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High G Training Profiles in a High Performance Human Centrifuge

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In this paper, profiles for training in a High Performance Human Centrifuge (HPHC) are presented. The main objective is to underline the significance of developing various training scenarios in order to achieve optimal preparedness of fighter pilots. This research is based on the NATO STANAG 3827 AMD, a standard that provides values of G tolerance that an aircrew must sustain. An aircrew who do not successfully complete a Rapid Onset Rate (ROR) 7G for 15 seconds centrifuge profile with anti-G suit and straining maneuver will be considered to have low G tolerance, which is explained in detail in this paper. Training profiles are presented graphically, as well as arm angular velocity, roll and pitch angle for each load. The main demand for the Human Centrifuge presented in this paper is to achieve an onset rate of 9G/s. The graphs in this paper are a part of the research conducted in the Lola Institute Belgrade. The examples of training scenarios of several countries are given briefly. G-Induced Loss of Consciousness (G-LOC) episodes are unavoidable during centrifuge training. Effective training of Anti-G Straining Maneuver (AGSM) and increasing pilots G-tolerance contribute to flight safety and thereby reduce the risk of G-LOC and aircraft accidents. The aim of this paper is to illustrate the complexity of parameter settings in order to achieve desired loads

Key words: **centrifuge, human centrifuge, pilot training, G-load.**

Introduction

THE concept of a high-agility flight was first described by Wolfgang Herbst and his colleagues at Messerschmitt-Boelkow-Blohm (MBB) during research conducted in the 1970s. [1]. At the same time, his contemporary Dr. Benjamin Gal-Or researched the high agility concept with Thrust Vectored Propulsion (TVP). High-agility flight challenged human protection as well as aircraft performances.

The term "high-agility" has been loosely used, but often refers to an aircraft's ability to maintain controlled flight at speeds below that of the airframe stall speed. An agreed definition of "agility" remains elusive. Even among experts in the NATO Four Power Group, the definition of agility evolved from one involving primarily airframe maneuverability to one including systems and weapons agility as well [1].

The principal physiological effect of high-agility flight on pilots will relate to abrupt changes in magnitude and/or direction of acceleration experienced by the pilot. Acceleration has been categorized as an "impact" (less than 1-second duration) or "sustained" acceleration (greater than 1-second duration). Sustained acceleration is important in aircraft as a result of centrifugal force during high velocity turns. Previously, impact acceleration was associated with collisions (crashes), turbulence, or ejection escape. Pilots of high-agility capable aircraft will experience both impact and sustained acceleration during maneuvers that may be complete in several seconds [2].

Acceleration is one of the major threats in agile flight. There are many unknown facts about agile flight, especially about its impact on human physiology. Modern, highly maneuverable fighter aircraft are capable of imposing excessive acceleration forces on the aircrew beyond their physiological tolerances [3].

In Aerospace medicine, terms such as A-LOC, and G-LOC are well known. A-LOC is an abbreviation for Almost Loss of Consciousness, while G-LOC represents G Induced Loss of Consciousness. Researchers are seeking the answers to whether fighter pilots can cope with physiological and psychological demands placed upon them, or whether the newest generation of fighters pushes the pilots beyond their limits. The symptoms like grey out, tunneled vision and black out can lead to fatal consequences, first performance decrements, mission failure and, finally, air crash. Pilots sense G forces as a great weight pressing down on them, the skin coming down on their face, the oxygen mask pressing their face. They also sense their lungs being pressed down, and many other physiological effects that are not welcome. When a pilot is subject to high G, the principal problem is that the blood pumped by the hearth weighs more, and can not reach the brain in sufficient amount. This causes oxygen insufficiency, which leads to G-LOC. The state-of-the-art fighters are equipped with intuitive systems. In case that the aircraft dives too fast towards the ground, the system will warn the pilot first. If he does not react, the aircraft takes over and flies the pilot to safety. If a pilot is exposed to a high G onset rate in a high performance human centrifuge,

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provided by an acceleration gradient of 9G/s, the symptoms such as greying out and tunneled vision are bypassed, and the occupant falls straight into unconsciousness. Engineers solved Air Combat Maneuvering (ACM) technical problems, but they did not fully solve the issues related to human sustainability.

With the possibility of pitch rotations of 400 degrees per second, it is possible that Enhanced Fighter Maneuverability (EFM) will involve completion of pitch-up to greater than 70 degrees Angle of Attack (AOA) and recover to straight and level flight in considerably less than 5s [2]. High AOA, flight in the Post Stall (PST) envelope with TVP are no longer a technical problem, but technicians and engineers do not deal with human physiology. This opens a problem of loosing pilots, not just because of air crashes, but also of high G exposure in flight. The pilot is pushed to the edge of his limits. The pilot must perceive all information provided by the instruments, while sustaining high G loads and being exposed to danger.

Fig.1 gives an example of an excessive supermaneuver - the Cobra.

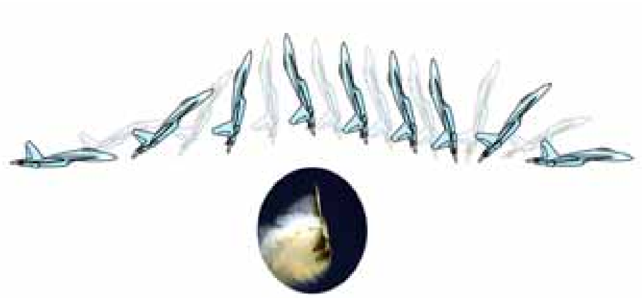

Figure 1. Pugachev Cobra supermaneuver [4]

Standard training profiles

The centrifuges vary in their capabilities, including the difference in profiles in terms of onset and offset rates. Several of the centrifuges, especially those focusing on aircrew training, use closed-loop flight profile and target tracking to make centrifuge training more realistic and acceptable to the aircrew [3]. According to the NATO Standardization Agreement (STANAG) NATO STANAG 3827 AMD, standard training profiles are recommended. The aim of this agreement is to determine the minimum requirements for aircrew training for duty in high onset rate, high-sustained G (HSG) environment [5]. For the purpose of this agreement, high sustained G (HSG) is defined as a gravito-inertial (G) force equal to or greater than +7Gz for 15 seconds for the aircrew wearing anti-G protection or +5Gz without G protection. A high onset rate is defined as an onset rate of at least 3G/sec [6].

In accordance with STANAG in this paper, the following profiles are presented:

4G-15s
5G-30s
6G-30s
7G-15s
8G-10s
9G-5s

Anti G Straining Maneuver (AGSM) has proven to be the most effective in providing the maximum protection against high G forces of ACM. The protection provided by AGSM is as good as its practice and performance by the aircrew. This realization and increased incidences of in-flight G-LOC in the air superiority fighter aircraft led to the introduction of centrifuge training [3].

The high-G training course has one primary and three secondary training objectives for trainees. The primary one is the increase in G tolerance resulting from improved skills in performing an AGSM**.** The secondary ones are a better understanding of the physiological mechanisms of G stress and G tolerance, a greater respect for the hazards associated with the high-G environment, and an increased confidence in the ability to tolerate high-G stress [7]. The AGSM consists of several training runs. The training goal is to sustain 7G for 15s with an anti-G suit (AGS).

This requirement of sustaining 7G for 15s without Peripheral Light Loss (PLL) of 56° to 52°on the GRADEPS has been adopted from the NATO STANAG 3827 AMD, which states that the aircrew who do not successfully complete a Rapid Onset Rate (ROR) 7G for 15s centrifuge profile with an anti-G suit and straining maneuver will be considered to have low G tolerance. Those who successfully complete the run are subjected to 8G -10s and 9G - 5s runs [3]. There are three types of onset runs:

a) **ROR run**

The ROR run is the Rapid Onset Rate (1G/s). If the onset is at least 3G/s, it is called High Onset Rate.

b) **Relaxed ROR run**

In this run, the trainee is subjected to 1G/s onset without AGS. The run ends with a PLL in order to determine their relaxed G tolerance.

c) **GOR run**

The Gradual Onset Rate, less than 1G/s.

Different countries provide a variety of training profiles. Some are given in Table 1.

Table 1. Training profiles in the world

Country	Profile
USA [8]	3 Diff. types for initial training: pilot instructor and training, Qualification profile each consisting of essential 5 profiles with rest period of 2 min between profiles 7G-15s
Germany [9]	Onset 10G/s, no value available
Turkey [3]	8G-15s
Sweden [3]	9G-15s/ Onset 14.5G/s

The onset value for Sweden in Table 1 is extreme, given that the onset rate for the most countries is not higher than 10G/s.

Sustained negative G tolerances are not presented in this paper. Negative G tolerance is very poorly tolerated by pilots, and lasts 1 to 2 seconds in training conditions. Pilots are usually stressed to -3G negative G. "Red-out" or "red-mist" is a visual symptom experienced during - Gz acceleration and is analogous to grey-out or black-out with positive Gz acceleration [10].

The High Performance Human Centrifuge (HPHC) presented in this paper is a part of the research being conducted in the Lola Institute Belgrade, Fig.2. Some basic design parameters are described in Table 2.

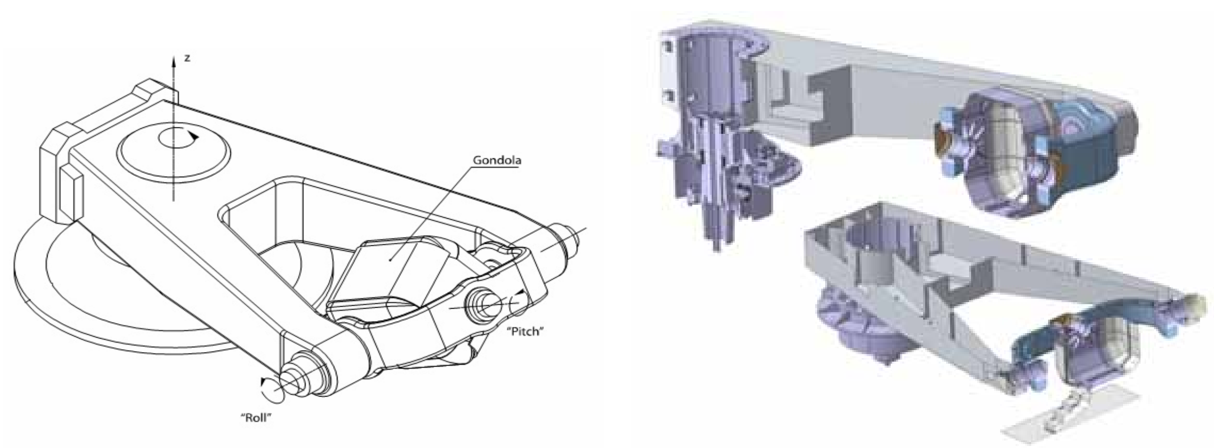

Figure 2. Human Centrifuge [11] and Centrifuge Cross Section

Table 2. Basic centrifuge design parameters [11]

Centrifuge parameter	Value
Max G - Research Mode - Training Mode 9g	15G 15G 9G
G onset value	9G/s
Arm length	8m
Mass (approximated)	90.000kg
Gondola equipment	adjustable pilot seat audio, video and inter-com equipment G-protection equipment medical monitoring
Medical monitoring system	32 channel

The HPHC has two basic functions:

a) Training of the aircrew (open-loop mode, closed-loop mode)

b) Material testing

The main drive may be an AC or DC motor with gear, as well as corresponding couplings and safety brakes. The centrifuge arm is mounted on the main shaft molded with the base of the main bearing of the centrifuge. The centrifuge is partially balanced in relation to the main axis of rotation with counterweight, which also carries the main shaft. The roll axis lies in the plane of the main arm rotation. The pitch axis is perpendicular to the roll axis. The distance between the main axis of rotation and the intersection point of roll and pitch axis is called the radius of the centrifuge arm and amounts 8m. With a larger centrifuge radius, an accompanying physiological effect on the pilot is minimized, which is known as the Coriolis effect. Performance requirements are defined with G loads and gradients of acceleration. The roll is performed with an angle of ± 180°, and the pitch with an angle of ± 360°. The roll and pitch axes have their mechanical brakes.

High g Training Profiles

In this section, the following functions are presented: load $G_z(t)$, angular velocity of the main rotational motion $\omega_z(t)$, roll angle $\varphi(t)$ and pitch angle $\theta(t)$ of the gondola, and tangential acceleration $a_t(t)$. The main rotational axis, the figure axis, is denoted with z and represents the axis of the coordinate system attached to the centrifuge base, which is not the axis in the expression G_z. Based upon the main request, to achieve a maximum onset rate of 9G/s, and an offset rate of 2G/s, the following graphs were conceptualized.

In Fig.3, the training profiles according to STANAG 3827 AMD and the main demand to achieve an onset rate of 9G/s, are shown. ROR runs of 4G -15 s, 5G - 30s, 6G - 30s, 7G - 15s, 8G - 10 s and 9G - 5s.

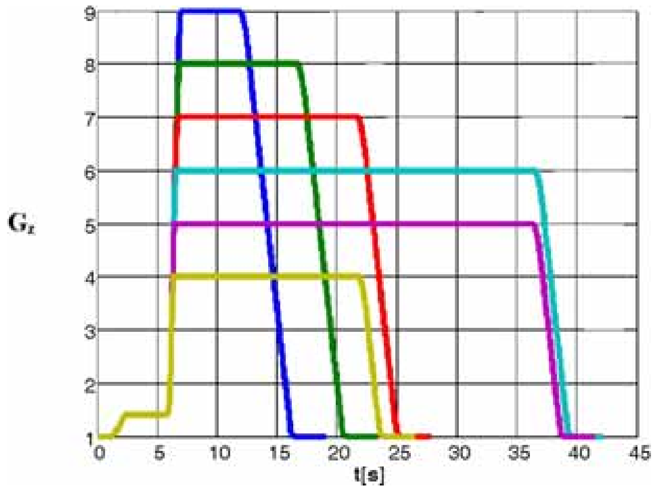

Figure 3. G Training Profiles

The training starts from the initial load-the plateau. The pilot's head is a reference point, representing the end effector, having in mind that a centrifuge is a robot manipulator in its essence. Pilot's head represents the intersection of the roll axis-x and the pitch-y axis of the gondola. At time t=0 s, when the training starts, the arm rotates around the figure axis z. The centrifuge is brought up to a 1.41G "base-G" condition, from which the RORs are initiated, to allow the generation of 6G/s -G-onset rates and to reduce the deleterious effects of prolonged high starting torques on the centrifuge drive mechanism. The trainee's anti-G suit is pressurized during the RORs in accordance with the standard USAF inflation schedule (1.5 psi/G above 2G**,** 10 psi maximum) [7].

The AGS may be pressurized in accordance with other standards, depending in which Air Force the training is conducted.

The gondola revolves around the x-axis by 45°. The sum of accelerations, acting on the gondola, gives the resultant acceleration vector of 1.41G magnitude (1). This value is considered as a plateau of acceleration, or more precisely, the initial acceleration value,

$$a = \sqrt{a_n^2 + a_t^2 + g^2} = \sqrt{r^2\omega_z^4 + r^2\dot{\omega}_z^2 + g^2} \qquad (1)$$

where a_n represents normal acceleration, and a_t tangential acceleration.

A centrifuge training has two components. This includes improving the aircrew's awareness about G forces and related human physiology through didactic lectures and centrifuge training [3].

The duration of centrifuge training varies from country to country. It usually lasts from one to five days. Table 1 and Table 3 show an example of a training in the USA.

Table 3. USA Training

Country	Duration	Max G	Onset	Offset
USA [8]	1 day	30Gz	6G/s	2G/s

The training goal is to sustain 7G for 15 seconds. The aircrew is subjected to ROR runs of 4G-15s, then 5G-30s, 6G-30s and finally 7G-15s. Those who successfully complete the 7G-15 seconds run, are then subjected to 8G-10s and 9G-5s. A successful 7G run according to STANAG is defined as a run sustained without PLL of 56° to 52°.

Those not qualifying are considered to have inadequate G level and duration tolerance for the air superiority fighter class of aircraft. However, after excluding causes known to produce low G tolerance, these pilots continue to be fit for fighter flying. They are further advised to improve their physical fitness and repeat the course at a later date [3].

In case of failure, due to G-LOC or PLL, the trainee has an opportunity to qualify in subsequent days. In case of repeated failure, the trainee is qualified as failed to qualify. The above mentioned run is the basic run for a pilot to qualify. There are many runs that an aircrew can be exposed to. The AGSM (Anti G Straining Maneuver) can be performed with SACM (Simulated Aircraft Combat Maneuver) which gives the trainee more realistic conditions. SACM profiles are not the subject of this paper.

It is important that during the training in the flight simulator in motion, the trainee does not feel 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. G_z load is, therefore, most important for training, because it has the highest value in real flight.

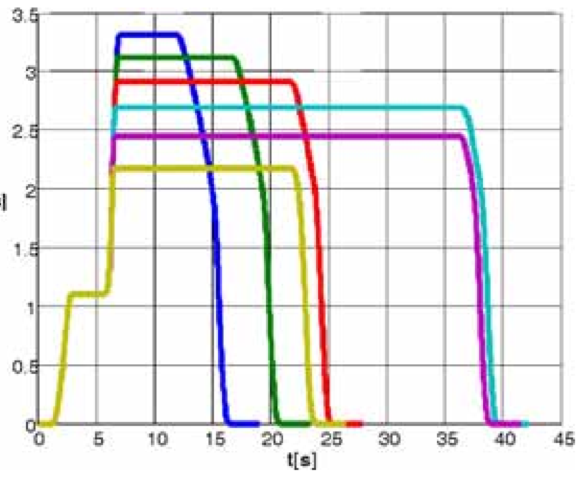

Figure 4. Function $\omega_z(t)$ – angular velocity of the main motion

Fig.4 provides the rate of change of angular velocity (ω_z) over time of the centrifuge arm, depending on the training regime, consistent with Fig.3. The angular velocity change is presented as (2):

$$\omega_z = \frac{d\varphi_z}{dt} \qquad (2)$$

where φ_z represents the angle of rotation around the figure axis.

The values for angular velocity as well as for roll and pitch angle changes are given in the following figures for a specific reason. The value of the angular velocity of the main motion is a value crucial for the main drive control. Roll and pitch angle values are significant for the roll and pitch axis drive control, and hence presented in this paper.

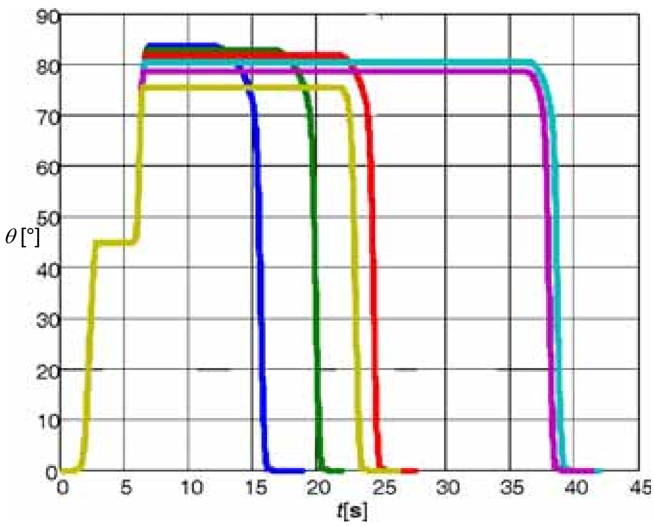

Figure 5. Function $\varphi(t)$ – roll angle

Fig.5 shows the adjustment of the roll angle for a given load, or a training profile**,** consistent with Fig.3. The roll angle is derived from (3):

$$\varphi = arctg\left(a_n\right) \qquad (3)$$

From t=0s, the roll angle rises from the value φ=0° to φ=45°, for the next few seconds, in the same way for each training profile. The yellow line (Fig.5) is a common line, for every training profile, consistent with Fig.3. When the value φ=45° is reached, i.e. the aforementioned plateau, with the base acceleration 1.41G, the training may start. For profile 9G-5s, it rises to a value above φ=80°, as if an aircraft in real flight, would make an extreme turn. The roll angle has no negative values on the graph, because the gondola revolves around the x-axis from right to left, which is the positive φ direction. As G-load sets off, the roll angle decreases rapidly.

Fig.6 shows the adjustment of the pitch angle for a given load, or a training profile, consistent with Fig.3.

The equation from which the pitch angle is derived:

$$\theta = arctg\left(\frac{a_t}{\sqrt{a_n^{\,2}+1}}\right) \qquad (4)$$

The presence of tangential acceleration, especially in the initial time interval, until the training regime is attained, requires an adjustment along the pitch axis, in order to achieve a pure G_z profile. Such profile is achieved in real flight in a coordinated turn. Because of a high value of tangential acceleration, the pitch angle is adjusted so that the resultant load vector has the direction along the pilots spine, from the head to the toes. For this reason, Fig.6 shows also a negative value of the pitch angle.

The negative pitch angle is considered to be the "nose down" angle.

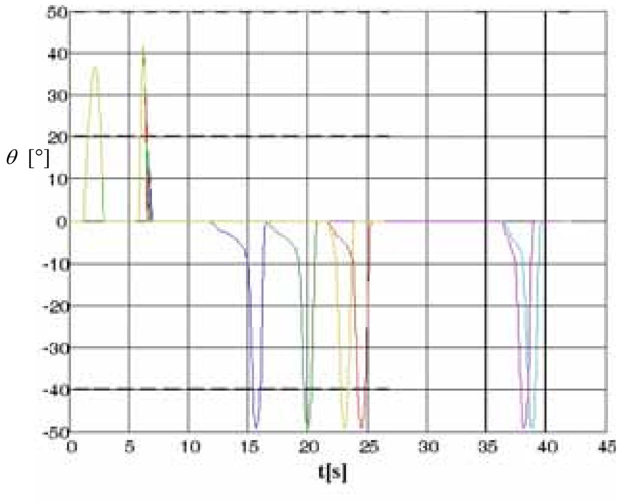

Figure 6. Function θ(t) – pitch angle

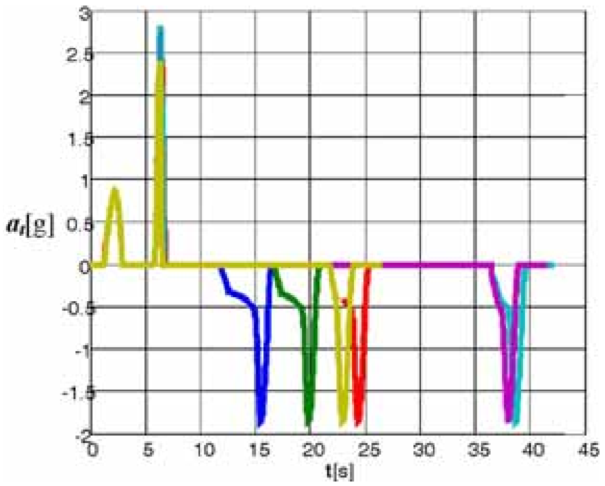

Figure 7. Function a_t(t) – tangential acceleration

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

where:

$$v = \omega r \tag{6}$$

r represents the centrifuge arm, v tangential velocity.

Tangential acceleration has a positive value, while the acceleration sets on, and negative while off setting. Because of very large tangential acceleration, especially in the first 0.3 seconds of the main arm rotation, the occupants sense a very strong transverse load. Fighter jets perform a coordinated turn with a large radius of action in real flight. As the centrifuge arm amounts to 8 meters, the emergence of large tangential acceleration is inevitable. The centrifuge has two additional drives-pitch and roll-axis drives, in order to adjust angles properly. In Fig.7, negative values of tangential acceleration for loads are obtained for 2G/s offset rates.

Conclusion

Air-to-air combat becomes more and more dynamic with time. Acceleration physiologists need to keep pace with the rapid development of modern fighter aircraft. Fighter pilots must be trained to be effective in combat, but also to sustain excessive G-loads. Phenomena like G-LOC, A-LOC and PLL must be minimized. In this direction, sharing experiences with different laboratories is a major step that needs to be encouraged. Exchange of scientific and technical information is also required in order to create an adequate training program. High performance human centrifuge training has one basic purpose-to expose the aircrew to high G profiles close to those being encountered in high performance aircraft. As a result, the aircrew will learn necessary skills in performing AGSM. The aim of this paper is to present training graphs in accordance with the main requirement, to achieve an acceleration gradient of 9G/s. The main centrifuge parameters, such as angular velocity of the main rotational motion $\omega_z(t)$, roll angle $\varphi(t)$, pitch angle $\theta(t)$ and tangential acceleration $a_t(t)$ are presented graphically in order to illustrate their dependencies on the $G_z(t)$ parameter, or more precisely, on the load that has to be achieved.

All calculations given in this paper are a part of the preliminary research currently being conducted in the Lola Institute. The main objective is to construct a model in the foreseeable future in a scale of 1:8.

Acknowledgments

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G profili za obuku u humanoj centrifugi visokih performansi

U ovom radu predstavljeni su profili za obuku u humanoj centrifugi visokih performansi. Glavni cilj je da se istakne značaj razvoja različitih trening scenarija, kako bi se postigla optimalna spremnost pilota borbenih aviona. Ovo istraživanje bazirano je na standardu NATO STANAG 3827 AMD-a, koji propisuje vrednosti G tolerancija, koju posada treba da podnese. Posada koja ne završi uspešno trening Rapid Onset Rate (ROR) 7G za 15 sekundi sa anti-G odelom i Anti-G Straining maneuver-om (AGSM), smatraće se da ima nizak prag tolerancije na G opterećenje, što je objašnjenjeno detaljno u ovom radu. Profili za obuku su grafički predstavljeni, kao i ugaona brzina kraka, ugao valjanja i ugao propinjanja-poniranja za svaku vrednost opterećenja. Glavni zahtev humane centrifuge predstavljene u ovom radu, je da se postigne gradijent ubrzanja od 9G/s. Profili koji su prikazani u ovom radu su deo istraživanja Lola Instituta u Beogradu. U radu su dati i primeri scenarija za obuku pilota koji se primenjuju u nekoliko zemalja. G-opterećenja koja prouzrokuju gubitak svesti kod pilota (G-LOC) su deo scenarija i neizbežna su tokom treninga u centrifugi. Efektivna obuka AGSM i povećanje G-tolerancija pilota, doprinose bezbednosti leta i na taj način se smanjuje rizik od G-LOC i vazduhoplovnih nesreća. Cilj ovog rada je da ilustruje značaj i složenost upravljanja i podešavanja parametara rada, kako bi se postiglo željeno opterećenje.

Ključne reči: **centrifuga, humana centrifuga, obuka pilota, G-opterećenje.**

G - профили для подготовки человека в центрифуге высоких характеристик

В этой работе представлены профили для подготовки человека в центрифуге высоких характеристик. Основной целью является - подчеркнуть важность развития различных видов обучения в целях достижения оптимальной готовности лётчиков-истребителей. Это исследование основано на стандарте NATO STANAG 3827 AMD, который предусматривает значения G-толерантности, которые экипаж должен перенести. Экипаж, который не завершает успешно обучение быстрыми темпами (ROR) «7G» в течение 15 секунд с анти-G костюмом и Anti-G Straining maneuver (AGSM), считается, имеет низкую толерантность на «G»-напряжение, что подробно объяснено в этой работе. Профили для подготовки представлены в графическом виде, а в том числе и угловая скорость силы, угол крена и тангажа, угол спуска для каждого значения нагрузки. Главное требование центрифуги для подготовки человека представленной в этой статье является достижение градиента ускорения 9G / с. Профили, представленные в настоящей работе, являются частью исследования института «Лола» в Белграде. В работе приводятся и примеры програмы для обучения лётчиков. Эффективное AGSM обучение и повышение G-толерантности лётчиков способствуют безопасности полётов, а тем самым уменьшают риск от G-LOC и авиационных катастроф. Целью данной работы является - показать важность и сложность управления и настройки параметров работы, для того, чтобы достичь желаемой нагрузки.

Ключевые слова: **центрифуга, центрифуги для подготовки человека, обучение лётчиков, перегрузка (G-нагрузка).**

Les profils G pour l'entraînement dans la centrifuge humaine de hautes performances

Dans ce papier on a présenté les profiles pour l'entraînement dans la centrifuge humaine de hautes performances. Le but principal est de souligner l'importance de différents scénario d'entraînement afin d'obtenir la préparation optimale des pilotes d'avions de combat. Cette recherche est basée sur les normes NATO STANAG 3827 AMD qui déterminent les valeurs de tolérance G que l'équipage doit supporter. L'équipage qui ne finit pas avec succès l'entraînement Rapid Onset Rate (ROR) 7G en 15 secondes avec vêtement anti G et Anti G Straining manœuvre (AGSM) sera considéré à bas niveau de tolérance à la charge G et on expliquera cela en détail dans le cadre de ce travail. Les profils d'entraînement ont été présentés graphiquement ainsi que la vitesse d'angle de bras, les angles de roulement et de tangage pour chaque valeur de la charge. L'exigence principale chez la centrifuge humaine, présentée dans ce travail, est de réussir le gradient d'accélération de 9G/s. Les profils présentés ici font partie des recherches au sein de L'institut Lola à Belgrade. Dans cet article on a donné aussi les exemples du scénario pour l'entraînement des pilotes. L'entraînement effectif AGSM et l'augmentation de la tolérance G chez les pilotes contribuent à la sécurité du vol et de cette façon on a diminué le risque du G-LOC et des accidents aériens. L'objectif de ce travail est d'illustrer l'importance et la complexité de commande et l'ajustement des paramètres de travail pour obtenir la charge désirée.

Mots clés: **centrifuge, centrifuge humaine, entraînement des pilotes, charge G.**