles is performed in the G profile editor. Desired acceleration profile refers to the desired acceleration change in the direction of G_z axis attached to a pilot (i.e. inertial centrifugal acceleration). The operator's program is transmitted to the PLC controller that executes the set G-force curve after editing in the form of a recipe via the RS232 serial channel. Also, this system allows recordings of various G-force curves, which could be called and downloaded to the controller (Fig. 3).

By using the monitoring window, it is possible to monitor and display all relevant signals that influence the performance of the position and speed control: reference speed value, the achieved speed value, programmed acceleration profile, measured acceleration (obtained by independent accelerometer). Communication between PC and PLC is established using Freeport mode in PLC controller [5]. A user-defined communication protocol for data transfer to PLC and vice versa has been created.

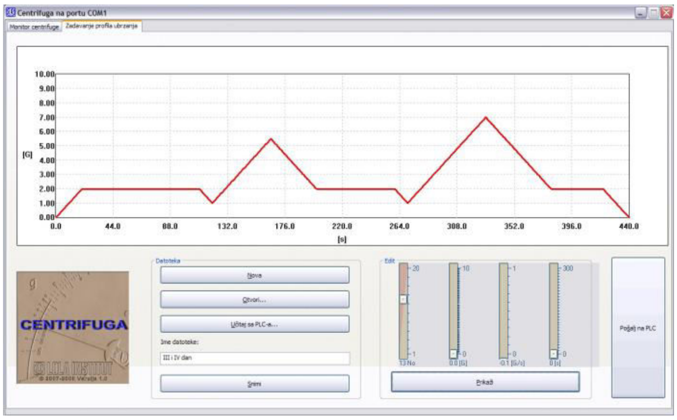

Figure 3. The graphical user interface of G-load profile editor

B. *Controller for automatic control*

In this case, the device for automatic control is the SIEMENS S7-226 PLC controller when enabled:

- establishing communication with the PC where G-load diagram screen is installed,
- reception and processing of encoder signal for calculation of current speed and centrifuge position,
- closing the speed and position control loop,
- setting the angular speed of the engine to obtain the desired G-load value,
- control of safety protocols regarding conditions of and in the centrifuge and protection of technological equipment through detection of equipment failures.

C. *Output signal power amplifier*

The output signal amplifier is a 3-phase, 4-quadrant thyristor controller adapted to the functional requirements of the centrifuge drive. In relation to the old solution, the thyristor regulator replaced the excitation generator G_g of the Ward-Leonard group generator. The advantages of installing a thyristor regulator and a static semiconductor rectifier in the Ward-Leonard drive group in relation to the excitation generators Gg and Gm are the following:

- significant reduction in the system time delay,
- less physical space required (two electric machines less),
- minimal maintenance (no moving parts),
- lower energy consumption.

III. IMPLEMENTATION OF PI AND P CONTROLLER

As the mathematical relation between the rotational speed of the centrifuge and the acceleration is square, in order for the absolute value of the acceleration to change linearly (as requested by the operators), the speed of rotation of the motor must change nonlinearly, according to the parabolic law. The G_z acceleration is measured in two ways: indirectly (by measuring the speed of rotation of the centrifuge shaft via incremental encoder and calculation) and directly (via an accelerometer placed on the cockpit seat). Due to the complexity of the drive group, programmed centrifuge control consists of several control algorithms (Fig. 4), which basically represent the realization of a digital PI algorithm.

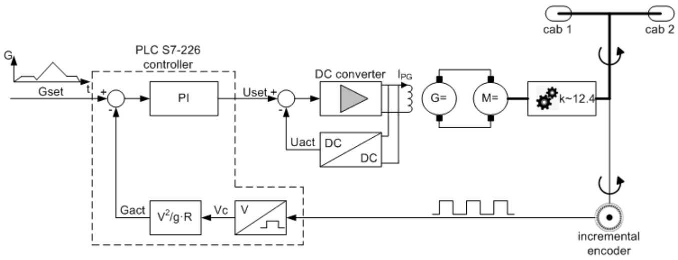

Figure 4. Block diagram of G load control

The G-load (G_z acceleration) controlling algorithm is based on the realization of a digital PI algorithm whose equation is given by the expression [6-7]:

$$u(k) = K_p\left[e(k) + \frac{T}{T_i}\sum_{i=0}^{k} e(k)\right], \tag{1}$$

where $u(k)$ is the control variable, $e(k)$ is the difference between the setpoint value and the measured value of the G_z acceleration calculated from the centrifuge angular velocity at discrete moment kT, T is sampling time, T_i is the integration time constant. In practice, T sampling time actually represents the refresh time of the control variable, i.e., how often the algorithm is executed. In the user PLC program, the PI algorithm is placed in a particular program that is executed cyclically, and T is the time interval between the two executions. The tracking performance of the controller is considered reasonably satisfying, taking into account the large transportation delay of the entire centrifuge drive system (Fig. 5).

Figure 5. The centrifuge monitor in during test - reference (black line) and actual (green line) G-force load

The operation of the centrifuge is regulated by acting on the excitation current of the excitation generator. The excitation winding of this generator has considerable inductance and ohmic resistance. Its time constant largely determines the delay of changes in centrifuge speed to changes in excitation current. Also, the time constant of the excitation winding of the main generator contributes to the delay. The time interval for achieving mechanical acceleration is also large and amounts to about two seconds. Measurements have shown that the centrifuge system as a whole is quite inert and that its total time control constant is about 3.6 seconds.

When the control program sequence is completed, the cockpit must be returned to its original position. Due to the residual magnetism of the electric machines, the centrifuge will continue to rotate slowly even when the set G-force load voltage is zero. Stopping the centrifuge is done by the control action, which originates from the integral action. The centrifuge position control algorithm is based on the realization of the digital P algorithm because, in this case, the integral member originates from the drive group. In this case, to compensate for the effect of rotor magnetization that affects the stationary positioning error in the final position control expression, we add a compensation member $u_z(k)$, approximately equal to the stop voltage obtained from the speed control algorithm at a given zero load:

$$u(k) = K_p e(k) + u_z(k). \tag{2}$$

After deceleration according to the speed algorithm to the stopping speed with a G-force load reduction of 0.1 G/sec, the position control algorithm is switched. This enables a smooth transition from speed to positional control algorithm, which allows us high positioning accuracy of centrifuge cockpit.

IV. Conclusion

The paper presents the successful modernization of the control system of the human centrifuge and in terms of implementation it is a unique solution. In order for the automatic control of the centrifuge to be set as a technical requirement, it was necessary to study the manual control system on the basis of which the detailed development of the program control system took place. The choice of equipment and the control structure met the required requirements while retaining the Ward-Leonard drive system. Automatic control of centrifuge is divided into two parts: G-force load control (speed control) and positioning control. In addition to a simple and modern user interface on the G-load diagram screen PC computer, the realized servo controller with output signal power amplifier, in addition to the satisfying accuracy of the execution of the given trajectory, also enables the high positioning accuracy of the centrifuge cockpit.

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