

# APPLICATION OF ELECTRIC CAPACITY MEASUREMENTS TO DETECTING DELAMINATION IN BLADES OF HELICOPTER'S LIFTING AND AUXILIARY ROTORS

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## ABSTRACT

*This paper represents a series of the authors' publications concerning effects of atmospheric conditions on aircraft [5-6, 11]. Hazards connected with separation ( delamination ) of heating elements from blade's spar , namely: increased susceptibility to ice formation as a result of change in aerodynamic profile, decreased deicing effectiveness, shortened life of heating elements , weakened strength of blade's structure, are described. In order to monitor the above mentioned delamination process during its early phase, these authors proposed to measure systematically electric capacity between the heating element and blade's spar by means of a technical method. The electric capacity measurements performed by these authors on blades both in laboratory and service conditions demonstrated their practical usefulness for assessing delamination extent as well as for identifying areas where heating element separation from spar occurred. The method in question is simple , cheap , fast and non-interfering (non-destructive) as well as it does not require dismantling the blades off the helicopter. As proved in practice , it is especially useful in sea-rescue or military operational conditions. Special attention was paid to application of the method to composite blades where coming-off the heating element tape causes local overheating the blade structure , that impairs flexibility of composite's layers and may lead even to local cracks which may trigger helicopter crash. These authors desire to apply the method as a standard unit of on-board diagnostic system in the future.*

**Keywords:** surface delamination of lifting blades, electric deicing installation, diagnostics of failures by using electric capacity measurements

## PREFACE

Atmospheric factors which occur over water areas such as seas and oceans, make aircraft operations greatly difficult, that consequently rises difficulty of task execution. It results in lowering safety during flight operations over such areas. Operations over or close to seas and oceans require from the designers and pilots to take into account first of all the following atmospheric conditions [5, 9, 13, 14, 20]:

- significantly higher humidity of air over sea than that over land,
- lower temperature of air over sea than that over land,
- higher wind speed over sea than that over land (there is no natural terrain obstacles),
- air salinity.

This is especially important issue for Polish Air Force which is responsible for carrying out search and rescue (S&R) actions over Baltic Sea area. Construction of aircraft which are on S&R duty as well as other craft operating over water

areas fundamentally differ from other aircraft. The differences result from:

- possible landing on water,
- executing tasks in high humidity conditions which are conducive to ice-formation on elements of wings and engines.

For rescue tasks carried out over water areas, e.g. in Poland, Navy helicopters are generally more often used than airplanes or boats, that results from their unique flying qualities which make it possible to fast locate and reach the target and then to safely take up injured person / castaway from hovering position [7, 10, 23, 26].

During ice formation to keep flight direction is difficult, increasing vibration of airframe occurs as well as its lifting force drops. Ice formation is more probable to occur over sea waters than over land. Unstable space position which accompanies ice formation constitutes significant danger during helicopter operation of taking-up castaways from ship's deck, offshore drilling unit or wind power plant. Extreme effect of intensive icing, i.e. sudden drop of lifting force, may be an additional

danger for both rescued and rescuing persons. To prevent it, sea rescue helicopters operating within SAR system in Poland are equipped with blades having heating resistance elements fed from on-board electric power network. This is an effective solution successfully used in Eastern Europe countries, a.o. in ice-formation conditions during service in Far North.

In any rotorcraft, lifting surfaces of main rotor blades are elements responsible for producing lifting force [18, 27]. At the beginning, lifting propellers made of wood were applied to light helicopters (e.g. SM-1) [2] and subsequently those made of metals. In present, designers implement more and more often composite blades especially for light and medium-size helicopters. Such blades are characteristic of much lower mass and equal strength compared with metal ones at obeying given operational regimes. However they are less resistant to moisture, delamination and temperature changes [1, 5-6, 17, 24].

In Polish Navy Air Force helicopters the following kinds of blades are used:

- Mi - 14 (metal blades),
- W - 3RM „Anakonda” (composite blades),
- SH-2G „Kaman” (metal blades)

Occurrence of ice formation on blades is not permissible in case of executing hovering operation by such helicopter over sea-going ship or navy vessel in order to take-up castaway because during ice forming to keep flight direction is difficult, vibration of airplane increases and lifting force drops. The extreme effect of intensive icing, i.e. sudden drop of lifting force, may be disastrous for both rescued and rescuing persons [8, 10, 22]. To prevent it, sea rescue helicopters operating within SAR system in Poland are equipped with blades having heating resistance elements fed from on-board electric power network [3-6, 15-16]. This way of preventing ice formation was implemented by Russian helicopter producers practically from the very beginning of their manufacturing in this country – whereas in Western constructions only increased flexibility of blades (the natural, mechanical breaking of ice layer, which is effective at low and medium gradients of thickness growing) and organizational restrictions of flights in icing zone, were preferred. Electric heating is a highly power-consuming method (during operation of the lifting blade heating installation more than 50% output of on-board electric power sources is usually consumed, however such system is extremely effective. Its effectiveness is proved by the fact [21] that in civil aviation of Union of Independent States where the electric heating is commonly used for rotor blades, no flight accidents due to icing were reported in the years 1990-2010. Simultaneously, in Western countries interesting proposals of application of ultrasounds [19], microwaves and infrared radiation etc to blade deicing have been developed. Unfortunately, information on their common practical application is still lacking. However, reports on installation of electrically heated blades (and on including such systems into helicopter's electric power network) „at special request” by Western producers, have been published [5-7]), that is an additional indirect evidence of effectiveness of the blade deicing system in question.

## INTRODUCTION

Metal blades differ from composite ones by many properties. Composite blades are superior because their much lower mass and higher corrosion resistance, however they are characteristic of higher susceptibility to mechanical failures. Possible deformation of blade surface as a result of delamination, especially close to edge of attack, may have straight disastrous consequences in intensive icing conditions [4, 11, 18-22]. Every such deformation results in change (usually drop) of lifting force and rise of aerodynamic drag. The changes cause the worsening of helicopter stability and manoeuvrability. Moreover, coming-off the blade heating element from spar produces thermal insulation between a given heating element section and spar body. The air cushion formed this way works as a circuit isolator and blocks heat flow toward spar thus exposing structural elements to overheating. Hence, areas exposed to overheating are formed.

In composite blades, local overheated areas result in hardening the composite layers, causing drop of elasticity and flexibility, that affects their work and strength in operational conditions intended for such structures [1, 6, 24]. Such places are more susceptible to fractures [1, 24]. Local overheated areas may form nuclei of fractures which may lead to heavy air accidents –Fig. 1.



Fig. 1. Illustration of consequences resulting from delamination of a composite blade of helicopter lifting rotor during flight

Composite blades require more precise overhauls than metal ones, that impacts operational costs and first of all safety. Sea helicopter aviation in Poland is limited to only military air force (other helicopters do not fully satisfy requirements for search and rescue operations over water areas) [23]. Because such aircraft must be specially prepared for executing rescue tasks in heavy weather conditions. In rescue action, time is the most important factor [26]. Use of helicopters for such tasks ensures the shortest time for their executing, i.e. location and evacuation of a castaway. Therefore helicopters taking part in such actions should be possible to operate in every weather conditions. For this reason, to make it possible to conduct on board current diagnostic tests of technical state of blades of lifting and auxiliary rotors, would be justified. It may be especially useful in executing actions close to areas prone to ice formation. For this reason these authors have proposed to apply the electric capacity measurement method to detecting and monitoring the delamination of the rotor's blades.

## POSSIBLE APPLICATION OF ELECTRIC CAPACITY MEASUREMENTS OF HEATING SECTIONS TO ASSESSING DELAMINATION IN HELICOPTER LIFTING BLADES

The basic method for diagnosing composite blades, used until now, consisted in dismounting the blade off the helicopter, placing it on a support and executing time-consuming test with the use of hammer to find departures from standard requirements [4]. The test requires highly experienced personnel, does not guarantee unambiguous results and is – in a sense – interfering (influence of hammer impacts on blade mechanical structure). Instead of it these authors propose a non-interfering method as it is enough to disconnect cable joints (of electric circuit which connects heating sections with on-board electric network) in the blade and install instead the system of electric capacity measuring by technical method. For such operation it is not necessary to employ a highly experienced personnel. Moreover, it is a non-interfering and objective method as results of electric capacity measurements can be compared with standard (model) values. In the future, according to opinion of these authors, it would be possible, after a relatively small alteration of electric supply system, to install on board such a system and carry out blade monitoring in flight.

During the investigations conducted in ITWL (Air Force Technical Institute) on structure and properties of lifting blade's heating elements, electric capacity measurements were made for a.o. 9 blades of Mi – 8 / 14 / 17 helicopter and 12 blades of W – 3 („Sokół”) helicopter [5-6]. A controlled delamination was also introduced to form an air gap (insulation layer) between the blade heating section and spar of Mi – 8 / 14 / 17 helicopter. A much lower value of electric capacity directly proportional to delamination area was obtained according to the formula:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d} [F] \quad (1)$$

where:  $\varepsilon_0$  – free space permittivity coefficient  $\left[\frac{F}{m}\right]$ ,  $\varepsilon_r$  – relative (dimensionless) dielectric permittivity coefficient characteristic for a given insulation material (air – in this case) placed between capacitor facings,  $S$  – surface area of one capacitor active facing (two heating tapes – one section)  $[m^2]$ ,  $d$  – distance between two capacitor surfaces (i.e. distance between heating element's tapes and spar)  $[m]$ .

During diagnostic tests the change in blade electric capacity  $\Delta C$  observed during service as well as its deviation from standard value, is estimated, that can be expressed as follows:

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d_{od} + \Delta d} - C_{od} [F] \quad (2)$$

where:  $C_{od}$  – reference capacity (standard capacity or initial capacity of a given blade heating section),  $\Delta d$  – increase of thickness of insulation gap between heating section tape

and lifting blade spar of,  $d_{od}$  – thickness of insulation layer (initial) between heating section tape and lifting blade spar.

## LABORATORY EXPERIMENTAL TESTS ON CONTROLLED DELAMINATION OF HELICOPTER'S LIFTING BLADE

Experimental tests on one blade for Mi – 8 / 14 / 17 helicopter were carried out to determine usefulness of measuring electric capacity between electric mass and elements of heating section. Fig. 1 presents schematic diagram of a blade with indicated places where delamination areas were introduced for test purposes.

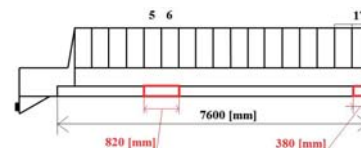


Fig. 1. Schematic picture of cut Mi – 8 / 14 / 17 rotor blade. (acc. the authors' report based on dismounting operations)

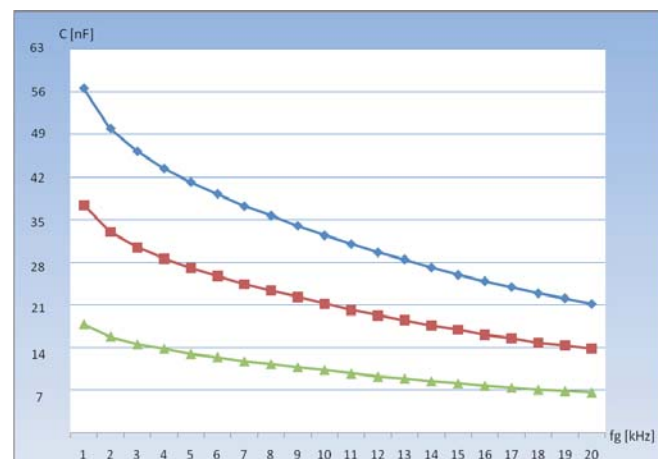


Fig. 2. Electric capacity  $C$  between lifting blade's heating section and spar of Mi-8 / 14 / 17 helicopter in function of the test voltage frequency fg: 1. – (marked green) significant delamination of 120 cm in length 2. – (marked bronze) small delamination of 38 cm in length, 3. – (marked blue) no delamination.

Delamination between blade's load-carrying structure and heating element, often met in service, is hard to detect initially by using traditional methods. The proposed method of measuring capacity reactance by using technical method makes it possible to test blade without its dismounting – it is enough to unscrew electric cable from blade and replace it with the measuring system, Fig. 3. It is theoretically possible, however not applied in practice, to test blade's electric capacity even during flight of helicopter. In case of W-3 „Sokół” helicopters, the proposed method - in view of specific geometry of their heating sections – could make it possible to very precisely detect location of delamination areas over the blades. The short heating sections shown in Fig. 4 allow to attribute delamination areas to appropriate surfaces of given heating sections, hence also to relatively

small surfaces of composite, that makes it possible to choose suitable repair means.

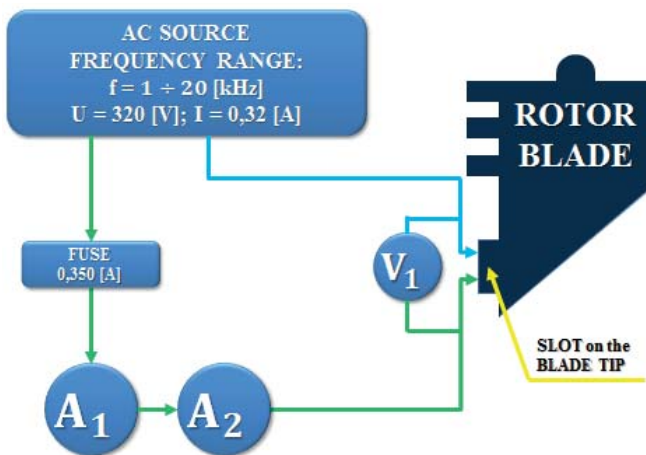


Fig. 3. Schematic diagram of the electric capacitance measuring system:  $A_1$  – Ammeter No. 1,  $A_2$  – Ammeter No. 2,  $V_1$  – Voltmeter No. 1.

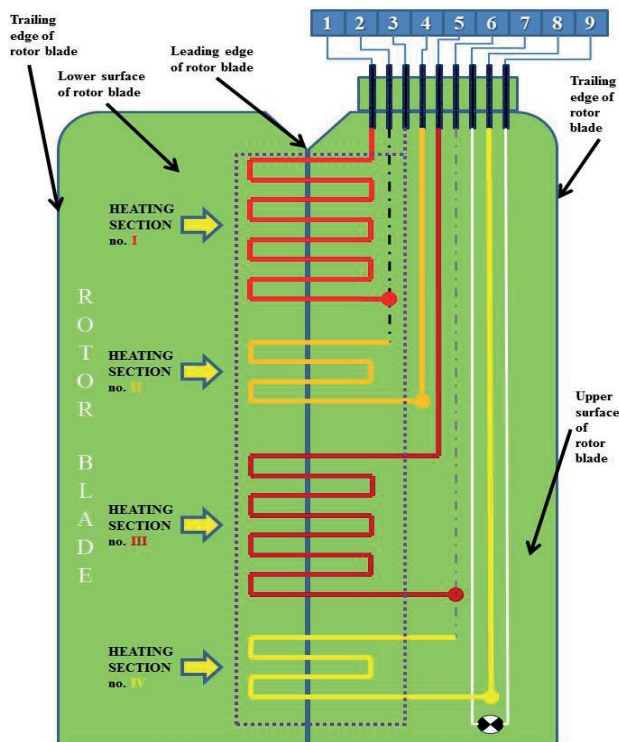


Fig. 4. Heating sections of W-3 „Falcon” helicopter’s rotor blade – schematic expansion of the upper and lower surface of the blade: 1, 2, 3, 4, 5, 6, 7, 8, 9 - numbers of wires and pins in the blade’s power socket which provides the heating sections and the lamp at the end of blade with electric power; respectively: 1-2 – to heating section No. I, 3 – to metal mesh placed along the entire blade (electric protective ground), 4-2 – to heating section No. II, 5-6 – to heating section No. III, 8-6 – to heating section No. IV, 7-9 – to the lamp at the end of blade.

Values of electric capacity of insulation of heating sections of WN ? blades (Fig. 2) were obtained by converting the reactance formula into that for capacity, as follows:

$$X_c = \frac{1}{2\pi f C} [\Omega] \rightarrow C = \frac{1}{2\pi f U} [F] \quad (3)$$

where:  $X_c$  – reactance (capacitance) [ $\Omega$ ];  $C$  – electric capacity [ $F$ ];  $I$  – measurement current intensity [ $A$ ];  $\pi$  – constant equal to  $\approx 3,14159$ .

All capacity measurements – Fig. 2 – were taken by means of the technical method implementing acoustic generator as a power source. During measurements the generator operated in the range of 320 [V] and 0,32 [A]. During measurements the electric current range between 0,05 [A] and 0,2 [A] was implemented most often. In order to get better penetrating qualities the greatest value of current intensity available from the generator was selected as far as possible. On the basis of an analysis of diagrams from previous investigations carried out in the range from 1 to 20 [kHz] these authors stated that to conduct measurements only within the test voltage frequency band from 8 to 12 [kHz], would be most favourable. Such limitation is favourable due to quasi-linear relation of electric capacity in function of test voltage frequency.

### POSSIBLE APPLICATION OF MEASURING THE ELECTRIC CAPACITY OF HEATING SECTIONS TO ASSESSING DELAMINATION OF HEATING ELEMENT TAPES OFF THE SPAR IN METAL LIFTING BLADES (IN CASE OF MI – (8 / 14 / 17) HELICOPTER)

The electric capacity between the spar and tapes of heating sections was measured for 9 blades of Mi – (8 / 14 / 17) helicopters. Results of the measurements were compared with data from the tests on 5 blades stored in ITWL grounds. One of them was shortened by about 1 [m] for purposes of previous tests. Electric capacity measurements were executed before and after the controlled delamination. For purposes of the tests the blade was marked No. V. Apart from the above mentioned blades, 2 blades (No. VIII and IX) being currently under operation, were tested. On the basis of the results given in Tab. 1 and Fig. 5 it is possible to determine mean value of electric capacity for serviceable blades of a given type. However to determine a correct electric capacity mean value a greater number of measurements on blades under operation should be done. The values obtained for the blades No. VIII and IX are much lower in comparison with the results achieved for the remaining blades. Such difference may result from the difference in conditions of storing the blades. The blades stored in ITWL grounds were kept on an unsheltered support in the so called corrosion station. Long-lasting keeping the blades rested by edge of attack against the support might lead to crushing the edge in which heating packet is placed. As a result an increase in electric capacity might happen due to a reduced distance between spar surface and heating tapes’ surface. In case of e.g. flat capacitor’s electric capacity such distance is equivalent to that between its two facings. In the conducted electric capacity measurements the spar surface and heating tapes’ surface constituted equivalents of the facings.

Tab.1. Capacitance and electric capacity values for particular Mi -8 / 14 / 17 helicopter blades

Test number and production number of the blade	Measurements – Mean values measured in the range of 8-12 [kHz] between 14th and 13th pin (back tape /spar) 8-12 [kHz] between 14th and 13th pin (back tape /spar)	
	Xc [Ω] – Capacity reactance (capacitance)	C [nF] from the formula after conversion of capacity reactance
Blade No. II – N67167	220,430	73,32
Blade No. III – N50167	275,560	58,66
Blade No. IV – N73902	253,370	63,81
Blade No. V – N76902	499,580	32,36
Blade No. VI – N75902	254,870	63,41
Blade No. VIII – N67358	1101,180	14,68
Blade No. IX – N68358	1123,000	14,39

Source: Own work of the authors

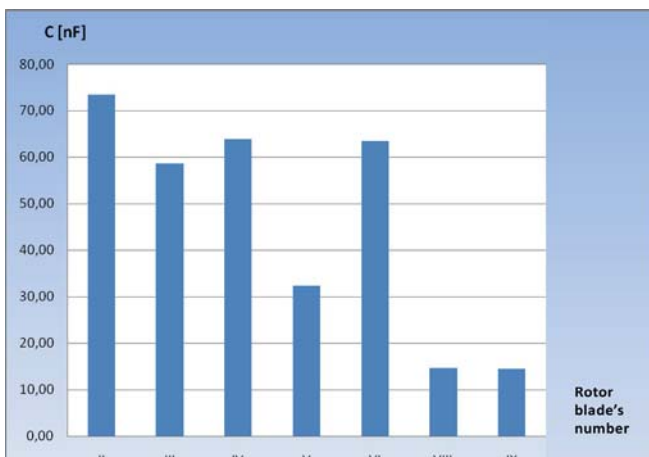


Fig. 5. Electric capacity diagram for particular Mi – (8 / 14 / 17) helicopter blades

## ELECTRIC CAPACITY MEASUREMENTS TO ASSESS DELAMINATION OF COMPOSITE BLADES (IN CASE OF W – 3 „SOKÓŁ” HELICOPTER)

### GENERAL INFORMATION

Depending on properties of fibres and resin, composite obtains different mechanical and thermodynamic qualities. The composite qualities are neither an arithmetic mean or sum of features of its components [12, 23]. At very dynamic use of composites their complex shape is also conducive to deforming the fibres (bending, wrinkling) and changes in direction of their arrangement.

The delamination areas between fibres and resin often occur as a result of material fatigue. It is demonstrated by

an insignificant drop of stiffness, however they expand very fast and lead to fractures or interlayer separation. Such failure is very difficult to detect by the „classical” methods have been used so far [17, 24-25]. The separation of composite layers is a typical fatigue failure of composite, it also occurs due to shocks. It can be detected and located by means of the classical methods, however to diagnose it, the blades should be dismantled and checked in laboratory conditions [17]. A subsequent step in developing such diagnosing tools should consists in making current diagnosing composite structures in operation, for instance in flight, possible. The electric capacity measuring method proposed by these authors fulfils the requirements.

Ageing rate of composites depends on many factors [1, 23, 25]. Ultraviolet radiation (UV) is one of the important factors conducive to accelerating the process. Until recently, UV-resistant epoxide resins have not been available on the market, therefore majority of aircraft structures are made of resins not resistant against UV radiation, and paint coating is the only protection against UV radiation for them. In case of an abrasion of the coating has been introduced during service, destructive UV radiation effects onto composite may occur. The ageing of composite is usually demonstrated by change in its colour and rise of its stiffness and brittleness. Additionally, high humidity, fast-changing temperature (from -70 °C to 35 °C) as well as high velocity of fluid flowing around (wet air – e.g. due to rainfall) result in erosion, i.e. the out-washing of composite. Excessive composite heating may lead to exceeding the limit temperature  $T_g$ . The investigations [12] based on experience gathered during production resulted in the criteria contained in Tab. 2.

Tab.2. Acceptance criteria for types of failures in composites [24].

Lp.	Type of failure	Acceptance criteria
1	Delamination	Area smaller than 80 mm <sup>2</sup> and not located close to a similar area
2	Separation (Coming-off)	Permitted only in the places (of area not greater than 12 cm <sup>2</sup> ) where blade's plating is additionally attached by screws to internal structure) - impermissible in other places
3	Foreign body inclusion	Areas smaller than 60 mm <sup>2</sup> and covering in total the area smaller than 5% of plating surface
4	Porosity	Area of porosity is not to exceed 10% of total plating surface

The typical structural failures of composites are presented in Fig. 6, 7 and 8. All of them may be detected and partly located by using the proposed method based on technical measuring electric capacity:

- failures consisting in geometrical separation within the blade (e.g. coming-off the parts) resulting in an increase in the insulation gap thickness  $\Delta d$  - (Eq. (2)),
- failures consisting in inclusion of foreign bodies or porosity resulting in a change in value of the relative (dimensionless) dielectric permeability  $\epsilon_r$ .



Fig. 6. Gas cavity – misrun bonding

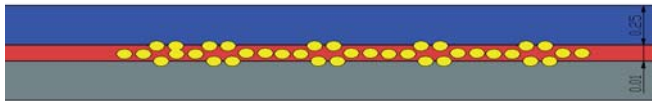


Fig. 7. Gas pores



Fig. 8. Foreign body inclusion

## POSSIBLE MONITORING OF GEOMETRICAL DELAMINATION IN COMPOSITE BLADE

The electric capacity was measured between the spar (metal mesh) and shorted tapes of the heating sections No. II and III. The measurements were conducted on 12 blades and a piece cut off the blade. 6 blades and the cut blade's piece (I - VI + XIII) were stored in ITWL grounds, the remaining 6 blades (VII - XII) were tested on helicopters in service. Results of the measurements are given in Tab. 3 and Fig. 6.

Tab. 3. Values of capacitance and electric capacity for particular W – 3 helicopter's blades

Test number and production number of blade		Measurements – The measured mean values 8-12 [kHz]	
		Xc [Ω] - Xc [Ω] – Capacity reactance (capacitance)	C [nF] from the formula after conversion of capacity reactance
B Blade No. I	7-5 (section II/III)	3211,440	5,05
Blade No. I K89/2 3005048	(7 + 5) - 1	394,910	40,94
Blade No. II	7-5 (section II/III)	3651,347	4,43
K89/3 3005049	(7 + 5) - 2	378,147	42,74
Blade No. III	7-5 (section II/III)	2847,853	5,68
K193/2 3009026	(7 + 5) - 3	441,960	36,57
Blade No. IV	7-5 (section II/III)	2885,827	5,61
K193/1 3009003	(7 + 5) - 4	428,767	37,70
Blade No. V	7-5 (section II/III)	2777,720	5,83
K193/4 3009031	(7 + 5) - 5	426,027	37,95
Blade No. VI	7-5 (section II/III)	2985,987	5,42
K193/3 3009030	(7 + 5) - 6	453,367	35,67
Blade No. VVIVVII	7-5 (section II/III)	4800,600	3,36

Test number and production number of blade		Measurements – The measured mean values 8-12 [kHz]	
		Xc [Ω] - Xc [Ω] – Capacity reactance (capacitance)	C [nF] from the formula after conversion of capacity reactance
Blade No. VII 302/1 A30.09.482	(7 + 5) - 7	529,847	30,51
Blade No. VIII	7-5 (section II/III)	3947,760	3,08
302/2 A30.09.486	(7 + 5) - 8	520,360	31,07
Blade No. IX	7-5 (section II/III)	4454,950	3,66
302/3 A30.09.487	(7 + 5) - 9	512,657	31,53
Blade No. X	7-5 (section II/III)	4836,500	3,42
302/4 A30.09.488	(7 + 5) - 10	500,110	32,33
Blade No. XI	7-5 (section II/III)	6287,363	2,64
355/1 A30.09.629	(7 + 5) - 11	540,081	29,93
Blade No. XII	7-5 (section II/III)	3754,840	4,31
355/2 A30.09.675	(7 + 5) - 12	534,710	30,23
Blade No. XIII (cut)	7-5 (section II/III)	5887,560	2,75
	(7 + 5) - 13	6409,440	2,53

Due to specific geometry of heating sections of W – 3 „Sokół” helicopter's blades, the measurement method could allow to find accurate location of delaminated places because particular heating sections cover only small areas – Fig. 4. In case if a producer or the ITWL established a delamination level permissible in service, then the presented method could be useful for fast assessment of serviceability of a given blade.

The electric capacity value measured between the terminals 7 and 5 is much lower than that measured between the shorted terminals 7 and 5 and the terminal 1 (metal mesh – shield) because in the last case it concerns much greater area S (see Eq. (1)):

- the electric capacity between the terminals 7 and 5 is measured between sides of two heating tapes,
- but the electric capacity between the shorted terminals 7 and 5 and the terminal 1 is measured between two heating tapes and the mesh.

The so significant differences occur due to directly proportional relation between surface areas of the heating sections (the heating sections are placed side by side) therefore the electric capacity between them is rather low [6]; on the other hand the tapes are placed flat on the mesh.

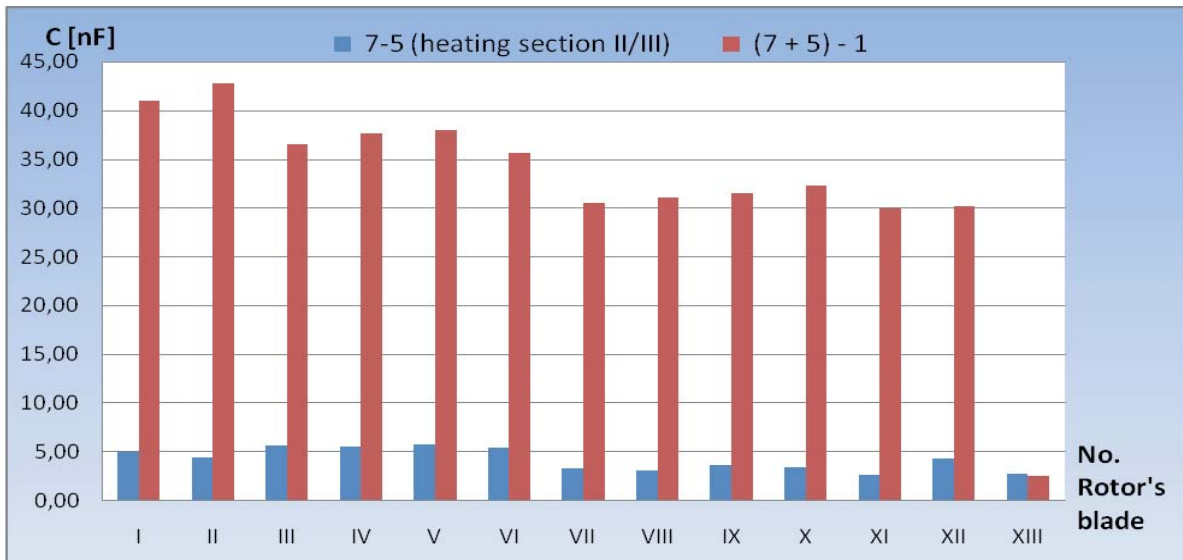


Fig. 6. Bar diagram of electric capacity for particular blades of W-3 "Falcon" helicopter: (7+5)-1 - capacity between the heating tapes II and III (the shorted terminals 7 and 5) and the metal mesh (blade's electric mass) 7-5 (the heating sections II/III) - capacities between the heating tapes (between the terminals 7 and 5).

## SUMMARY

Development of structures and structural materials requires new operational and diagnostic methods. The testing method for determining extent of delamination in blades, especially in case of composite blades, may provide invaluable services for aircraft operational safety. The proposed method of measuring capacity reactance by means of technical method makes it possible to test state of blades without their dismounting. In the near future it will be possible to diagnose blades in flight. Areas where delamination between blade's spar and heating element occur, form additional, local thermal insulation for heating tape, that results in local drop in transferring heat from heating tape to spar. Consequently, it leads to local rise in heating element temperature when electric current is supplied as well as to a significant delay of cooling process after switching – off electric current circuit [6]. Such places found during the tests are zones of potential surface burnouts as well as form nuclei for progressing delamination of blade internal layers. The phenomenon of local overheating the blade zone around heating element is especially dangerous for composite structures because the overheated structures show lower elastic properties after cooling down, hence greater susceptibility to micro-cracks. The above mentioned solutions greatly elevate level of operational safety of the aircraft in which composite blades are used. Moreover, such solutions are capable of increasing the combat action effectiveness of military aircraft. The proposed diagnostic method does not require dismantling the blades, that may significantly shorten down-time of helicopters as well as make application of it to any type of blades, possible.

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