STUDY CONDITIONS OF DISMEMBERMENT OF BIRDS COLLISION ON THE AIRCRAFT ENGINE PROTECTIVE MESH SYSTEM

[1]VAZHA KELIKHASHVILI, [2]NIKA TIKANASHVILI, [3]BIDZINA ABESADZE, [4]ANDRO MAISURADZE

Scientific-Research Center, Georgian Aviation University, 16 Ketevan Dedopali Ave. 0103, Tbilisi, Georgia
E-mail: v.kelikhashvili@ssu.edu.ge

Abstract - This paper presents a methodology, based on two different approaches, which determines the conditions under which birds caught on the protective mesh placed on the device entering the air turbine engine will be separated. It is taken into account the speed of the bird, the dimensions of the mesh cells, the diameter of the constituent fibers, the resistance of the mesh to the strength, etc. On the basis of specific examples, the mentioned characteristics are defined. For several specific safety mesh materials, their durability indicators have been evaluated. Recommendations on defining the parameters of such protective mechanisms have been developed.

Keywords - Aviation, Flight Safety, Foreign Body, Safety Mesh, Aviation Engine.

I. INTRODUCTION

During the operation of aircrafts, when flying at low altitudes, one of the main dangers is a collision with birds and the possible catastrophic consequences caused by it. A special danger is created by birds getting into gas turbine engines, which in many cases become a significant damaging factor. One of the approaches to solve this problem is to attach a protective mesh to the engine air intake, which will act as a deterrent to birds that collision it. When a bird collision the mesh at a high speed, it can be broken, as a result, the bird will run into the aircraft engine at a significantly reduced speed, and the degree of its damage will be quite small. fig. 1 shows the case when an airplane passes through a flock of birds during takeoff.

For modern aircraft, both on airplanes and helicopters, such protective meshes can be found in the form of both stationary and mobile structures. However, it should be noted that in most cases the calculation is made on the retention of the bird - it will stay on the mesh or be thrown from it. Because of this, the construction of the protective mesh is extremely rigid, contains relatively large diameter fibers and the cell sizes of the mesh are also small. For these reasons, the construction of the protective mesh turns out to be quite heavy and, most importantly, significantly increases aerodynamic resistance of the airplane. A number of theoretical studies have been carried out for the mentioned topic [1, 2].

The problem can be solved as follows: the protective mesh will be made with relatively large cells and small diameter fibers and the caught bird will experience fragmentation on it. This method will give us important advantages, namely: the parts of the separated bird will have a relatively small mass and the value of the velocity significantly reduced from the impact speed, as well as the parts will be scattered over the entire area of the device entering the engine. As a result, the degree of damage to the engine will be significantly reduced. It is also possible to use a second or third additional mesh, on which the dismembered parts of the bird will undergo secondary or tertiary dissection or remain on it. The risk of damage, in such a case, will be minimized. The use of thin fibers will lead to the deterioration of the flying characteristics of the aircraft.
The presented paper deals with the mathematical calculation of such cases.

II. MAIN PART

When assessing the condition of bird separation on the protective mesh, theoretical calculations are carried out by two methods: in the case of a high-speed bird collision, a method similar to the approach used in hydrodynamics and aerodynamics is used and in the case of collisions with relatively low speeds the energy evaluation of the current process is done

Consider the case when a grid with dimensions $a \times a$ is placed near the air intake device. The diameter of the fiber in the mesh is d.
For simplicity, let's imagine that the bird is a uniform cylindrical body with diameter $-$ D and height $-$ h, average density $-\rho$, and the diameter of the protective mesh is D_0 (see Fig. 3).
When cutting the bird, the cutting area is created by the fibers placed in the touching part of the mesh. The resistive force generated during cutting will be proportional to the total length of the fiber, which will be calculated as follows: $l_T = \frac{2D^2}{a}$.
The Similarly of the laws of hydro and aerodynamics [4], the resistance force acting on the fibers touching

the mesh from the bird's side will be proportional to the square of the impact speed and the area touching the fiber:

$$F_R = k \cdot v^2 \cdot S = k \cdot v^2 \cdot l_T \cdot d (1)$$

The corresponding schematic is given in Fig. 4.

The dynamic equation that describes this process can be easily written according to Newton's second law:

$$M \cdot \frac{d^2x}{dt^2} = -F_R = -k \cdot v^2 \cdot l_T \cdot d = -k \cdot \left(\frac{dx}{dt}\right)^2 \cdot l_T \cdot d (2)$$

where M is the mass of the bird and k - coefficient of proportionality.

The solution of the (2) equation, with initial conditions: when $t = 0$, then $v = v_0$ and $x = 0$, will take the form:

$$v(t) = \frac{1}{\frac{k}{M} \cdot l \cdot d \cdot t + \frac{1}{v_0}} \quad (3)$$

$$x(t) = \frac{M}{k \cdot l \cdot d} \cdot \ln\left(\frac{k \cdot l \cdot d \cdot v_0}{M} \cdot t + 1\right) \Rightarrow t = \frac{M}{k \cdot l \cdot d \cdot v_0} \cdot \left(e^{\frac{k \cdot l \cdot d}{M} \cdot x} - 1\right) \quad (4)$$

For a bird of equal heightx = h, the time it takes to pass through the mesh will be:

$$t_h = \frac{M}{k \cdot l \cdot d \cdot v_0} \cdot \left(e^{\frac{k \cdot l \cdot d}{M} \cdot h} - 1\right) (5)$$

According to the formulas$(3, 5)$, the final speed of the parts of the divided bird will be:

$$v_{fin} = v_0 \cdot e^{-\frac{k \cdot l \cdot d}{M} \cdot h} \quad (6)$$

Within the framework of the considered theory, it is important to know other parameters to estimate the minimum speed required for complete dismemberment of the bird. In particular, the minimum force required to start the splitting process should be estimated, the moment (the minimum impact speed should be estimated) when the cutting process should start.

If the minimum force required to start the cutting process per unit contact area of the fiber, based on experimental data, is determined by the f_{lim} value, then the cutting resistance force must exceed the threshold value $F_R \geq F_{ilm}$, where $F_{lim} = f_{lim} \cdot l \cdot d$. Taking (4) into account the formula $k \cdot v^2 \cdot l \cdot d \geq f_{lim} \cdot l \cdot d$, from which $v \geq \sqrt{\frac{f_{lim}}{k}}$. Also, to achieve complete separation, the bird parts, after leaving the mesh, must have a final speed, which is estimated as follows:

$$v_{fin} = v_0 \cdot e^{-\frac{k \cdot l \cdot d}{M} \cdot h} \geq \sqrt{\frac{f_{lim}}{k}} (7)$$

And the initial speed will be according to (7):

$$v_0 \geq \sqrt{\frac{f_{lim}}{k}} \cdot e^{\frac{k \cdot l \cdot d}{M} \cdot h} (8)$$

Within the framework of the present research, a duck is considered as a bird striking on a gas turbine engine. The data of this bird is presented [2]. The required data are: $M \approx 6{,}8$ kg, and the average density is $\rho \approx 600$ kg/m3. Based on them, for the value of the coefficient k we will have: $k \approx 390$ kg/m^3, and $f_{lim} \approx \frac{F_{lim}}{l \cdot d} = 6.9 \cdot 10^6$ N/m^2 [1].

In addition, the geometric dimensions of the bird are required. It is presented as a cylinder with a diameter $D \approx 30$ cm, and a height $h \approx 20$ cm.

According to the formula (7), the minimum speed that the bird must have in order to start its dismemberment process is: $v \geq \sqrt{\frac{f_{lim}}{k}} = 133$ m/sec ≈ 479 km/h. This is a quite big speed. According to operational data of aircraft, collisions of birds occur within the speed limits of $100 - 300$ km/h.

The minimum force required for cutting is determined by the value $F_{lim} = f_{lim} \cdot l \cdot d$. In the event of a bird collision at lower speeds, the dynamic force required to break it apart must exceed this value. This is achieved by rapid braking on the bird mesh, which means that a significant change in momentum in a short period of time produces a large force.

The process of bird collisions at low speeds is evaluated using an energy-based approach. It is believed that at such a time the cutting force in the process of dividing the bird is of minimum value (equal to F_{lim}). The kinetic energy of the bird will be used for the work of the cutting force and the accumulation of potential energy when the mesh fibers are stretched.

$$\frac{M \cdot v_0^2}{2} \geq A_{cut} + W_{Pot} \quad (9)$$

The work of cutting can be easily calculated under conditions of constant force $F_{cut} = F_{lim}$:

$$A_{cut} = F_{cut} \cdot h = \frac{2 \cdot f_{lim} \cdot D^2 \cdot h}{a} \cdot d \quad (10)$$

As for the potential energy of stretching the fibers of the mesh, it is calculated according to the scheme given in Fig 4:

$$F_2 = -F_1 = \frac{F_{lim}}{n} = \frac{f_{lim} \cdot l \cdot d}{\frac{2 \cdot D}{a}} = f_{lim} \cdot D \cdot d \quad (11)$$

where F_1 is the tensile force, and F_2 is the resistive force acting on a unit fiber of the mesh.

The tension force of the fibers making up the mesh is calculated from the condition of equality of forces $T = \frac{F_2}{2 \cdot \sin\vartheta}$, and the stress induced in the wire is given in the form:

$$\sigma = \frac{T}{S_{sec}} = \frac{2 \cdot f_{lim} \cdot D}{\pi \cdot d \cdot \sin\vartheta} \quad (12)$$

It is known from the theory of plastic material deformation that the deformation energy (energy in a unit volume of the material) is calculated by the formula $w = \frac{\sigma^2}{2 \cdot E}$ [3], where E is the elasticity modulus of the material, and the total energy $W_{pot.} = w \cdot V = w \cdot S_{sec} \cdot D_0$. For the total tension energy over the entire length of the fiber, we will have:

$$W_{pot.} = \frac{\sigma^2 \cdot D_0}{2 \cdot E} \cdot \frac{\pi \cdot d^2}{4} = \frac{f_{lim}^2 \cdot D^2 \cdot D_0}{2 \cdot \pi \cdot E \cdot \sin^2\vartheta} \quad (13)$$

and the total potential energy of the fibers in the area of contact with the bird mesh:

$$W = n \cdot W_{pot.} = \frac{f_{lim}^2 \cdot D^3 \cdot D_0}{\pi \cdot E \cdot a \cdot \sin^2 \vartheta}. \quad (14)$$

It should be noted that it means a protective mesh in which mutually arranged threads are not interwoven (not presented in woven form). Otherwise, counting would have to be done for all threads in the grid, which would complicate the process. Taking into account (9), the minimum speed required for complete dissection of the bird:

$$v_0 \geq \sqrt{\frac{4 \cdot f_{lim} \cdot D^2 \cdot h}{M \cdot a} \cdot d + \frac{2 \cdot f_{lim}^2 \cdot D^3 \cdot D_0}{\pi \cdot E \cdot M \cdot a \cdot \sin^2 \vartheta}} \quad (15)$$

After dismembering the bird, the final speed of the parts:

$$v_{fin} = \sqrt{v_0^2 - \frac{4 \cdot f_{lim} \cdot D^2 \cdot h}{M \cdot a} \cdot d - \frac{2 \cdot f_{lim}^2 \cdot D^3 \cdot D_0}{\pi \cdot E \cdot M \cdot a \cdot \sin^2 \vartheta}} \quad (16)$$

The condition for the strength of the fibers included in the mesh (so that it does not break) is given in the form:

$$\sigma = \frac{2 \cdot f_{lim} \cdot D}{\pi \cdot d \cdot \sin \vartheta} \leq \sigma_{tem} \rightarrow d \geq \frac{2 \cdot f_{\text{бр}} \cdot D}{\pi \cdot \sigma_{tem} \cdot \sin \vartheta} \quad (17)$$

where σ_{tem} is the strength limit of the material (temporary maximum stress).

Let's consider some examples for cases of different materials of protective mesh threads:$v_0 = 250$ km/h ≈ 70 m/s is taken as the bird collision speed, based on the average statistical data of similar cases in practice.

Calculations were made based on the air intake dimensions of the real helicopter gas turbine engine:

- Protective mesh diameter taken according to the diameter of the engine air intake device $D_0 = 500$ mm;
- Cell size of the protective mesh is $a \times a = 50 \times 50$ mm;
- Diameter of mesh fiber $d = 1$ mm;
- The total length of fibers touching the bird mesh, which in this case $l \approx 1300$ mm;
- The dimensions of a cylinder equivalent to a bird imitation are: $D = 200$ mm, $h = 200$ mm;
- the weight of the bird $M = 6{,}28$ kg.
- It is considered as the permissible angular size of deviation of mesh fibers $\vartheta = 20°$.

The maximum deviation of the grid in such a case can be estimated geometrically:

$$\Delta x = \frac{D_0 - D}{2} \cdot \text{tg}\vartheta = 54{,}6 \text{ mm} \quad (18)$$

In Table 1,there is presentedseveral kind of bird protection mesh materials and required mechanical characteristics determined within the scope of the study [5, 6, 7, 8]:

Formulas (16) and (17) evaluate the condition of the final fastness of the divided parts of the bird and the strength of the threads constituting the mesh, the results are presented in Tab. 2.

It is worth noting that in the case of VECTRAN with normal characteristics, there will be a failure of the mesh before the end of the process of completely dividing the bird, while the data for Kevlar 49 are close to the limit values.

For each material, the minimum deviation angle of the mesh fiber can also be estimated using the formula (17), assuming that the tension force in the fiber reaches the value σ_{tem} and at which they are on the verge of breaking. In this case, the amount of fiber deviation can also be calculated according to the formula (18). The results are given in Table 3.

Analysis of the results: in the case of the given overall dimensions of the protective mesh, Kevlar 49 and VECTRAN materials cannot meet the requirements. Meshes made of other materials are useful in this case.

III. CONCLUSION

The theoretical calculations presented in the paper allow to estimate, for a wide class of speeds of the bird collision on the protective mesh, the conditions of its separation, taking into account the dimensions of the net and the strength characteristics of the fibers included in it. It is possible, in the case of specific parameters of the mesh, to estimate the speed required for the complete separation of the bird and the conditions of its rupture. It is also possible to solve the inverse problem, to estimate and select the parameters of the protective mesh in a certain range of bird collision speeds.

In the case of the specific parameters of the bird and the mesh, several possible specific cases are analyzed, which enables the further development and practical application of the research methodology.

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Fig. 1 The plane will pass through a flock of birds during takeoff [9].

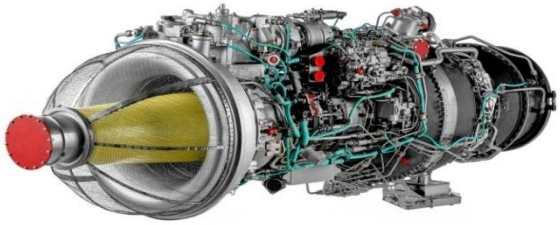


Fig. 2 protective mesh system installed at the entrance to one of the helicopter engines [10].

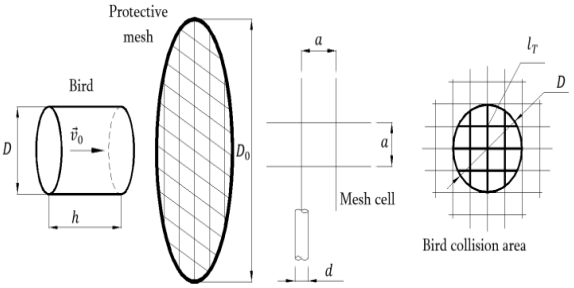


Fig. 3 Bird collision scheme and mesh parameters.

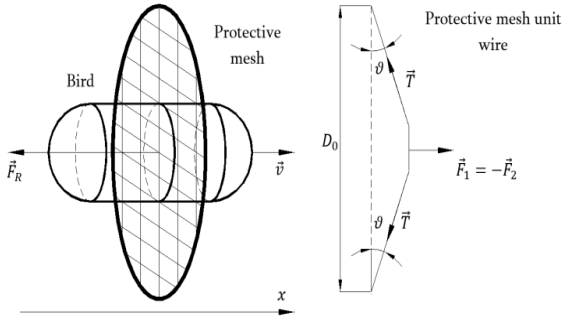


Fig. 4 Schematic of the bird division on the protective mesh and the forces acting on the unit fiber of the mesh.

Material	Modulus of elasticity E (Gpa)	Strength limit σ_{tem} (Mpa)
Kevlar 49	151,7	2757,9
Kevlar 29	70,3	2920,0
Zylon (with normal features)	180,0	5800,0
Zylon (with high features)	270,0	5800,0
DYNEEMA*SK78/SK75	132,0	3900,0
VECTRAN (with normal features)	52,0	1100,0
VECTRAN (with high features)	75,0	3200,0

Table 1 Mechanical characteristics of different materials

Material	The final velocity of the dismembered parts of the bird v_{fin} (m/sec)	Voltage induced in the thread forming the protective mesh σ (Mpa)
Kevlar 49	64,61	$2568{,}67 \leq \sigma_{tem}$
Kevlar 29	64,42	$2568{,}67 \leq \sigma_{tem}$
Zylon (with normal features)	64,64	$2568{,}67 \leq \sigma_{tem}$
Zylon (with high features)	64,69	$2568{,}67 \leq \sigma_{tem}$
DYNEEMA*SK78/SK75	64,59	$2568{,}67 \leq \sigma_{tem}$
VECTRAN (with normal features)	64,29	$2568{,}67 \geq \sigma_{tem}$
VECTRAN (with high features)	64,44	$2568{,}67 \leq \sigma_{tem}$

Table 2 Values of final speed and fiber strength condition

Material	The minimum angle of deviation of the fibers of the protective mesh ϑ_{min}	Deviation the fibers of the protective mesh Δx (mm)
Kevlar 49	18,6°	50,41
Kevlar 29	17,5°	47,32
Zylon (with normal features)	8,7°	22,99
Zylon (with high features)	8,7°	22,99
DYNEEMA*SK78/SK75	13,0°	34,68
VECTRAN (with normal features)	53,0°	200,0
VECTRAN (with high features)	15,9°	42,83

Table 3. The minimum angle and distance of deviation of mesh fibers

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