Theoretical-experimental study of optimization of operational parameters of protective nets of aircraft power units

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DOI: https://doi.org/10.52340/building.2025.71.01

Abstract. This scientific work discusses increasing the effectiveness of a bird-proof mesh for aircraft components (propeller, fan, compressor, etc.) by optimizing the mechanical, geometric, and aerodynamic parameters of its constituent cells.

Instead of steel wires, ropes made from high-strength composite fibers produced by world-renowned companies were selected for the protective net: Dyneema (DSM-Holland), Spectra-75 (Honeywell USA), Zylon (Toyobo MC Corporation, Japan), VECTAN (DuPont); Kevlar (DuPont). Taking into account the specific type of aircraft and its flight and operational conditions, the geometric parameters of the ropes of the cells constituting the protective net were specified (diameter, dimensions of the sides of the net cell, etc.). On a modernized tensioning machine UTM-M, the breaking strength limit of selected ropes was determined within the framework of extreme environmental operating temperature conditions of +60 -60 ^{0}C. A net was made from Dyneema fiber rope with the best characteristics and was tested on a dynamic stand at various bird weights and impact speeds.

Using a mathematical model and computer simulation programming created by scientists at the Scientific Research Center of the Georgian Aviation University, the conditions for the containment, fragmentation, and tearing of the net when birds hit a protective net were determined.

Key words: Aircraft, air intake device, fan, bird, protective net.

Introduction

The number of aircraft, and especially unmanned aerial vehicles, and consequently the number of flights performed by them, is increasing significantly every year in the world. The number of different species of birds is also increasing significantly, which significantly increases the likelihood of a collision between an aircraft and a bird.

In the publication of the International Civil Aviation Organization, "ICAO" Aviation Safety Network, which is based on data from 91 countries, there were 33,376 cases of damage to aircraft as a result of bird collisions in 2008-2015, of which 48.9% were caused by engines.

Fig. 1. Boeing-737 aircraft during a collision with a flock of birds

Collisions between aircraft and birds occur most frequently during takeoff and landing at relatively low altitudes of 150-300 m, accounting for 75% of cases. 20% of collisions occur at altitudes of 300-1500 m and only 5% above 1500 m [1], [2].

Currently, some helicopter engines are equipped with protective grid [3]. The use of protective nets has both positive and negative aspects: the positive aspect is that their use significantly reduces the risk of a single large mass of bird entering the engine, which could cause significant damage to its components. The downside is that if the net is designed solely to contain birds, the diameters of its constituent threads increase significantly, which in turn leads to a significant increase in the coverage coefficient of the engine air intake inlet and, consequently, aerodynamic drag.

Scientists and employees working in the aviation field of leading countries are actively involved in solving this problem.

Main part

One effective measure to solve the above problem is to use a protective mesh or mesh system in the front part of the engine air intake, the mesh of which has the smallest possible diameter and is made of modern high-strength composite fibers.

In this case, the flight speed of the aircraft and the outer diameter and, accordingly, the cross-sectional area of the air intake inlets are taken into account, as well as the weights and speeds of the birds involved in the collision with the engine. The cruising speeds of civil aviation aircraft are in the range of 800–1000 km/h, and their takeoff and landing speeds are within 250–280 km/h. As for helicopters and drones, their flight speeds are in the range of 150-300 km/h.

When manufacturing protective nets, the geometric and mechanical parameters of their constituent ropes must be determined to meet the following technical requirements:

a) The geometric dimensions of the protective mesh cell must ensure that small birds cannot enter the engine while at the same time having minimal aerodynamic resistance;

b) The material of the protective net must ensure that a bird that has crashed into the net is stopped or dismembered. In the rare case that the mesh breaks due to unforeseen reasons, the mesh fragments that enter the engine should not be able to damage its components.

Among the parameters determining the effectiveness of a protective net, the geometric parameters of the net cell and its constituent rope (diameter, length, and cell area) are important, over which the tension σ induced when a bird hits the net is distributed, both for its individual elements and for the net as a whole. It is also important to consider the importance of the air intake coverage coefficient with the mesh-fitting ropes, on which the aerodynamic drag and air flow rates of the engine significantly depend [7].

To determine the optimal physical parameters of the rope required for the production of a protective net, let's use the following method: let's say a bird with mass M_b and density ρ_b collides with an aircraft with a certain contact area S_f. In this case, we can imagine the bird as a cylindrical object with base area S_b and height H_b. When a bird with these parameters collides with the protective net of the air intake, the kinetic energy that is transferred to the impact surface is expressed by the formula.

$$E_{kin} = \rho_b V_b (V_{\chi o \mu} + V_b)2 /2 = \rho_b S_b H_b (V_{\chi o \mu} + V_b)2 /2 \quad (1)$$

Based on the laws of impulse constancy, it is easy to calculate the impact force of a bird of mass m_b and length l_b with the concept given in {5}. Table 1 presents the parameters of some birds and the forces of collision with aircraft.

Table 1

N	Bird name	Bird flight speed, km/h	Total collision speed km/h (m/s)	Poultry weight kg	Bird length cm	Impact force, N (kgf)
1	Quail	60	340(94,4)	0,1	18	4951 (556)
2	Seagull	50	330(91,7)	1,4	40-60	26508 (2867,2)

3	Wild duck	90	370(102,8)	1,0	58	18220 (2048)
4	Canadian goose	90	370(102,8)	6,8	55	124892 (14039)

As can be seen from the table, the range of direct impact force values of birds of various weights on an aircraft during takeoff or landing is approximately 500 – 14,000 kgf. It is necessary to determine what the strength of the rope and the net structure made from it should be in order to withstand the above-mentioned collision forces and not tear, i.e. to ensure the containment or dismemberment of the bird.

In the work [3], a hydrodynamic model of a bird is used and, as an example, the strength and diameter of the wire constituting a steel mesh are calculated that will withstand and not tear when hit by a 6.8 kg goose at a speed of 77.8 m/s (σ= 3846 MPa, d = 8 mm, mesh cell dimensions 20x20 mm). The above results are unsatisfactory, because if we use the calculation method of the data in Table 1, we will find that a steel wire mesh with a diameter of 8 mm will cause the aircraft engine to cover almost half of the air intake inlet, which is unacceptable. At the same time, it is important to consider the significant increase in the weight of the mesh when using steel material and the danger that can arise from steel fragments entering the engine's exhaust system. Therefore, it is necessary for the protective net to be made of smaller diameter and high-strength composite fiber ropes. For this purpose, the authors selected and analyzed the characteristics of various brands of modern high-strength composite fibers (see Table 2).

Table 2

N	MSP **fiber** name	Specific gravity [g/cm3]	Tensile strength σ [GPa]	Elongation modulus E [GPa]	Deg. Temp. [0C]	Humidity %
1	HMWPE-Dyneema, Spectra, Izanas)	0.97-1	C	120-180	147	0,01-0,05
2	Zylon	1.55-1.65	3-5.8	140-280	500-750	0.2-3.5
3	Kevlar	1.44-1.46	2.6-3.6	70-150	250-350	0.5-1
4	Vectran	1.38-1.45	2.8-3.5	110-180	300-400	0.3-0.8

It should be noted that the tensile strength of the above composite fibers and the ropes made from them differ significantly depending on the purpose of the specific brand of rope, therefore this difference must be taken into account when conducting theoretical and experimental work.

Ropes made of Kevlar, Vectran, Dyneema and Zylon fibers were purchased and their samples were tested for breaking on a modernized tensile machine UTM-M. The tests were carried out taking into account the extreme operating temperature conditions in the range of -60 ^{0}C to +60 ^{0}C, for which it was equipped with a Cryo-thermo camera. Table 3 presents the geometric parameters of the ropes made of these brands of fibers and the results of the tests for breaking.

Table 3

	MSB rope	Factory marking Φ [mm]	Actual cross-sectional area [mm^2]	Fg. [kg]	Tensile strength. [GPa]
1	Zylon	1.3	1.1	110	1.0
2	Spectra	1.3	1.69	153	1.1
3	Dyneema	1.4	0.96	91	1.0
4	Kevlar	1.6	1.26	96	0.8
5	Vectran	1.6	1.27	97	0.8

As can be seen from the table presented, threads (ropes) made of Zylon and Dyneema fibers are distinguished by the highest strength characteristics. However, it should be noted that threads (ropes) made of Zylon fibers are characterized by the ability to absorb water moisture in their surface layers (up to 3%), which creates the risk that during take-off and landing of an aircraft, when there is a sharp change in air temperature, the elements of the mesh made of Zylon may be damaged due to the formation of ice in its structural layers. For these reasons, preference was given to threads (ropes) made from Dyneema strands.

Dyneema fiber belongs to the family of ultra-high molecular weight polyethylene (UHMWPE) fibers (Dyneema – DSM, Netherlands), aka Spectra – Honeywell USA, aka Izanas – Toyobo Japan). As members of the thermoplastic polyethylene family, they are characterized by very long molecular chains that effectively transfer loads through polymer intermolecular interactions. It is characterized by high strength and lightness. It has high tensile strength and low density, high abrasion resistance and low elongation. It can handle rapid deformations under high loads. In addition, it is resistant to solar ultraviolet radiation and its moisture absorption is close to zero.

Based on experimental data on strength and the operating conditions of aircraft, ropes made from Dyneema fibers best meet the technical requirements for the production of protective nets.

Computer simulation modeling has been used to better assess the impact of bird strikes on protective nets [5], [6]. To calculate this task, the 2022 version of the Workbench program was used. This version includes the LS-DYNA module, which is designed to calculate collision and ballistic problems.

Fig. 2 shows images of the fragmentation of a simulated cylindrical body of a bird with a mass of 0.1 kg (d=40 mm; L=80 mm) in the mesh cells of a mesh made of Dyneema fiber yarns (d=1.4 mm. a x a 20 x 20 mm) during a collision at a speed of V=58.92 m/s. As a result, the impact force generated during the collision was determined to be 3492.3 N.

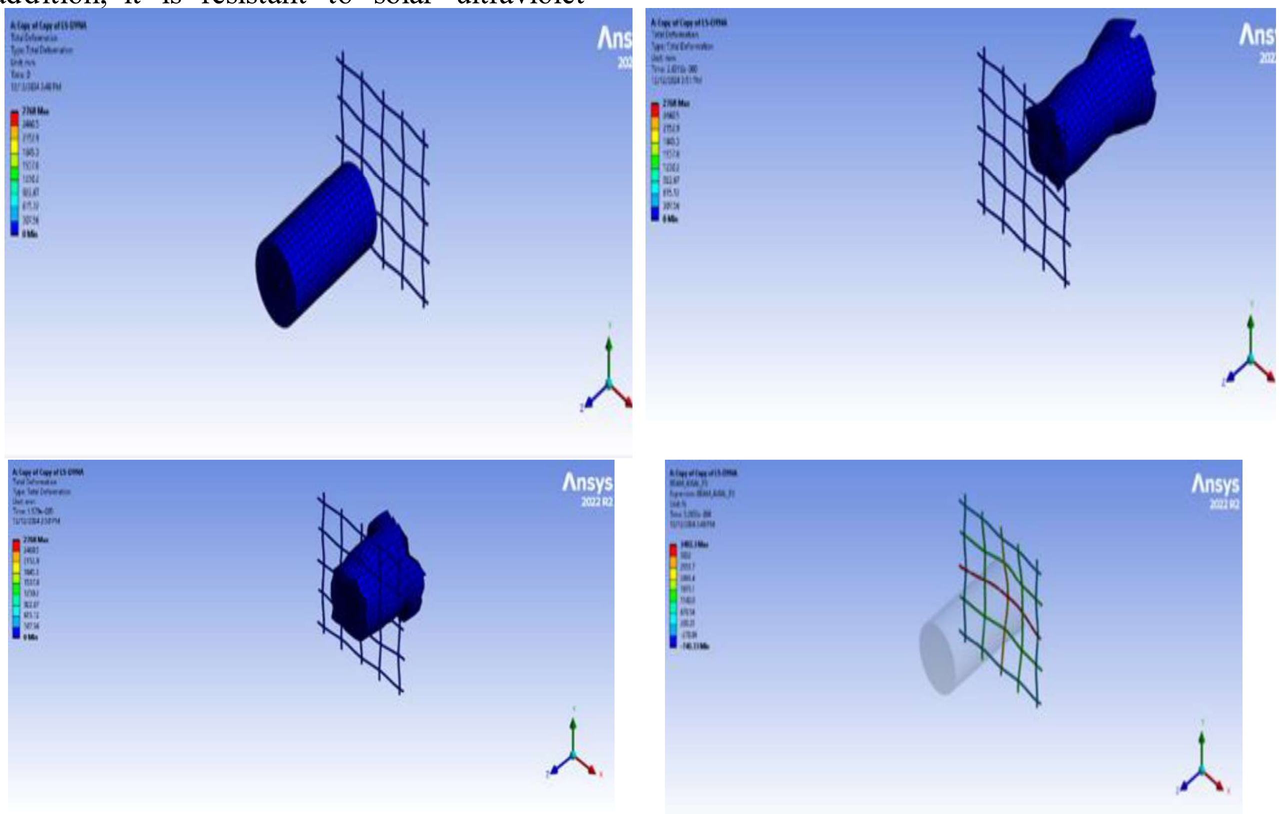

Fig. 2 Simulation of a bird hitting a net

A mesh with cell sizes of 20 x 20 mm was made from Dyneema ropes with a diameter of d = 1.3 mm, which was placed in a 100x100 mm metal frame and equipped with a special sensor device for dynamic tests (Fig. 3).

Fig. 3 Protective net with a strong frame after a bird hit it

The dynamic test stand consists of a pneumatic firing device and an electronic complex for measuring the speed of a simulated mass of a thrown bird. The test sample of the protective net was subjected to dynamic tests during bird strikes at various masses and speeds (Fig. 4).

Fig. 4 shows an experiment conducted on a dynamic stand, where a 0.1 kg bird model hit 20x20 mm mesh cells made of Dyneema fibers at a speed of V=58.92 m/s, generating a force impulse of 3788 N.

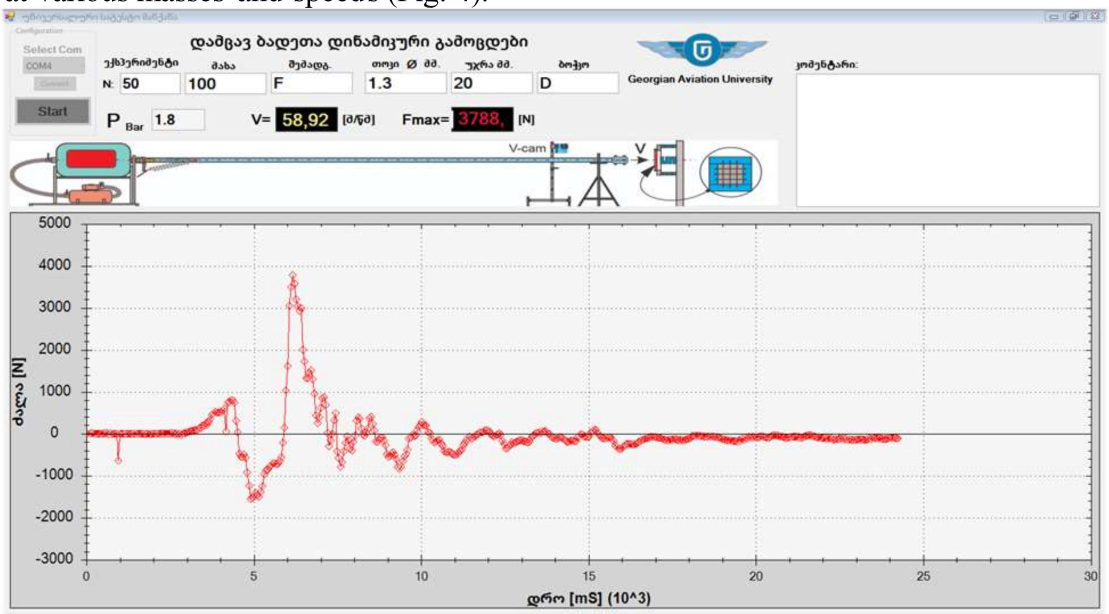

Fig. 4 Graph showing the impact force of a cylindrical bird (D = 0.04 m, L = 0.08 m) with a mass of M = 100 g hitting a 20x20 mm Dyneema fiber net.

Based on the initial data for this task, the magnitude of the impact force impulse was estimated in accordance with the model given in the literature [6]. In particular, using the values of the voltage induced in the mesh threads calculated by the energy method, which has the form:

$$\sigma = \frac{2 \cdot f_{lm} \cdot D}{\pi \cdot d \cdot sin\vartheta} \qquad (2)$$

where D is the diameter of the bird model, d is the diameter of the mesh thread, ϑ is the angle of deviation of the mesh thread from the plane of the mesh frame, which according to experimental data is $\vartheta \approx 11.5°$, and f_{lm} is the limiting value of the shear resistance force exerted on a thread with a unit longitudinal area [6], which is related to the limiting shear force by the ratio $F_{lm}=f_{lm} \cdot l \cdot d$, where l is the length of the mesh thread in contact with the bird, and d is the diameter of the thread. Based on new experimental data, the value of f_{lm} was specified and it is $f_{lm} = 15.71 \cdot 10^6$N/m^2.

During the experiment, a cylinder representing a bird model encounters two intersecting ropes, which have a total of 8 suspension points on the net frame, with the end of each thread tilted from the plane at an angle ϑ. The magnitude of the impact impulse on the mesh frame, taking into account formula (2), will be:

$$F = 8 \cdot \sigma \cdot \frac{\pi \cdot d^2}{4} sin\vartheta = 4 \cdot f_{lm} \cdot D \cdot d = 3519 \text{ N} \quad (3)$$

The results obtained from the three approaches presented are quite close to each other.

Conclusion

This scientific work concerns the improvement of flight safety of aircraft by significantly reducing the damaging factors caused by birds hitting the working elements of their power units (engine, propeller, fan) through the use of protective nets.

Instead of the steel wires traditionally used for protective nets, threads based on high-strength composite fibers produced by world-renowned companies were selected: **Dyneema** (DSM-Holland), **Spectra-75** (Honeywell), **Zylon** (Toyobo MC Corporation, Japan), **VECTAN** (DuPont); **Kevlar** (DuPont).

Samples of yarns of this designation were subjected to tensile tests on a modernized UTM-M stretching machine, within the operating extreme temperature range of +60 - 60 ^{0}C. Based on the results of strength tests and taking into account the specific requirements regarding the resistance of protective nets made of composite fibers to the action of ultraviolet radiation and their percentage of moisture content, the best characteristics were found for yarns made of Dyneema fibers.

A mesh with cells of 20x20 mm was made using a thread made of Dyneema fibers with a diameter of 1.3 mm. When using meshes of this size, the overlap coefficient of the CFM-56 air intake of the Boeing-737-is turbofan engine is 13%, and the TB3-117 turbofan engine of the Ми-8MTB helicopter is 14%.

Theoretical and computer simulation modeling of bird collisions with the net in the range of 100 g mass and velocities (V= 0 – 70 m/s) was conducted for a mesh with given parameters, as a result of which the conditions for bird retention, fragmentation, and mesh tearing on the net were determined.

To calculate the bird-net collision problem, the 2022 version of the Workbench program was used. This version includes the LS-DYNA module, which is designed to calculate collision and ballistic problems.

Experimental studies have shown that a net made of Dyneema ropes (with parameters: dimensions of the sides of the power frame 90 mm; drop=1.4 mm; lru = 20 mm) completely withstood the impact of a bird weighing 100 g with it at speeds (V= 50 – 70 m/s) and completely disintegrated it (10% of feathers and bone fragments remained on the front part of the net, and the remaining 90% was thrown out of the back part of the net in the form of small particles over a large area).

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