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SCIENTIFIC BASIS FOR THE TRAINER AIRCRAFT ANTI-G EQUIPMENT REQUIREMENTS

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The design process of a new aircraft (AC) is always associated with the issue of choosing its basic technical parameters, or, in other words, the formation of its conceptual design. In case of a civil aircraft, the choice of these parameters is defined by the requirements for operational safety, market conditions, norms that specify the tolerable harmful impact of the aircraft on the environment, etc. In case of a military aircraft, its outlay mostly depends on the concept of potential military threats, ways of using the military aircraft in military conflicts. Some of these requirements are formulated in regulatory documents – the Aviation Requirements for Civil Aircraft and the General Tactical and Technical Requirements of the Air Force for Military Aircraft. For example, Part 25 of the Aviation Requirements for Civil Aircraft defines the Airworthiness Standards for transport aircraft. It should be noted that the stated above requirements are often a tool of competition, for example, when tightening the aircraft noise abatement procedures provides advantages for particular manufacturers, not admitting other manufacturers to enter the market, whose aircraft do not conform to the new standards. Thus, complying with the requirements virtually involves additional costs both in the aircraft development and during its operation. In addition, the implementation of the requirements stated above can lead to the deterioration of the aircraft's performance, and hence, to the decrease of its competiveness and combat effectiveness. Therefore, each requirement of the regulatory documents should have a profound scientific rationale. This article analyzes one of the regulatory documents requirements referring to the necessity of anti-g system on board aircraft. The authors propose the approach to specify the existing criterion to provide the scientific basis for the anti-g system on board aircraft by assessing the actual level of pilot load when maneuvering. The subject under study is of particular importance for the Yak-152 trainer aircraft. The actual level of loads during pilotage of the Yak-152 trainer aircraft does not require the use of the anti-g system but if to be based on a formal criterion, namely, in terms of the maximum operational overload value, the aircraft should be fitted out with such a system.

Key words: g-load, anti-g system, trainer aircraft.

INTRODUCTION

According to the adopted classification, aircraft, depending on the maneuverability parameters, are subdivided into highly maneuverable, maneuverable, limitedly maneuverable and non-maneuverable. The aircraft belong to the class of highly maneuverable if they sustain the maximum available g-load of $n_y{}^{э}{}_{max.}$>7 and perform the entire list of complex and aerobatic maneuvers.

To ensure the effective working pilot capacity, it is prescribed to equip this class aircraft with a special anti-g system that increases the tolerable g-level. Simultaneously, no distinction is made between a high-speed and low-speed aircraft, although the tolerable g-level directly depends on the time of its action, which is specified by a maneuvering airspeed envelope.

It is proposed to introduce a pilot load level assessment criterion, which is calculated on the basis of mathematical modeling of complex aerobatics typical maneuvers to determine the actual pilot load and to establish the scientific basis for the practicability of the use of anti-g equipment for various aircraft types.

RESEARCH METHODS AND METHODOLOGY

The impact of g-load on a human body has been well studied [1–5]. It can be asserted that there is some kind of the upper threshold of g-load, which even an untrained person can suffer without any health problems.

The integral load on the pilot under g-load, exceeding the threshold value during the time of Δt, can be defined using the following formula:

$$N_л = \int_0^{\Delta t} \Delta n_{ул} dt$$

where $\Delta n_{ул} = n_{ул} - n_{ул}^{пор}$;

$n_{ул}$ – current g-load affecting the pilot in the direction “head-pelvis”;

$n_{ул}^{пор}$ – the g-load threshold value impacting the pilot without time limit.

G-load, impacting the pilot in the direction of “head-pelvis”, differs from the normal speed g-load that is characteristic for a maneuvering aircraft and rated by the following formula [6]:

$$n_{ул} = \cos[\phi_к + \mathrm{arctg}(\frac{n_x}{n_y})] \cdot \sqrt{n_{ya}^2 + n_{xa}^2},$$

where n_y, n_x – the normal and longitudinal g-load constituents in the projections on the coordinate system axis;

n_{ya}, n_{xa} – the normal and tangential g-load constituents in the projections on the velocity coordinate system axis;

$\varphi_к$ – an angle of the pilot's seat inclination to the corresponding coordinate system Oy axis.

In order to facilitate the evaluation, it is reasonable to use a dimensionless criterion or a normalized pilot load level when maneuvering the aircraft during t_m time:

$$\bar{N}_л = \frac{N_л}{t_м}.$$

The maximum normalized pilot load level is achieved if the aircraft instantly imposes and sustains g-load of $n_{ул}$, which is equal to aircraft maximum operational g-load of $n_y{}^э{}_{max}$, during the whole time of maneuver t_m.

The regulatory requirements for maneuverable aircraft calculate the g-load threshold value, which makes it possible to operate the aircraft without using pilot anti-g equipment. It equals $n_{ул}^{пор} = 3$. Hence, at $n_y{}^э{}_{max} = 8$ the maximum possible normalized pilot level equals $\bar{N}_{л\,макс.} = 5$ units.

Let us assess the pilot’s capabilities under physical load on two aircraft: a high-speed jet combat training Yak-130 [7] and a low-speed light training Yak-152 [8]. Both aircraft have the equal maximum available g-loads of $n_y{}^э{}_{max} = 8$, therefore, they are subjected to the requirement to be equipped with an anti-g system as a part of aircraft hardware.

For comparison, the actual normalized pilot load level $\bar{N}_л$ is used as a criterion when performing complex aerobatics maneuvers with the highest level of g-loads. All the maneuvers start at the maximum instrumental speed for this aircraft using the maximum operating engine mode (EOM).

RESEARCH RESULTS

Figures 1–5 show the actual laws of g-loads variations acting on the pilot in the direction of "head-pelvis". The corresponding normalized pilot load levels of $\bar{N}_л$ are shown in Table 1.

While calculating $n_{ул}$, it was considered that for the Yak-130 aircraft $\varphi_к$ = 17°, but for the Yak-152 aircraft an angle of seat inclination is increased and equal to $\varphi_к$ = 25° in order to reduce the impact of g-load on the pilot.

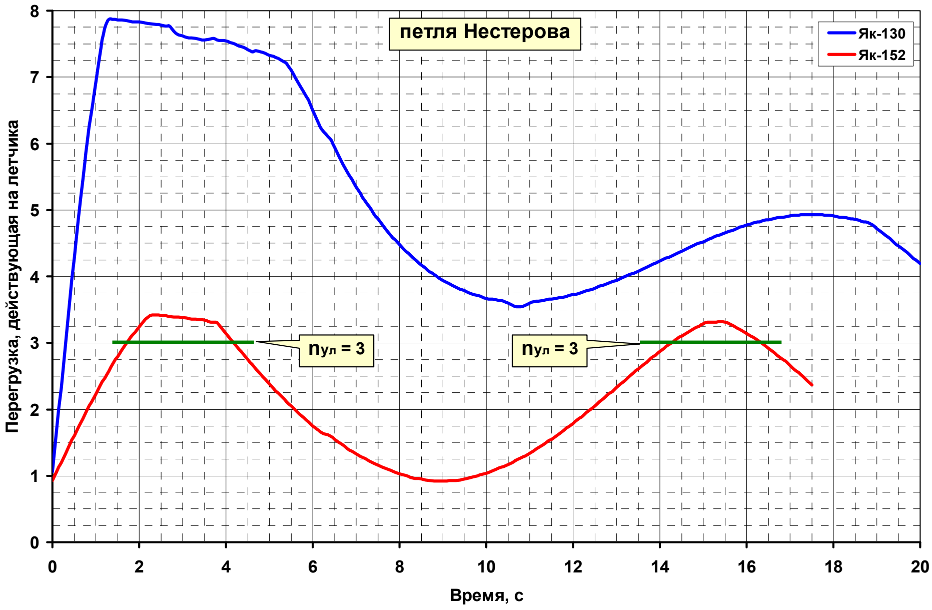

Fig. 1. G-load variation while performing the complete loop (Nesterov loop)

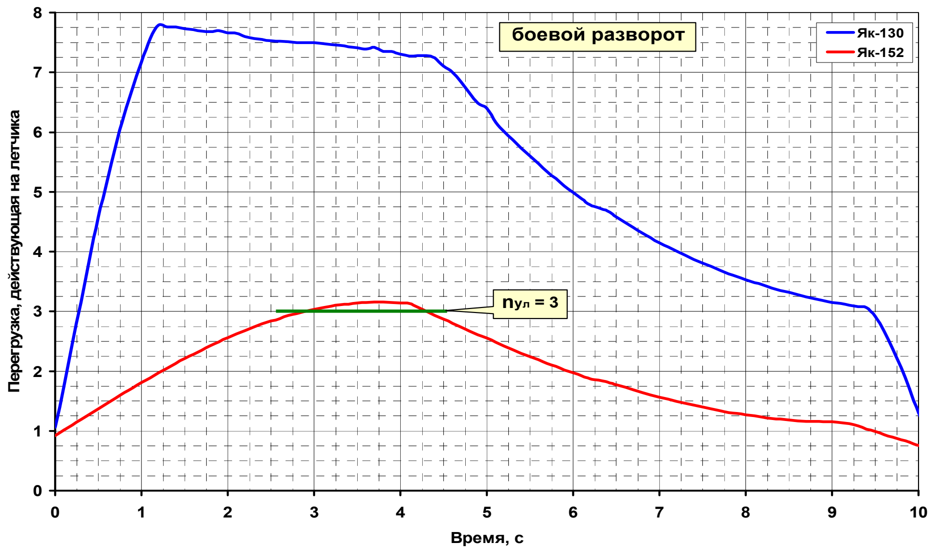

Fig. 2. G-load variation while performing a combat turn

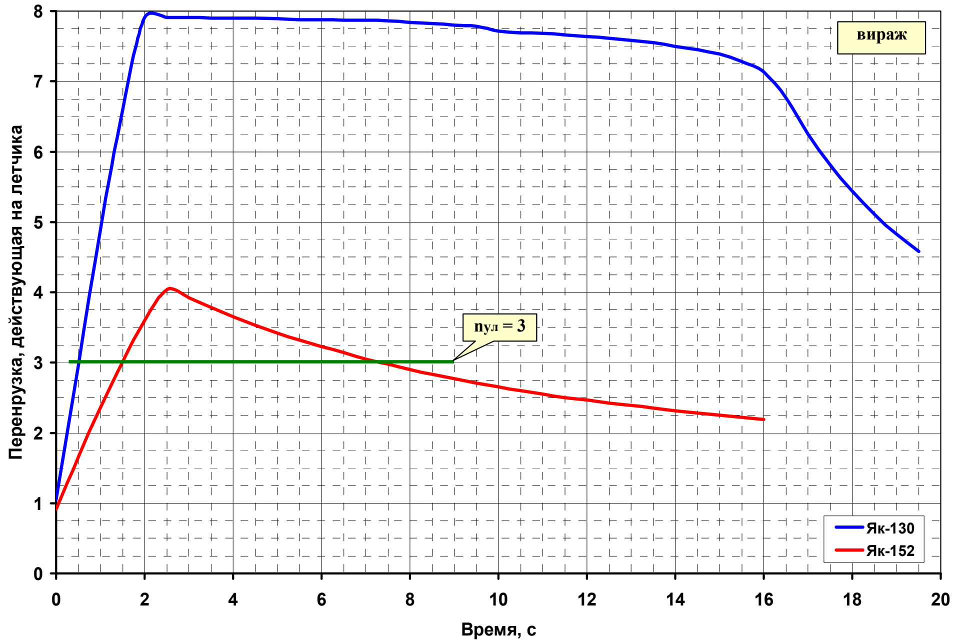

Fig. 3. G-load variation while performing an accelerated turn

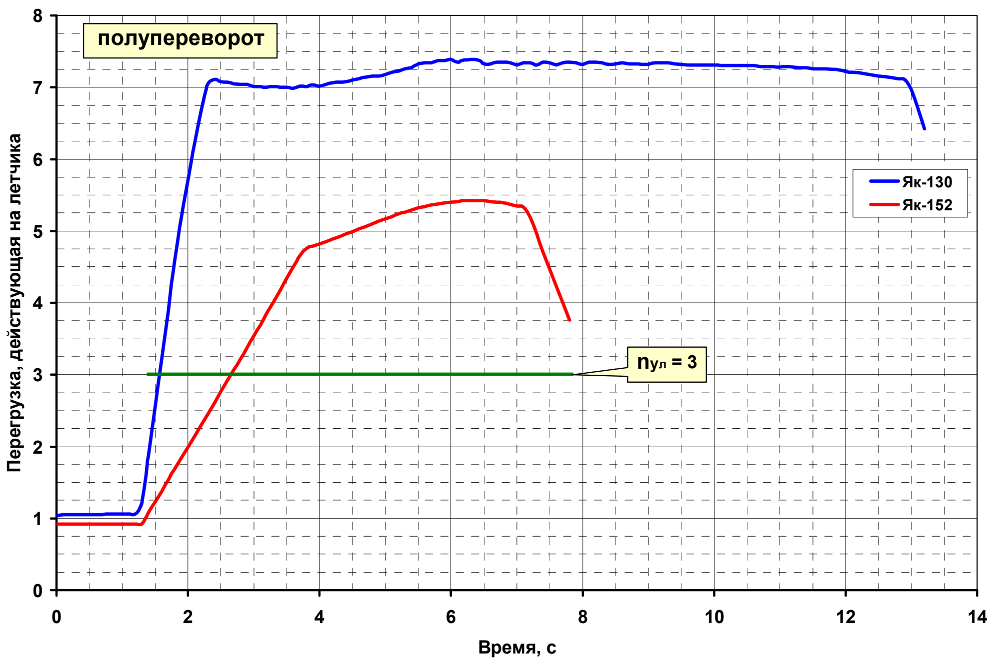

Fig. 4. G-load variation when performing a half roll

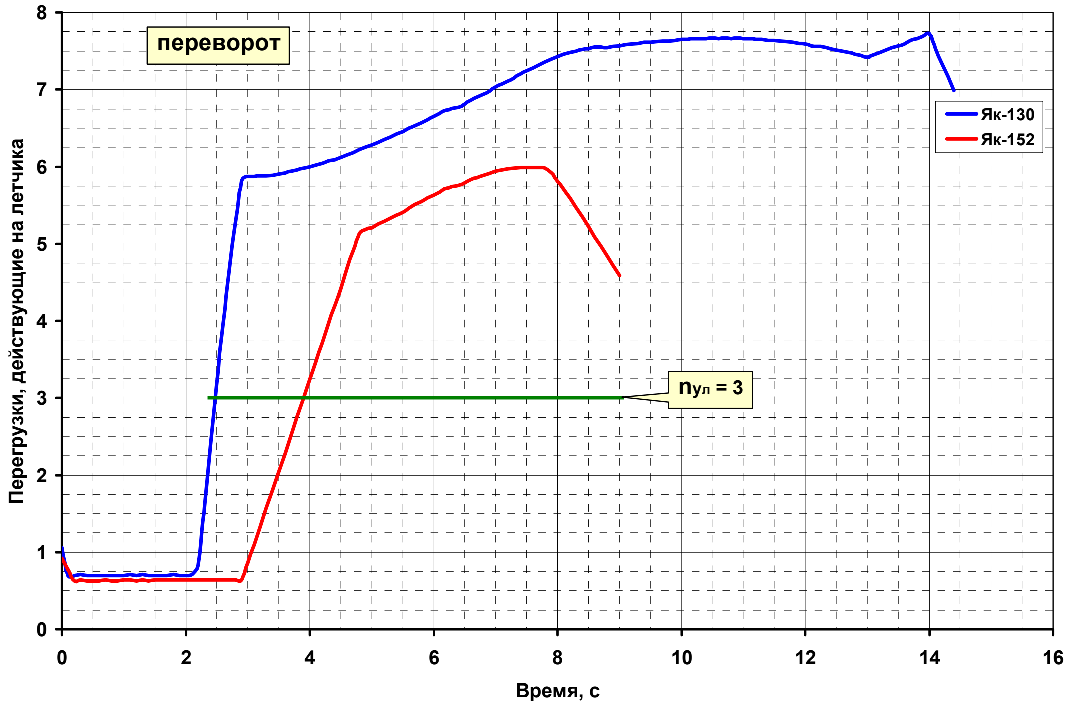

Fig. 5. G-load variation when performing a full roll

Table 1

Summary indexes of complex aerobatics typical maneuvers

Type of maneuver	Yak-130		Yak-152	
	T_m, sec	$\bar{N}_{\text{л}}$, units	T_m, sec	$\bar{N}_{\text{л}}$, units
Complete loop (The Nesterov loop)	20.0	2.19	17.5	0.066
Combat turn at η = +60°	10.0	1.89	10.0	0.013
Accelerated turn	19.5	4.10	16.0	0.158
A half roll at η = –60°	13.5	3.59	8.0	1.47
A full roll	14.5	3.32	9.0	1.29

The obtained results show that the summary integral indexes of pilot load for the Yak-152 are many times lower than those ones for the Yak-130, despite their maximum available g-loads equality.

In order to make a decision about the reasonable installation of the anti-g system on board aircraft, it is necessary to compare the achieved load level $\bar{N}_{\text{л}}$ on the given aircraft with $\bar{N}_{\text{л мин.}}$ which the pilot experiences without any special equipment.

G-load capability is considered to be overloaded that do not cause noticeable disorders or cause minor and transient health problems. The capability to withstand acceleration stresses under an assigned level of training is specified as: the g-load magnitude, rate of its increase, direction and duration.

The pilot in the sitting position withstands g-load quite satisfactorily in the "head – pelvis" direction up to 6 units during Δt = 1...2 seconds without any trouble to sight, maintaining working capacity. Physically well-trained, experienced pilots satisfactorily withstand g-loads of 7...8 units, but in some cases they do 9...9.5 units with the duration of up to Δt = 1 second. The shorter the time of the g-load effect is, the easier a human body can withstand. A man can tolerate g-load of 20 units during the time of Δt = 0.1...0.2 seconds without any discernible visual and central nervous system disorders. Sportsmen-pilots can reach $n_{ул}$ of ≥ 12 units without any signs of physiological disorders [9].

Trained pilots withstand g-loads of $n_{ул}$ = 4 quite satisfactorily for three minutes on centrifuges. An untrained person starts suffering visual disorders in the form of peripheral vision loss (gray veil) in Δt ≈ 10...15 seconds of being subjected to g-load equal to $n_{ул}$ = 3...4 units.

If we present this data in the form of a diagram of possible tolerance g-load based on the time of g-effect, it will be possible to make a boundary of tolerance $n_{ул}$ over the maneuvering time (fig. 6 – red line). Taking into account the fact that due to the loss of airspeed, the time of powerful training aircraft maneuvering does not exceed tm = 10...15seconds, so, the tolerable and normalized load level of the pilot is $\bar{N}_{л\,мин.} = 1,4...2,1$.

Having compared $\bar{N}_{Лmin}$ with the data given in Table 1, we have concluded that the pilot load level on the Yak-130 aircraft exceeds significantly the pilot's physiological abilities ($\bar{N}_л = 2,19...4,10$), and this fact makes it necessary to equip the aircraft with an anti-g system.

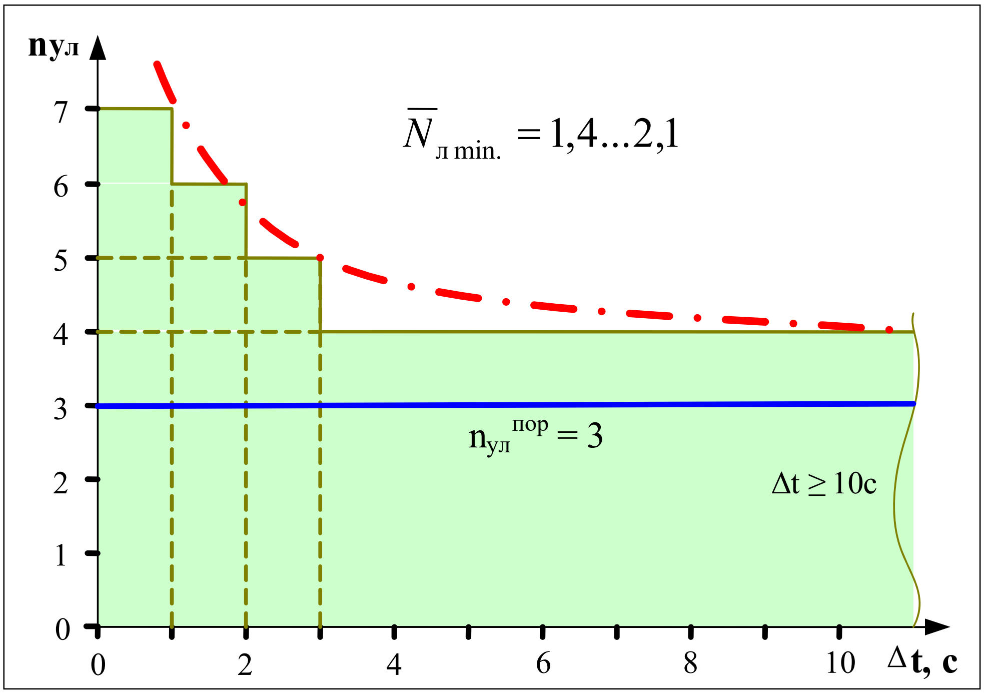

Fig. 6. The boundary of tolerable g-load

While flying the Yak-152 aircraft, the load pilot level does not virtually exceed the pilot's physiological abilities ($\bar{N}_л \le 1,47$) even while extremely powerful maneuvering, which does not make it reasonable to complicate a trainer aircraft, also to increase costs and weight by mounting a redundant amount of equipment.

An adequate ability to withstand short-term overloads by a trained pilot makes the installation of anti-g systems on low-speed aircraft impractical. Thus, neither a single trainer nor an aerobatic aircraft with a piston engine has such a system, despite the high level of available g-loads:

SU-26 – $n_y{}^{э}{}_{max.}$ = –10…+12;
SU-29 – $n_{ymax.}$ = –10…+12;
YAK-54 – $n_y{}^{э}{}_{max.}$ = –6…+9;
YAK-55 – $n_y{}^{э}{}_{max.}$ = –6…+9;
YAK-52 – $n_y{}^{э}{}_{max.}$ = –5…+7;
YAK-152 – $n_y{}^{э}{}_{max.}$ = –6…+8.

In order to assess the actual g-loads level on pilots of the Yak-152 aircraft, a simulation of complex aerobatic maneuvers, stipulated by the corresponding exercise of the Flight Training Course for a training aircraft and performed in compliance with the requirements of the Aircraft Flight Manual, was carried out.

When flying into the zone for complex aerobatics, the successive maneuvers are prescribed: the complete loop (the Nesterov loop), full roll, dive at a flight-path angle of –45° (entering by two half rolls), pitch-up maneuver at a flight-path angle of +45 (exiting by two half rolls), a combat maneuver by the type of a skewed loop at a flight-path angle of η = +45°, a steady orbit with the ultimate engine thrust overload (γ ≈ 60°).

The summary results of the complex aerobatic maneuvers modeling with the stated pilot load are shown in Table 2.

Table 2

Complex aerobatics maneuvers summary indexes in accordance with the Aircraft Flight Manual

Type of maneuver	YAK-152 maneuvering indexes			
	Δt, sec	$t_м$, sec	$n_{ул\ max}$, units	$\overline{N}_л$, units
Complete loop (The Nesterov loop)	4.2	17.5	3.42	0.066
Combat maneuver at η = +45º	2.2	10.9	3.35	0.044
Orbit with γ = 60º	0	29.0	1.77	0
Pitch-up maneuver at υ = +45º	0	14.0	2.8	0
A dive at υ = –45º	2.2	14.0	4.2	0.098
Full roll	3.2	14.0	3.65	0.093

The research results show that in training flights according to the program of initial and basic training on a Yak-152 trainer aircraft with the engine-propeller power plant, the maximum g-load on the pilot ($n_{ул\ max}$) barely reaches four units, and the load level is significantly lower ($\overline{N}_л << \overline{N}_{л\ мин.}$) than that one an untrained person can tolerate.

The Yak-152 aircraft technical capability to impose and sustain high g-loads is clearly illustrated by the g-load polar in Figure 7. It can be seen that under a normal g-load, which is above the threshold value of $n_{ул}{}^{пор}$ = 3, significant negative values of tangential g-load occur in the entire speed range. This leads to a rapid loss of speed, and, accordingly, to the available normal aircraft g-load.

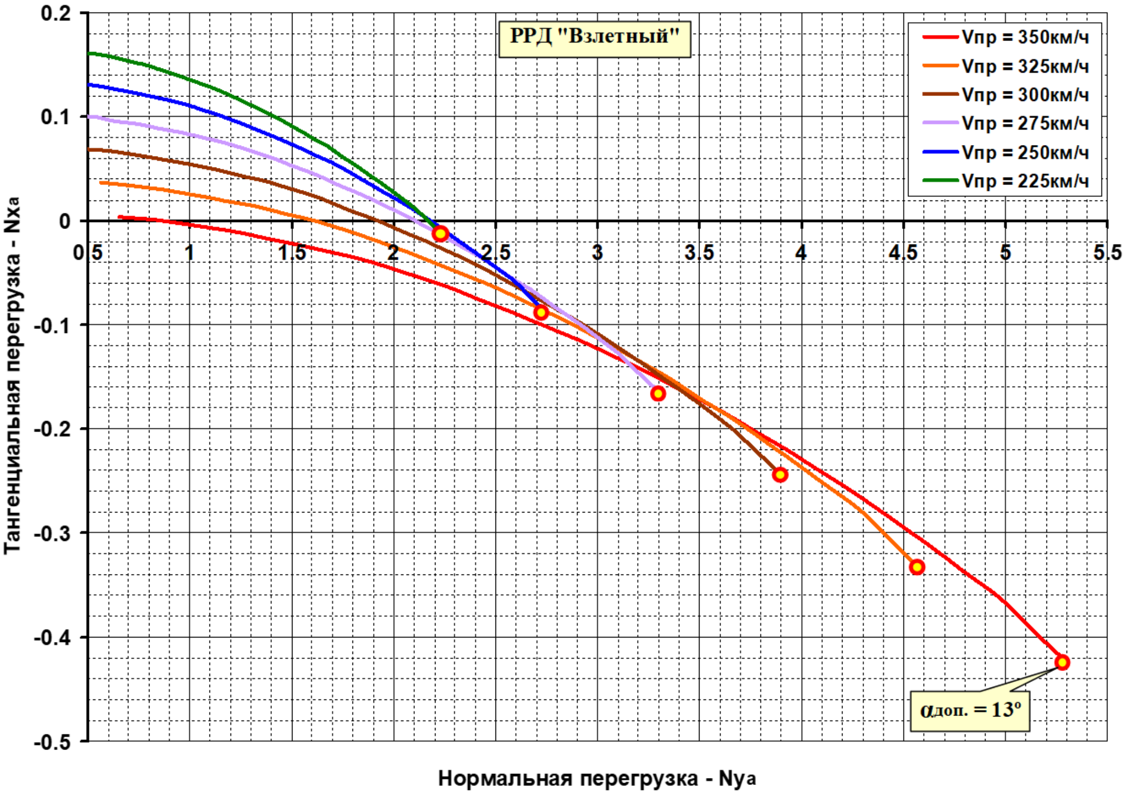

Fig. 7. G-load polar of the Yak-152 aircraft

DISCUSSION OF THE RESULTS OBTAINED

The research results presented above have shown that an untrained person on a Yak-152 aircraft can only exceed the boundary of g-load tolerance by maneuvering with the amount of g-load equal to $n_{ул} \approx 4$ at the speed almost equal to the maximum when descending with the vertical speed of about 30 m/s (for example, performing a steep spiral down). Besides, the Yak-152 aircraft is designed for the initial training and selecting cadets capable to master the profession of a highly maneuverable aircraft pilot in the future, which means to withstand continuous maneuvering with the normal overload of 9 units without loss of working capacity. The problem of resistance of the pilot to the heavy g-loads effects is relevant today [10, 11] since it is directly related to flight safety [12, 13]. Therefore, as early as on the stage of initial training, the future pilot must master effective respiratory and muscular protection techniques that increase resistance to g-loads by 3...3.5 units [4, 14]. Consequently, on the basis of the results stated above, it can be concluded that there is no scientific basis to install the anti-g protective system on the Yak-152 aircraft.

CONCLUSION

When forming a list of hardware equipment for a trainer aircraft, it is unacceptable to adopt a formal directive approach that can turn excessive equipment into ballast, deteriorating aircraft performance. Availability of any additional system should be substantiated by the requirements of operational safety, improvement of flight-technical, operational, training or other aircraft performance that are essential in terms of the aircraft characteristics tasks being solved. On the aircraft with the pilot load level of $\overline{N}_л \le 2$, the installation of anti-g equipment is not merely impractical, but also adverse, since it impairs the future pilot training quality. Weight increase, associated with the installation of additional equipment, affects a trainer aircraft. It can significantly worsen maneuverability, takeoff, landing and piloting performance, and consequently, deteriorate operation safety. So, requirements validation for the trainer aircraft anti-g equipment must be necessarily based on the results of comparing the achieved pilot load level of $\overline{N}_{л}$ on this aircraft with that of $\overline{N}_{л\,мин.}$ which the pilot tolerates well without any special equipment. The article presented the results of comparing the achieved pilot load level of $\overline{N}_{л}$, on the Yak-152 trainer aircraft with load level of $\overline{N}_{л\,мин.}$ which the pilot tolerates well without any special equipment. The given results convincingly indicate the inexpediency of equipping the Yak-152 with anti-g system.

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ОБОСНОВАНИЕ ТРЕБОВАНИЙ К ПРОТИВОПЕРЕГРУЗОЧНОМУ ОБОРУДОВАНИЮ УЧЕБНО-ТРЕНИРОВОЧНОГО САМОЛЕТА

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Создание нового воздушного судна (ВС) всегда сопряжено с проблемой выбора его основных технических параметров или, другими словами, формированием его внешнего облика. В случае гражданского ВС выбор указанных параметров определяется требованиями безопасности эксплуатации, конъюнктуры рынка, нормами, определяющими допустимое вредное воздействие самолета на окружающую среду и т. п. В случае военного ВС его облик во многом определяется представлениями о характере будущих военных угроз, способах применения ВС в военных конфликтах. Часть указанных требований формулируется в нормативных документах – авиационных правилах для гражданских ВС и общих тактико-технических требованиях ВВС для ВС военного назначения. Так, например, часть 25 авиационных правил определяет нормы летной годности ВС транспортной категории. Следует отметить, что зачастую указанные требования являются инструментом конкурентной борьбы, когда ужесточение, например, требований по шуму ВС обеспечивает преимущества для конкретных производителей, не допуская на рынок иных производителей, ВС которых не удовлетворяют новым нормам. Таким образом, реализация требований почти всегда связана с дополнительными затратами как при разработке ВС, так и при его эксплуатации. Кроме того, реализация указанных требований может приводить к ухудшению летно-технических характеристик ВС, а значит, к снижению его коммерческой привлекательности, боевой эффективности. Поэтому каждое требование нормативных документов должно иметь под собой глубокое научное обоснование. В данной статье анализируется одно из требований нормативных документов, касающееся необходимости наличия на ВС противоперегрузочной системы. Авторы предлагают подход, обеспечивающий уточнение существующего критерия наличия противоперегрузочной системы на ВС за счет оценки фактического уровня физического нагружения летчика при маневрировании. Особую важность исследуемая проблема имеет для учебно-тренировочного самолета Як-152, фактический уровень нагрузок при пилотировании которого не требует использования противоперегрузочной системы, но по формальному признаку, а именно по величине максимальной эксплуатационной перегрузки, такая система на самолете должна быть.

Ключевые слова: перегрузка, противоперегрузочная система, учебно-тренировочный самолет.

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