Methodology of the Main Drive Selection for a Human Centrifuge

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In this paper, the issue of the main drive selection for a Human Centrifuge is is explained, starting from the flight envelope that needs to be simulated. The main objective is to emphasize the complexity of choosing a drive, since it is a high power drive. The methodology for the main drive selection of a Centrifuge for pilot training, which is a manipulator with three degrees of freedom of motion, is built upon the main demand to achieve an extreme gradient and load coeficient per unit of time. The methodology consists of determining the necessary torque and power of the main drive of the Centrifuge. To achieve the main requirement, the engine has to work with an overload in a given time interval at the beginning. For calculations and diagrams, the MATLAB program was used. In this paper, an example of a motor of the Swiss manufacturer ABB is given. Its features are explained in detail, according to the needed torque and power of the main drive. All numerical values in this paper, are a part of a preliminary calculation.

***Keywords**: Human Centrifuge, Flight Dynamics, Velocity, Acceleration, Main Drive, Torque, Power.*

1. INTRODUCTION

The use of supermaneuverable aircraft in aviation, led to the need to develop sophisticated flight simulator. Their purpose is to simulate as closely as possible real flight conditions and thereby provide an effective pilot training. Drastic increase in the angle of attack, engine thrust vectoring, flight in the post-stall regime and other characteristics of supermaneuverability opened the problem of efficient pilot training. On the other hand, durability of materials, used for constructing such aircrafts, avionics and overall equipment are also put on the endurance test.

The concept of a Human Centrifuge is significant from two aspects: from pilot training, and sustainability of materials. Over time, a large number of simulators were developed. Primarily, they differ in purpose, and therefore constructive characteristics. Some simulators have the task to train pilots, exposing them to a very high g-load, while others are tasked to increase pilot situational awareness.

In the case of pilot endurance test, the pilot is exposed to a preprogramed training profile to a certain extent, in the so called open- loop regime, or in a closed-loop regime, where the pilot chooses by himself certain training by pulling the stick in the gondola, in limited conditions. In the case of training to increase situational awareness, the emphasis is on disorientation, like visual deception of the trainee rather than straining the physiology. The pilot is exposed to different motions and scenarios on the screen and other effects, in order to lose confidence in its own senses and to trust only the indicators in the cockpit. The development of Human Centrifuges is fully justified from an economic point of view. Taking into account the price of just one-hour flight of an aircraft, it is clear that training in simulators is justified. In the world, today, there are simulators with six, five, four and three degrees of freedom motion (DoF).

The Human Centrifuge explained in this paper has three Degrees of Freedom of Motion. The problems of the Centrifuge, in this case, are related primarily to a very harsh demand. There is a requirement to achieve a load gradient of 9 g/s. Consequently, the selection of the main drive is done in accordance with that requirement.

2. CENTRIFUGE SIMULATOR

2.1 Flight Dynamics and Supermaneuverability, Coordinated turn

Supermanuverable flight is characterized by high angle of attack α, $\alpha > \alpha_{kr}$, high g-load onset rate, so that the aircraft stays controllable [1]. Supermaneuverability is a term that describes the capability of an aircraft to operate beyond the conventional flight envelope limits in a controlled way.

Although no strict guidelines exist for categorizing an aircraft as supermaneuverable, there is a qualitative consensus that these aircraft must exceed a threshold of maneuverability beyond the limit of that afforded by conventional aerodynamic control, i.e. the control capabilities afforded by standard control surfaces such as elevator, rudder, etc. [2]. Supermaneuverability refers to unusual flight trajectories presently investigated with high performance fighter aircraft.

Due to the cost and danger of supermaneuver, currently, most supermaneuverable flight trajectories have not actually been flown in aircraft, but studies with 1/7th size prototypes and also in motion simulators, e.g.

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a Centrifuge, are conducted to investigate structural problems and the measurement of the linear and rotational accelerations and forces that would act on a pilot during a specified maneuver [3].

For example, a maneuver that requires a transition to an extreme dynamic post stall regime is the Pugachev's Cobra supermaneuver Figure [1].

Figure 1. Pugachev Cobra supermaneuver, Viktor Georgiyevich Pugachyov, test pilot

2.2 Structure of the Human Centrifuge

The Human Centrifuge consists of three main components: main arm, forming the main planetary axis, gimbaled gondola at the end of the arm, capable of rotating in two axes, roll and pitch axis.

The appearance of the motion simulator is shown in Figure 2. The following table shows some basic Centrifuge characteristics. The Centrifuge is a three axis device which has been used to replicate agile flight or supermaneuvers that an aircraft may fly in a combat scenario. In order to simulate the maneuvers, it requires the. Centrifuge is required to utilize simultaneous multiaxes motion [4].

3. SELECTION OF THE MAIN DRIVE

3.1 Methods

The basis for calculations related to the Centrifuge, is the main requirement, as stated above, to achieve an onset of 9 g/s. It is important that during the training in the flight simulator in motion, the trainee does not feel the sudden jumps and falls of g load. This means that there is to be provided a continual growth of g-load. On the other hand, side-load g_y and transverse-load g_x must be minimized to simulate coordinated turn, although the Centrifuge may provide all three loads. Load g_z is therefore most important for training, given that it has the highest value in real flight.

For this reason, training is performed with the so called pure g_z load. The motion in which the following conditions are met:

$$g_r = g_z, \quad g_x = 0, \; g_y = 0 \,, \tag{1}$$

is called coordinated motion.

Table 1. Centrifuge design parameters

Centrifuge parameter	Value
Maximum g	15 g
Research Mode	15 g
Training Mode	9 g
g onset value	9 g/s
Arm lenght	8 m
Mass (approximated)	90,000 kg
Gondola equipment	adjustable pilot seat audio, video and intercom equipment G-protection equipment medical monitoring equipment
Medical monitoring system	32 channel

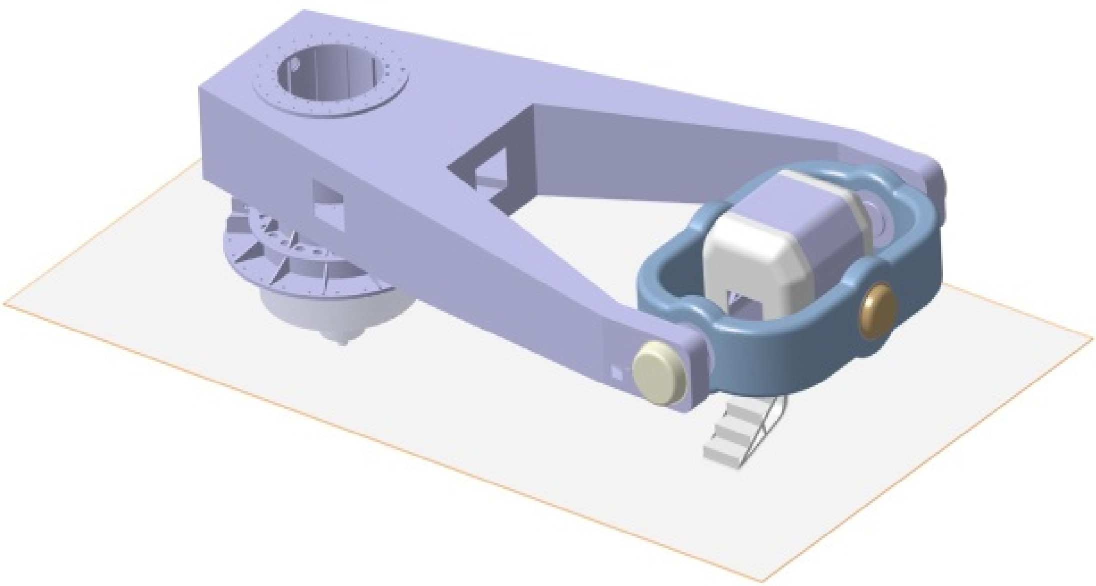

Figure 2. Human Centrifuge [1]

Another, very important condition for coordinated motion in a Human Centrifuge is adjusting the roll angle -φ and pitch angle -θ to achieve the desired training profiles. By adjusting the pitch angle -θ, large tangential acceleration can be compensated. Tangential acceleration is not of that magnitude in real flight. The graph of the continual onset of g_z load is given in Figure 3.

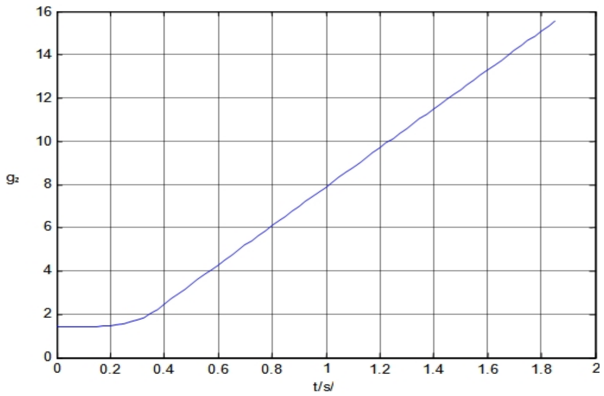

Figure 3. Function of time - g_z(t), with transient process

Figure 3. shows the continual onset of g_z load as a function of time in coordinated motion of the Centrifuge, from the moment t = 0 s. At time t = 0 s, g_z load is not equal to zero, but 1.41 g. Constructors of Human Centrifuges, such as the Austrian AMST-Systemtechnik GmbH, use this value of initial acceleration of the Centrifuge. Baseline acceleration is a constant value from which the Centrifuge training profile starts (in any control mode) [5]. When the main arm rotates, specified accelerations act on the pilot, such as acceleration of gravity and normal acceleration.

The tangential acceleration equals zero, because the number of revolutions per minute is constant. The magnitude of the resulting acceleration vector, which is given by the sum of these two vectors, is $\sqrt{2}$ g and 1.41 g. respectively When the arm starts rotating, it does not accelerate from time t = 0 s to load 9 g directly, but from a plateau of the aforementioned initial acceleration.

It is very important to expose the trainee to a large load in a short time, to avoid tiredness of his body, even before the training profile is reached. A value of 1.5g as the initial reference value, as stated by Swedish researcher Britta Levin, with his collaborator Dennis Kiefer. Aircraft Gz is mapped into DFS Gz with a smooth nonlinear mapping which provides a 1.0 aircraft Gz trim point when the DFS motion base is typically at 1.5 Gz. The pilot adapts quickly to this new trim acceleration. It allows some pushover effect when the pilot moves the stick forward [6]. One U.S. patent provides initial acceleration value from 1.55 G [7]. From Figure 3. g_z load increases linearly from t = 0.3 s. In the interval from t = 0.2 s to t = 0.4 s, there occurs the transient process.

Figure 4 shows the change in load g_z, for coordinated motion, with marked transient process. When the motor accelerates, a transient period is created until the motion becomes linear. To select a motor, except the g_z characteristic, the characteristic of angular velocity changes of the Centrifuge arm is needed.

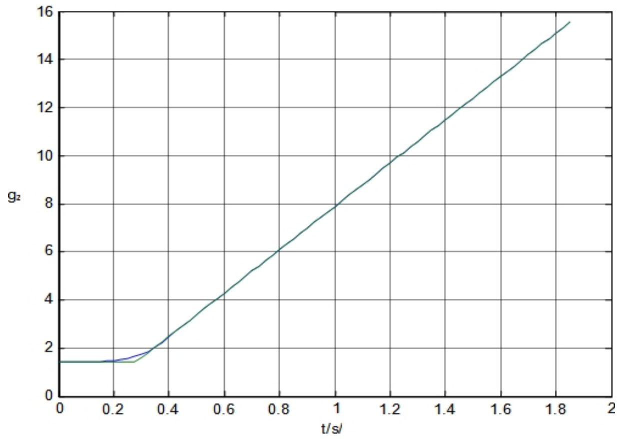

Figure 4. g_z function with marked transient process

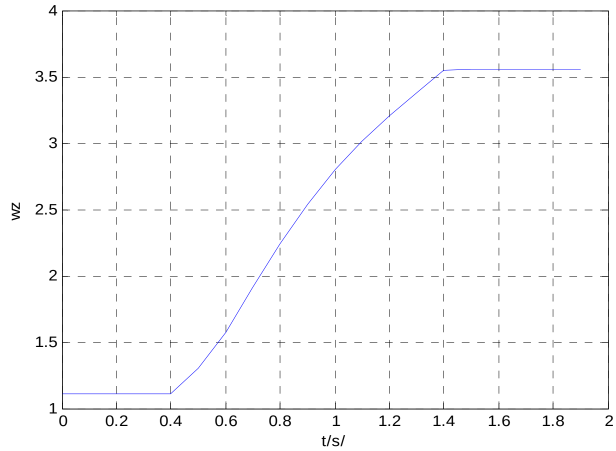

Figure 5. Change of ω_z as time function ω_z (t)

Figure 5. shows the onset of arm angular velocity depending on time t. From the diagram it is evident that the onset from t = 0 s to t = 0.4 s has a constant value, and then it rises in an interval from t = 0.4 to t = 1.4 s. The onset is not linear, because of very large tangential acceleration. In real flight, fighter jets perform a coordinated turn with a large radius of action. As the Centrifuge arm is 8 meters, the emergence of large tangential acceleration is inevitable. In order to avoid that pilots sense a strong transverse load ratio, which is a consequence of tangential acceleration, the pitch angle θ has to be adjusted. The onsets of normal and tangential acceleration are given in Figure 6 and Figure 7.

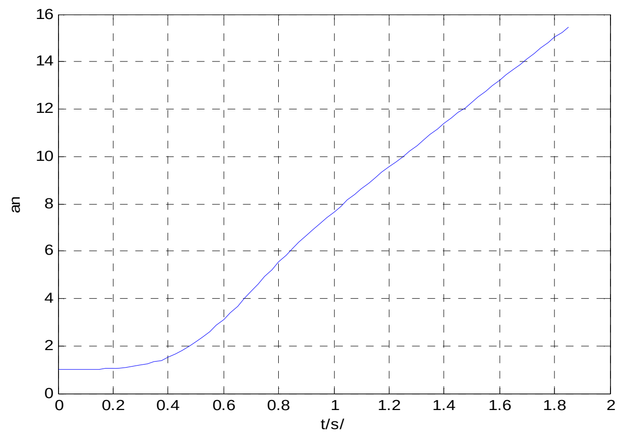

Figure 6. Change of normal acceleration as function of time an. in unit [1/g]

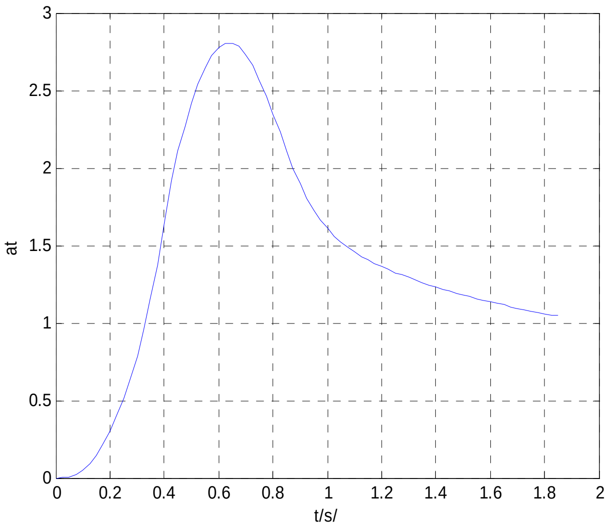

Figure 7. Change of tangential acceleration with transitient process a_t in unit [1/g]

Values of a_n and a_t have to be multiplied with g, to be expressed in [m/s^2]. Equations which were used for the given distribution of g_zi ω_z are the following:

$$g_z = \sqrt{a_n{}^2 + g_x{}^2 + 1} = f(\omega_z)\,, \tag{2}$$

$$\omega = \frac{d\varphi}{dt}, \tag{3}$$

where φ_z is the angle of arm rotation about the main axis.

$$a_n = r\omega_z^2\,, \tag{4}$$

$$a_t = \frac{dv}{dt}\,. \tag{5}$$

The onset diagrams of g_z and ω_z are very important, because the principles of these changes are essential to determine the required torque and engine power. Coordinated motion of the Human Centrifuge requires that values g_y and g_x, as mentioned above, are zero. In other words, there is a requirement for a, so-called, pure g_z profile, or more precisely, that the resultant load g_r reduces only to g_z.

3.2 Results

First, it is necessary to perform a calculation of mass moments of inertia of all members of the Centrifuge. The Centrifuge consists of the following main elements: counterweight, central part, centrifuge arm, gondola with equipment, roll and pitch axis drives.

The preliminary Centrifuge structure is shown in Figure 2. Initial conditions for the analysis, in conjunction with the main rotational motion of the Centrifuge are: the onset of acceleration, arm length and moment of inertia for the main axis of rotation z, which is the figure axis:

$$\frac{\Delta a}{\Delta t} = 9\ \mathrm{g/s},\ \ r = 8\ \mathrm{m},\ \ J_z = 350000\ \mathrm{kgm}^2\,. \tag{6}$$

The value of the mass moment of inertia J_z from (6) is not obtained directly from the calculation. The value obtained is enlarged by a particular value, as in all cases of mechanical structures design. The onset of values is analyzed for a small time increment.

This paper presents an analysis for time increment of 0.1 seconds, although, in reality, calculations are performed with very small increments. The Equations used are given in the previous section. Results are shown in Table 2. Based on data from Table 2, it can be concluded that for achieving an acceleration onset of 9 g in one second, the required engine power is 1.9519 MW. At the initial moment, when the arm starts rotating, the acceleration in t = 0 s, g_z is 1.41 g, after a time interval of 1 s, as shown in Table 2, there is a total of 10.41 g_z.

In Table 2 kinematic and dynamic equations were used to calculate speed and accelerations, thus torque about the main axis, and consecutively the necessary motor power. By calculating the acceleration, a large value of tangential acceleration is obtained. The diagram of tangential acceleration is given in Figure 7.

The diagram of tangential acceleration is given illustratively to explain the deviation of angular velocity from a linear characteristic. The equation that determines the engine torque is:

$$M = J_z \cdot \dot{\omega}_z\,. \tag{7}$$

Table 2. Required torque and power

t [s]	ω_z	a_n	a_t	g_z	φ [°]	θ [°]	$Mz\cdot 10^6$ [Nm]	P [MW]
0	1.1074	1.0000	0	1.4142	45.0000	0	0.0194	0.2146
0.1	1.2479	1.2700	1.6557	2.3139	51.7836	40.9971	0.7106	0.8868
0.2	1.5062	1.8501	2.4298	3.2136	61.6083	43.3225	1.0429	1.5708
0.3	1.8385	2.7564	2.8846	4.1132	70.0596	40.1812	1.2380	2.2761
0.4	2.1996	3.9456	2.9260	5.0129	75.7782	33.4429	1.2558	2.7623
0.5	2.5360	5.2447	2.5403	5.9127	79.2050	24.6160	1.0902	2.7649
0.6	2.8098	6.4385	1.9892	6.8125	81.1716	16.7295	0.8537	2.3988
0.7	3.0269	7.4715	1.6303	7.7124	82.3767	12.1118	0.6997	2.1180
0.8	3.2146	8.4272	1.4675	8.6123	83.2328	9.7629	0.6298	2.0247
0.9	3.3878	9.3595	1.3716	9.5122	83.9015	8.2616	0.5887	1.9943
1.0	3.5509	10.2824	1.2983	10.412	84.4452	7.1441	0.5572	1.9786
1.1	3.7059	11.1996	1.2375	11.312	84.8977	6.2680	0.5311	1.9683
1.2	3.8540	12.1131	1.1856	12.212	85.2806	5.5624	0.5088	1.9611
1.3	3.9963	13.0236	1.1403	13.111	85.6093	4.9828	0.4894	1.9558
1.4	4.1334	13.9328	1.1003	14.011	85.8947	4.4991	0.4722	1.9519

Based on Table 2, the required torque of the motor is given in Figure 8.

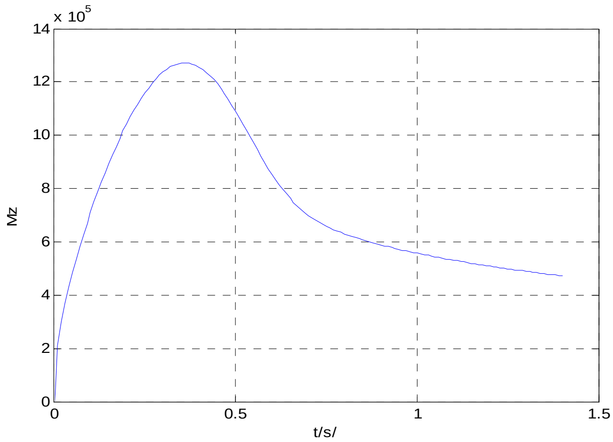

Figure 8. Required torque of the main motion M(t)

Diagrams of the required torque and power are given without the transient process.

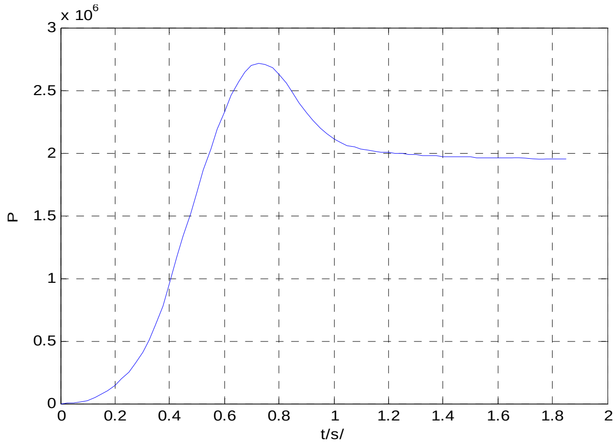

Figure 9. Required power of the main motion

Equations for determining the required power of the main motion:

$$P = M_z \omega_z \,. \tag{8}$$

After determining the necessary engine power, an example of a motor is introduced in this paper and selected from the catalogue of the Swiss manufacturer ABB. As an example, the following ABB motor is mentioned: ABB AMZ 0560LU10_AM [8], 690 V nominal rpm $n_N = 600$ min^{-1}, maximum rpm in the field of weakening magnetic field is $n_{Fmax} = 720$ min^{-1}, nominal power is P_N=2594.201 kW, nominal torque is M_N = 41.288 Nm. Motor overload factor, in case that revolutions per minute are less than the nominal rpm:

$$n_m \le n_N \,, \tag{9}$$

$$f_p = \frac{M_z}{M_N k \eta} \,. \tag{10}$$

Motor overload factor, in case that revolutions per minute are greater than the nominal rpm:

$$n_m \ge n_N \,. \tag{11}$$

$$f_p = \frac{M_z n_m}{M_N k \eta n_N} \,. \tag{12}$$

In Figure 10 the overload factor as function of time is shown:

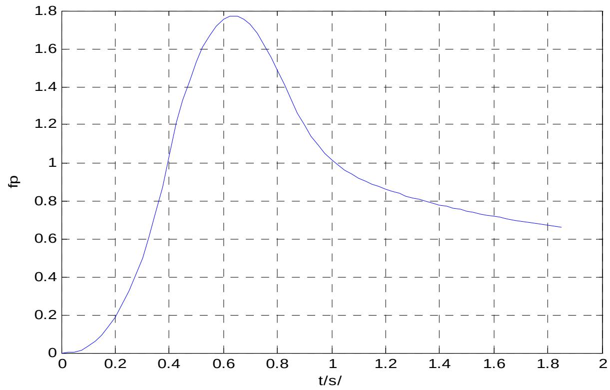

Figure 10. Overload factor, motor. ABB AMZ 0560LU10_AM

For $n_m \le n_N$:

$$M = P_N \frac{n_N}{n},\ P = P_N = const., \tag{14}$$

$M_{max}/M_n = 1.8$, for $n_m \le n_N$, $M_N = 660$ Nm, and for value $n_m \ge n_N$ value $P_N = 4150.7$ kW. If we choose that the centrifuge has to achieve a normal acceleration of a_N = 15 g, the required angular velocity would be ω_z =4.288806 s^{-1}, ie. Arm rpm n = 40.948 min^{-1}. The transmission gear ratio is chosen so that the motor rpm is n_{Fmax}= 720 min^{-1}, arm rpm is n = 41 min^{-1}, so:

$$k = \frac{n_m}{n} = 17{,}5 \,. \tag{15}$$

Then, time t_N is calculated , for which the motor reaches the nominal rpm n_N = 600 min^{-1}, in case that the arm accelerated from the initial normal acceleration a_N = 1.41 g with maximum power and with the overload factor f_p = 1.8. Motor efficiency factor of η = 0.94 is adopted. Based on calculations and data from Table 2, the following conclusion for the given motor can be given: To reach the normal acceleration of $\Delta a_n/\Delta t$ = 9 g/s, and assumed moment of inertia J_z = 350000 kgm^2, the engine runs with the overload factor f_p = 1.8. Overloading continues to steadily declining.

Based on these information, it can be inferred that the motor AMZ 0560LU10_AM (ABB) [5], along with the transmission ratio k = 17.5, completely satisfies the criteria for the centrifuge main drive. Using this method, a comparison of several motors can be performed. The optimal motor is the one that satisfies technical and economical requirements.

4. CONCLUSION

As it was assumed, a high-power engine is obtained by calculation. This opens up many structural problems, such as sustainability of the overall construction and materials, because at high engine revolutions per minute the so called. perceived (artificial) gravity is very high. Due to the engine as the most important component, it will be possible to achieve the necessary load and thus, possible to simulate the exact level of load, which the pilot feels in real flight. High-power engines are among the non-standard engines, because very few mechanical constructions have load requirements of this order of magnitude.

ACKNOWLEDGMENTS

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МЕТОДОЛОГИЈА ИЗБОРА ГЛАВНОГ ПОГОНА ЗА ХУМАНУ ЦЕНТРИФУГУ

Зорана Данчуо, Бошко Рашуо, Владимир Квргић, Владимир Зељковић

У овом раду је изнет је проблем избора главног погона за хуману центрифугу, почев од анвелопе лета коју је потребно симулирати. Основни циљ је да се нагласи сложеност избора погона, јер је у питању мотор велике снаге. Методологија избора главног погона центрифуге за обуку пилота, која представља манипулатор са три степена слободе кретања, заснована је на главном захтеву, да се постигне екстремни градијент и коефицијент оптерећења у јединици времена. Методологија се састоји у одређивању потребног обртног момента и снаге главног погона центрифуге. Да би се постигао основни захтев, мотор мора радити са преоптерећењем у датом временском интервалу у почетном тренутку. За прорачуне и дијаграме, програм МАТЛАБ је коришћен. У овом раду дат је пример мотора швајцарског произвођача АББ. Његове карактеристике су објашњене детаљно, у односу на потребни обртни момент и снагу главног погона. Све нумеричке вредности у овом раду, су део прелиминарног прорачуна.