

Zbigniew CZYŻ  
Paweł MAGRYTA

## ANALYSIS OF THE OPERATING LOAD OF FOIL-AIR BEARINGS IN THE GAS GENERATOR OF THE TURBINE ENGINE DURING THE ACCELERATION AND DECELERATION MANEUVER

### ANALIZA EKSPLOATACYJNYCH OBCIĄŻEŃ GAZOWYCH ŁOŻYSK FOLIOWYCH ZESPOŁU WYTWORNICOWEGO SILNIKA TURBINOWEGO PODCZAS MANEWRU PRZYSPIESZENIA I HAMOWANIA\*

*The paper examines loads acting on the drive unit of an unmanned helicopter during maneuvers of acceleration and braking. Particular attention is paid to loads of gas generator bearings nodes of a turbine engine which is applied in the helicopter designed. The study is based on the time courses of changes in velocity of the manned PZL W3-Falcon. The correlation of flight velocity change and time was approximated by the least squares method to determine changes in acceleration. This enabled to determine the values of the forces acting on gas generator bearings under static and dynamic conditions. These values were compared with the values obtained for jump-up and jump-down maneuvers. The investigation enabled to determine the extreme components loading of the drive unit, including gas generator bearings nodes.*

**Keywords:** *helicopter, turbine engine, gas bearings, foil-air bearings.*

*W artykule rozpatrzono stany obciążeń działające na zespół napędowy śmigłowca bezzałogowego podczas manewru przyspieszenia i hamowania. Szczególną uwagę poświęcono obciążeniom węzłów łożyskowych zespołu wytwornicowego silnika turbinowego, w który zostanie wyposażony projektowany śmigłowiec. Analizę dokonano na podstawie przebiegów czasowych zmian prędkości lotu załogowego śmigłowca PZL W3-Sokół. Zależność zmiany prędkości lotu w czasie aproksymowano metodą najmniejszych kwadratów, a następnie wyznaczono dla niej zmiany przyspieszeń. Na tej podstawie wyznaczono wartości sił działających na łożyska zespołu wytwornicowego w warunkach statycznych i dynamicznych. Wartości te porównano z wartościami uzyskanymi podczas manewru skok w górę i skok w dół. Przeprowadzone analizy służą do określenia ekstremalnych stanów obciążeń podzespołów zespołu napędowego, a w tym węzłów łożyskowych zespołu wytwornicowego.*

**Słowa kluczowe:** *śmigłowiec, silnik turbinowy, łożysko gazowe, gazowe łożyska foliowe.*

#### 1. Introduction

The technology of foil-air bearings was developed already in 1960 for high rotational speeds in designs of boosters for diesel engines, auxiliary power units for aircraft (APU) and selected sections of turbine engines [2, 8, 9]. Gas bearings can operate often where conventional oil-lubricated bearings cannot most often, because of their too high stiffness, too high rotational speed and thermal requirements [1]. Generally, manufacturers of all kinds of technical devices such as turbochargers, turbo-generators, turbine engines, spindles, etc. claim that foil-air bearings are too risky if attempted to be implemented in new applications. Meanwhile, the researchers conducted a series of very extensive research to demonstrate their superiority over conventional bearings in many applications, especially for turbochargers and small oil-free gas turbines [8]. Besides, there are many methods to predict the lifetime of equipment, even if based the monitored diagnostic parameters. Kosicka [14] claims that appropriate mathematical models to analyze the data make it possible to make decisions about the need for maintenance and repair. If warning symptoms are detected, it is possible to determine residual operational time for devices. Such activities can minimize fears about the implementation of foil gas bearings in non-standard applications.

Studying scientists achievements on gas bearings, it can be said that three generations of the gas bearing foil have been developed by

far. First generation projects have relatively simple adaptive/flexible elements such as foils in bearing shells. They are typically uniformly stiff. Unfortunately, such gas bearings show like rigid gas bearings of the same size (without adaptive/flexible elements) a similar capacity. Second generation foil bearings are equipped with a more complex flexible base (Fig. 1) where stiffness is adjusted to a single direction, e.g. axial. This activity is aimed at adjusting the bearing to the environment in which it operates. This is particularly true about the correction of misalignment or prevention of fluid leakage at foil edges. The load capacity of generation second foil bearings is twice larger than that of solutions of generation I. A sample of a design solution by [5] is depicted in Figure 2.

Third generation of foil-air bearings are composed of advanced, highly complex, flexible foil bases stiffness of which is adjusted in two directions (often axially and radially). This level of designing

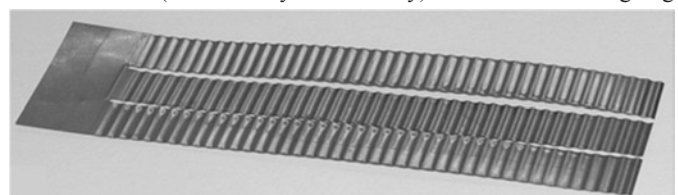


Fig. 1. The view of an exemplary foil which was shaped to the foil-air bearings of generation II [2]

(\*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie [www.ein.org.pl](http://www.ein.org.pl)

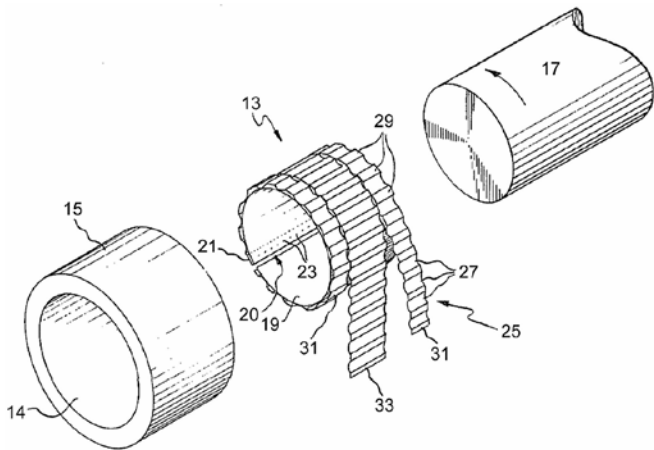


Fig. 2. The view of construction solution of foil-air bearings according to patent [5]

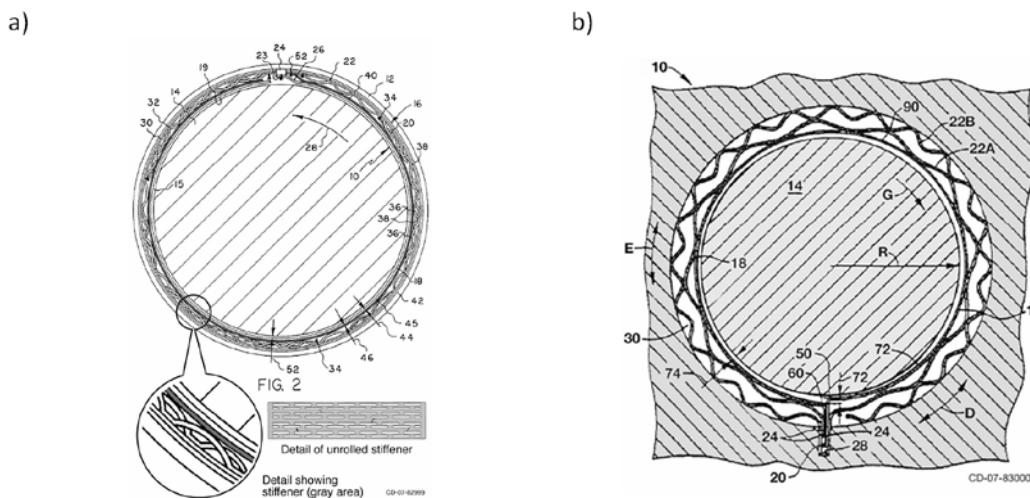


Fig. 3. The view of foil-air bearings in third generation: a) a stiffener to prevent flexing of the upper foil layer [7], b) foil bearing with adjustable transverse stiffness [10]

flexibility of foil in bearings enables the control of edge effects and optimization of bearing's stiffness for different loads. Third generation of foil-air bearings proved to have a load capacity of three to four times larger than that of the bearing of first generation. A sample of such a bearing is shown in Figure 3 based on [7] and [10].

Combat helicopters, including unmanned ones need to show an excellent maneuvering capability to perform reliable avoidance maneuvers in air combat. The resulting operational loads have a significant impact on bearing nodes of rotor system in the aircraft drive unit. Unmanned aircraft are constantly developed and improved as they are an indispensable machinery to carry out, for example, missions dangerous for crew. There has been already developed in Poland a number of such constructions, including unmanned helicopter ILX-27. This helicopter has been designed as an unmanned aircraft of a 1,000 kg storage class [4]. Another example of work on unmanned aircraft (unmanned helicopters) is a construction based on the SW-4 Puszczuk, a helicopter manufactured by PZL-Swidnik S.A. [6]. Some investigation is also underway on unmanned helicopters of a low take-off mass.

The use of the turbine engine in unmanned helicopter platforms is basically justified by its mass. It appears that the mass of the turbine engine set, including fuel is considerably less than the mass of the assembly with the piston engine for one hour of flight. A coefficient behind the power-to-weight ratio [kW/kg] in the case of aircraft turboshaft engines is higher than in the piston engine. This means that during short (about one hour) flights of unmanned aircraft it is more convenient to apply turbine engines. Unfortunately, the discrepancy in mass decreases with increasing time of operation. This involves a larger unit fuel consumption which is 0.4-0.7 kg/kWh and 0.35 kg/kWh for the turbine engine and piston engine, respectively. However, the cost-effectiveness of the use of gas turbine engines increases even more due to different fuel prices [3]. In the case of the FSTC-1 turbine engine, designed at the Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems of Lublin University of Technology, it is important to determine the status of the loading of bearings nodes, especially those of gas bearings (transverse and axial) on which the gas generator operates. The jump-up and jump-down

maneuver is described in [16]. The study of the maximum loads on bearing nodes of the drive unit shows that during the jump-up and jump-down maneuver the maximum loading force acting on radial bearings is  $P_p = 17.1$  N and the force acting on axial bearings resets, given the working components of the gas generator are designed so that axial aerodynamic forces they create could balance each other.

## 2. Research object

Analysis of the operating load of foil-air bearings is to choose the correct type of bearings in the gas generator set in turbine engine with a power of 18 kW. The object of the research is a turboshaft engine. The rotational speed of the gas generator turbine, and also the whole gas generator set is 96,000 rpm while the turbine of drive set is 60,000 rpm. Despite the relatively high value of rotational speed of gas generator turbine (relative to the drive turbine), bearing are subjected to large values of temperature, which results from the positioning between the shaft and the combustion chamber (Fig. 4).

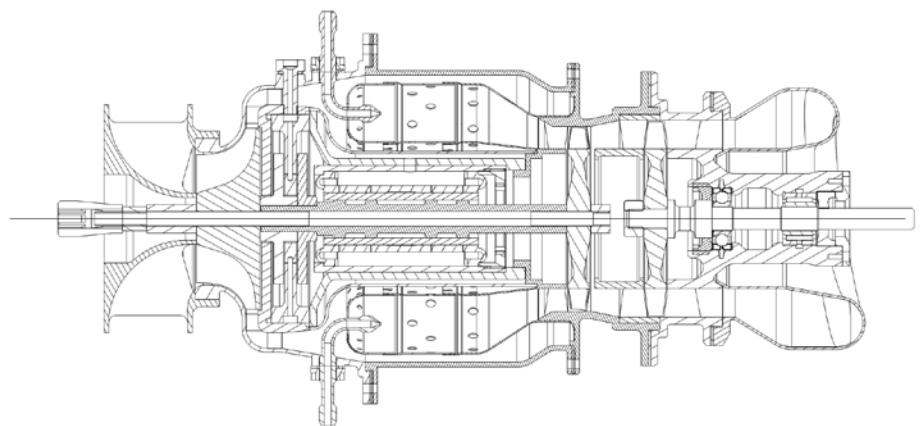


Fig. 4. FSTC-1 turbine engine with a power takeoff on shaft, own study

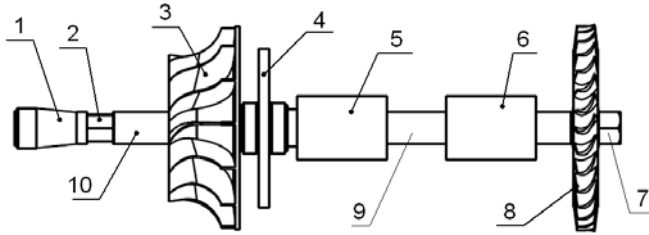


Fig. 5. Diagram showing the components of compressor drive unit rotor set of the turbine engine, 1- clamping sleeve with the internal splines, 2- clamping nut from rotor compressor, 3- compressor rotor, 4- thrust disc of axial bearing, 5, 6- radical bearing sleeve, 7- clamping nut from rotor of compressor drive unit turbine, 8- rotor of compressor drive unit turbine, 9- compressor drive unit shaft, 10- compressor rotor sleeve, own study

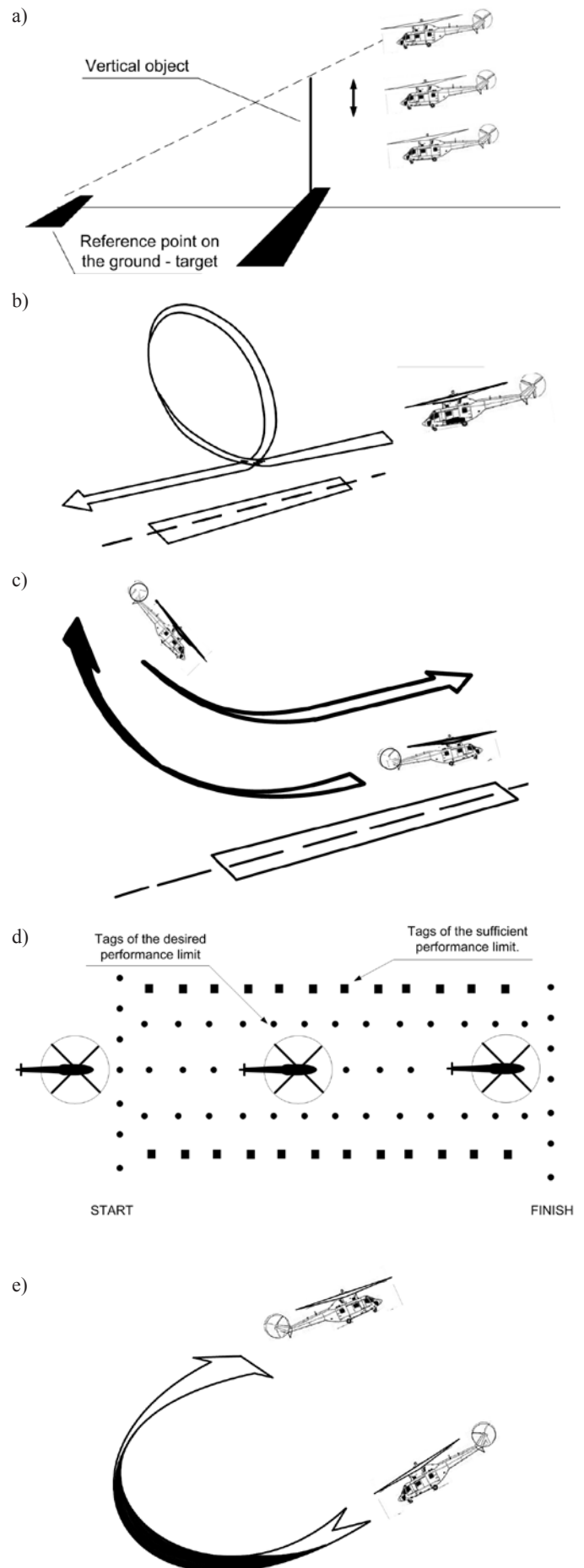
The scheme of gas generator set in FSTC-1 engine is shown in Figure 5. All components of gas generator set have been described and parameterized in [16]. Difficult operating conditions (high rotation speeds, high temperatures, difficult access), in the case of gas bearings are acceptable [11, 13, 15]. Assembly of gas generator, which is analyzed consist of a shaft on which the deposited centrifugal compressor rotor and the axial turbine rotor. The whole parts are mounted on the two radial gas bearings and one axial bearing. Axial and radial air bearings are arranged inside the engine (between the compressor and the turbine), the bearing cores are fragments of the shaft and the axial plate of the axial bearing is connected with the shaft. For the analysis it was taken that the engine is placed longitudinally on a helicopter, and states of the operating load of foil-air bearings depend on the profile of the flight path and the flight mode, wherein the several cases of helicopter operation were distinguished.

### 3. Analysis of the load states of drive set during an acceleration and deceleration maneuver

State model of operating load of bearing shafts are based on the actual values obtained from the analysis of PZL W-3 Sokol helicopter data flight. Despite the difference in size of the helicopters, it was assumed that the unmanned helicopter of 100 kg take-off mass, fitted with a designed engine will be able to perform missions with the profile moves such as a manned helicopter. The analysis of acceleration, which are acting on rotor set of designed engine was based on the results of experimental studies of the W-3 Sokol helicopter in flight behavior of the NOE [12]. Helicopters, especially unmanned must perform specific combat tasks such as: observation of the enemy, the discharge of the explosive materials, taking a shot at its sufficient maneuverability to avoid possible shoot down. These maneuvers are sufficient to enable a helicopter to achieve them. It is assumed that the helicopter does not take air combat. The subject of analysis is due to the lack of experimental data, relating to the behavior of unmanned helicopters in extreme flights.

The most common maneuvers that occur during the execution of the flight mission of unmanned helicopters include: jump-up and jump-down, acceleration and deceleration, braking before the attack, a tight curve and the return to target.

Among maneuvers listed in this article, it has been decided to analyze the maneuver of acceleration and braking, which is shown in figure 6d. Acceleration and braking maneuver is starting with the rapid increase of hover power, almost to the maximum and maintaining a constant altitude with the constant tilt of the helicopter. After reaching a certain velocity there is a braking. Like other combat maneuvers, this one is used on the battlefield and allows for quick hiding from enemy fire. The maneuver is based on a dynamic acceleration from



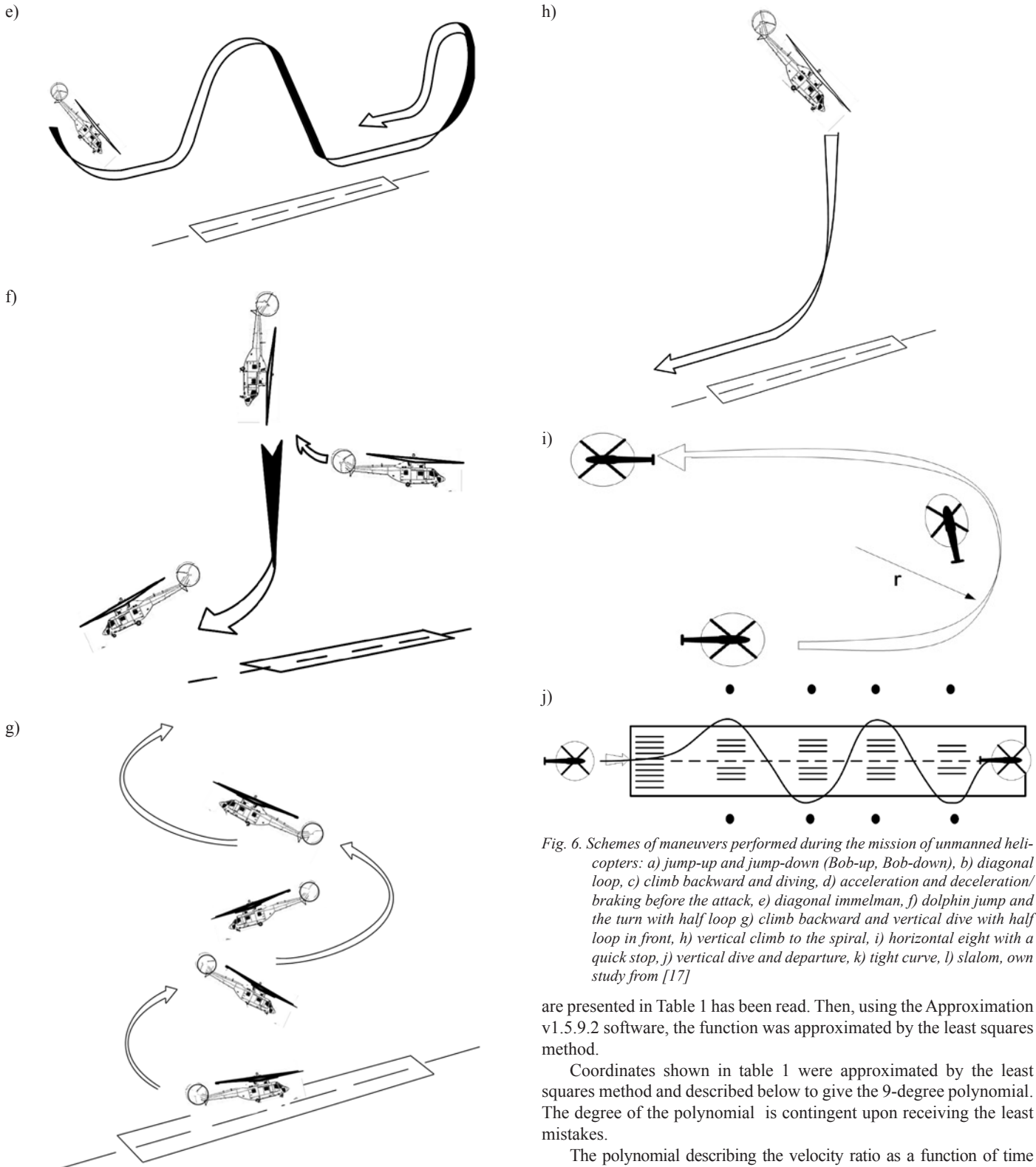


Fig. 6. Schemes of maneuvers performed during the mission of unmanned helicopters: a) jump-up and jump-down (Bob-up, Bob-down), b) diagonal loop, c) climb backward and diving, d) acceleration and deceleration/braking before the attack, e) diagonal immelman, f) dolphin jump and the turn with half loop g) climb backward and vertical dive with half loop in front, h) vertical climb to the spiral, i) horizontal eight with a quick stop, j) vertical dive and departure, k) tight curve, l) slalom, own study from [17]

hovering, to obtain velocity of over 90 km/h, and the braking before the cover (Fig. 6d). Braking must take place quickly, because the slow braking extends much its length, and thus, the helicopter is longer exposed to shooting down and is easier to trace. However, too late starting of braking process can cause helicopter will not be able to brake before the cover, which eventually had to protect him and will be destroyed.

The analysis was carried out taking into account the time-course of helicopter flight velocity. From [12] coordinates of the points that

are presented in Table 1 has been read. Then, using the Approximation v1.5.9.2 software, the function was approximated by the least squares method.

Coordinates shown in table 1 were approximated by the least squares method and described below to give the 9-degree polynomial. The degree of the polynomial is contingent upon receiving the least mistakes.

The polynomial describing the velocity ratio as a function of time  $V=f(t)$  during performing the acceleration and deceleration maneuver was described by Equation 1 and following differentiation of equation 1 acceleration (equation 2) was obtained:

$$\begin{aligned}
 V = f(t) = & (1.38181953695982E - 6) * x^9 + (-9.91464119063688E - 5) * x^8 + \\
 & (0.002952125097356) * x^7 + (-0.04720222844170) * x^6 + \\
 & (0.438522675128192) * x^5 + (-2.39455119465) * x^4 + \\
 & (7.33950678618245) * x^3 + (-10.6168068378714) * x^2 + \\
 & (6.24301355403459) * x^1 + (-0.00312803628420411) * x^0
 \end{aligned}
 \tag{1}$$

Table 1. Coordinates of the velocity changes depending on the time for acceleration and deceleration maneuver, based on [12]

No.	Time [s]	Registered velocity [m/s]	No.	Time [s]	Registered velocity [m/s]
1	0	0	10	9	32.86
2	1	0.97	11	10	33.10
3	2	1.78	12	11	30.97
4	3	5.32	13	12	27.66
5	4	9.81	14	13	23.64
6	5	14.21	15	14	18.51
7	6	18.68	16	15	10.52
8	7	23.88	17	16	0
9	8	29.31			

$$a = \frac{\partial V}{\partial t} = (9 * 1.381819536959E - 6) * x^8 + 8 * (-9.914641190636E - 5) * x^7 + 7 * (0.00295212509735611) * x^6 + 6 * (-0.0472022284417062) * x^5 + 5 * (0.438522675128192) * x^4 + 4 * (-2.39455119465) * x^3 + 3 * (7.33950678618245) * x^2 + 2 * (-10.6168068378714) * x^1 + (6.24301355403459) * x^0 \quad (2)$$

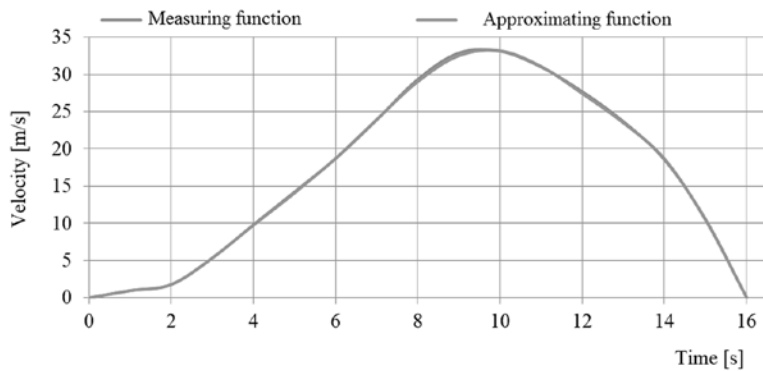


Fig. 7. Measurement and approximation functions of the PZL W-3 Sokol helicopter velocity, depending on the time

Table 2. Measurement and approximation data of velocity changes of PZL W-3 Sokol helicopter flight depending on the time, during the acceleration and deceleration maneuver

Time [s]	Measurement velocity [m/s]	Calculation velocity [m/s]	Relative error [%]	Acceleration [m/s <sup>2</sup> ]
0	0.00	0.00	-	-0.62
1	0.97	0.96	0.73	2.47
2	1.78	1.78	0.06	4.29
3	5.32	5.37	-0.89	4.36
4	9.81	9.76	0.49	4.38
5	14.21	14.09	0.84	4.97
6	18.68	18.73	-0.31	5.37
7	23.88	23.97	-0.38	4.55
8	29.31	29.06	0.87	2.19
9	32.86	32.54	0.98	-0.85
10	33.10	33.21	-0.34	-3.15
11	30.97	31.10	-0.41	-3.91
12	27.66	27.45	0.78	-4.07
13	23.64	23.50	0.61	-6.08
14	18.51	18.67	-0.88	-10.47
15	10.52	10.44	0.77	-7.10
16	0.00	0.03	-	6.24

Figure 7 shows the function obtained from a measurement of the velocity of the PZL W-3 Sokol helicopter versus time during the acceleration and deceleration maneuver, and the approximation function on the basis of the resulting from acquired data points.

Comparing the characteristics based on the measurement points and the polynomial, which was obtained from the approximation function, it can be seen that the relative error resulting from the approximation does not exceed 1% (Tab. 2 and Fig. 8).

The polynomial function describing the acceleration which is a derive of the velocity by the time are shown in Figure 9.

#### 4. Loads of gas generator bearing nodes

According to developed in [16] states model of the operating load for the foil-air bearings of the engine, which is the subject of research, we can mention the following forces acting on the radial bearing of the rotor set:

- gravity of the rotor set;
- caused by the jump-up/jump-down maneuver;
- caused by the gyroscopic moment;
- centrifugal caused by the tight curve maneuver;
- caused by the return on purpose maneuver;
- residual unbalance.

In the case of thrust bearing we can be mentioned forces:

- gas from aerodynamics;
- axial caused by the acceleration and braking maneuver;
- centrifugal caused by the derived from jump over the obstacle maneuver.

On the rotor set, in addition to the static forces with the time-varying values, a dynamic loads work also. While in the first case, there are only fixed values, directions and points of application of forces, in dynamic loading, we are dealing with the situation in which the body (research object) sudden external force and inertia force generated as a result of acceleration of the body mass are acting. The value of overload depends mainly on the acceleration and in extreme conditions can overload the tested bearing as well as in certain situations underload. The purpose of the analysis of dynamic load of bearing nodes of rotor set is to determine such *k* coefficient, depending on the maximum acceleration values that guarantee correct operation of the bearing in the test load range.

To determine the value of the overload, the various maneuvers in terms of acceleration and the direction of their actions, and thus the type of loaded bearings (axial, radial) should be analyze. During the maneuver of acceleration, deceleration and braking before the attack we have to deal with the forces (Fig. 10):

$$R_{A1}^y / R_{B1}^y - \text{gravity of the rotor set};$$

$$R_{B1}^x - \text{gas from aerodynamics};$$

$$R_{B2}^x - \text{centrifugal caused by the derived during the maneuver.}$$

It is assumed that the working components of the gas generator set are structured such that the formed axis aerodynamic forces will equilibrate. This fact is causing  $R_{B1}^x$  force to

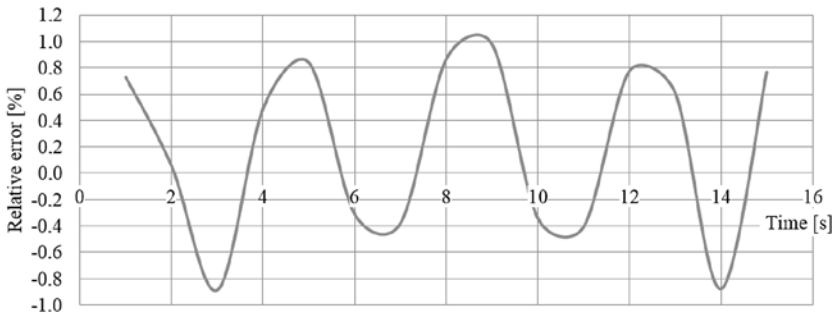


Fig. 8. Figure showing relative error of approximation of PZL W-3 Sokol helicopter velocity, depending on the time during the acceleration and deceleration maneuver

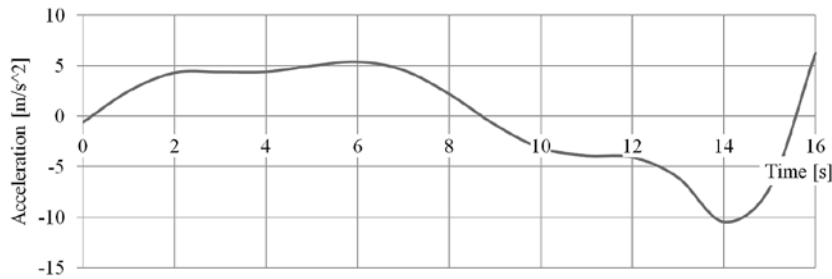


Fig. 9. Figure showing acceleration of the W-3 Sokol helicopter during the acceleration and deceleration maneuver

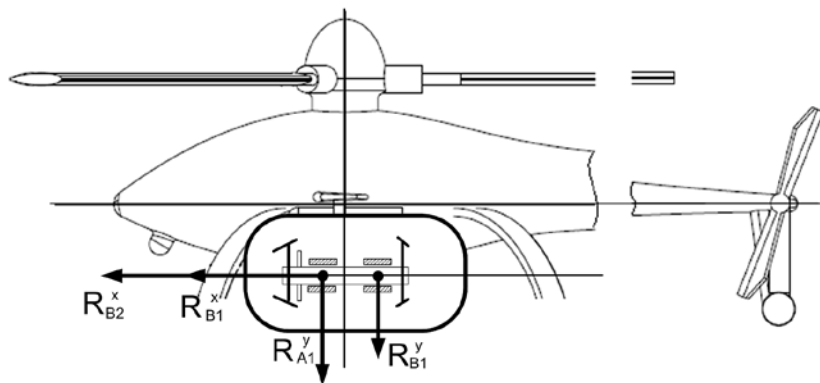


Fig. 10. Diagram of load of bearing nodes during the acceleration, deceleration and braking maneuver before the attack, own study

Table 3. Basic parameters of the components of compressor drive unit rotor set

No.	Element name	Material	Volume [m <sup>3</sup> ]	Mass [kg]	Weight [N]
1	Clamping sleeve with the internal splines	Titanium	2.644e-6	0.012	0.118
2	Clamping nut from rotor compressor	Steel	6.761e-7	0.005	0.049
3	Compressor rotor	Titanium	3.413e-5	0.152	1.491
4	Thrust disc of axial bearing	Steel	1.325e-5	0.104	1.020
5,6	Radical bearing sleeve	Steel	0.843e-5	0.067	0.657
7	Clamping nut from rotor of compressor drive unit	Steel	8.284e-7	0.007	0.069
8	Rotor of compressor drive unit turbine	Steel	2.091e-5	0.164	1.609
9	Compressor drive unit shaft	Steel	1.824e-5	0.143	1.400
10	Compressor rotor sleeve	Titanium	1.763e-6	0.008	0.079
Density of used materials: - steel, density= 7.860 kg/m <sup>3</sup> - titanium, density= 4.460 kg/m <sup>3</sup>					

reset. In contrast, the forces of gravity are (on the basis of statistic calculations):

$$R_{A1}^y = P_{A1}^{st} = 5.638 \text{ N}$$

$$R_{B1}^y = P_{B1}^{st} = 1.631 \text{ N}$$

The forces acting on the radial bearings arise only from the mass of rotor set, therefore:

$$a_{\Sigma} = g = 9.81 \text{ m/s}^2$$

$$k = \frac{a_{\Sigma}}{g} = 1 \tag{3}$$

$$P_{A1}^{dyn} = k \cdot P_{A1}^{st} = 5.638 \text{ N}$$

Inertial forces acting on the thrust bearings, are caused by acceleration during the maneuver and represent multiples of gravity force of the whole set  $Q_c$ , where the multiply coefficient is the value of the overload. The force of gravity  $Q_c$  is the sum of the components of the gas generator set shown in Figure 5. The mass of each component, together with other basic parameters is shown in Table 3.

The result of the analysis gives the maximum acceleration  $a_{max}=10.47 \text{ m/s}^2$ . Hence:

$$a_{\Sigma} = a_{max}$$

$$a_{\Sigma} = 10.47 \text{ m/s}^2$$

According to equation (3), the coefficient  $k$  is:

$$k = \frac{a_{\Sigma}}{g} = 1.067$$

Force  $R_{B2}^x$  is caused by axial acceleration during the maneuver is therefore:

$$P_{B2}^{dyn} = k \cdot Q_c = 7.63 \text{ N}$$

## 5. Conclusion

During the acceleration and deceleration maneuver, we have to deal with the forces of gravity of the gas generator set, gas aerodynamics force and force caused by axial acceleration during the maneuver. If we assume that the working components of gas generator set are designed so that, they made an axial gas aerodynamic forces interactions to equalize, the remaining forces work with a value that results from motion profile of the helicopter. Based on the presented analysis we can make a results compilation. For this maneuver gravity forces (on the basis of statistical calculations) are respectively for bearing A= 5.638 N and for the bearing B= 1.631 N. As the coefficient  $k$  in this direction is equal 1, these forces result only from the mass of the

rotor set. From Table 2 and Figure 9, the acceleration value was  $a_{\max}=10.47 \text{ m/s}^2$ . The coefficient  $k$  is 1.067. After multiplication of  $k$  factor and the mass of all components of gas generator set that act on the bearing, the  $R_{B2}^x$  axial force called axial acceleration during braking maneuver is 7.65 N.

In the maneuver jump up and jump down [16] this force was omitted, in this case is one of significant value. With respect to the radial forces, during the maneuver jump-up and jump-down radial bearing A is more loaded than the bearing B and the maximum value of the loading force radial bearings (bearing node A) is  $P_p=17.1 \text{ N}$ .

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**Zbigniew CZYŻ**

**Paweł MAGRYTA**

Department of Thermodynamics, Fluid Mechanics and

Aviation Propulsion Systems

Lublin University of Technology

ul. Nadbystrzycka 36, 20-618 Lublin, Poland

Emails: z.czyz@pollub.pl, p.magryta@pollub.pl