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INVESTIGATION OF THE DYNAMIC PROPERTIES OF ENGINE FAN TITANIUM ROTOR BLADES IN A HIGH MANOEUVRABILITY AIRCRAFT IN FOD ASPECT

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Abstract

A current problem concerning the use of military and civilian aircraft is the damage caused to turbine compressor blades by 'foreign objects'. Here the term 'foreign objects' means small stones, pieces of metal, cement pitch, asphalt, etc., left on runways and taxiways. Foreign objects also include ice and iced lumps of snow as well as birds sucked into aircraft engine air ducts. All such objects pose a serious threat to proper engine operation. They are very harmful in two respects. One is the direct danger during flight when a bird or some other object is sucked into the engine. The other danger is in what might occur in later flights if the engine, especially the compressor and turbine blades, are not inspected for durability reassessment.

This paper presents an analysis of how the size and distribution of defects on blade edges affect, the frequencies and fatigue strength of titanium blades in the first four stages of a high manoeuvrability jet engine fan (low pressure compressor). In particular, damaged high manoeuvrability aircraft fan stage rotor blades and measured natural vibration frequencies and logarithmic decrement of damping of high manoeuvrability aircraft fan titanium blades are presented in the paper.

Keywords: *aircraft, combustion engines, turbine engines, engine diagnostic, blades*

1. Determining the influence of the size and distribution of removed edge damage on the natural frequencies of titanium rotor blades in a high manoeuvrability aircraft engine

The objective of these studies is to assess the possibility of extending technical permission to remove damage form high manoeuvrability jet engine fan titanium rotor blades and to develop suitable grinding and polishing technologies for this purpose. Such an analysis regarding steel blades was presented in the previous chapter.

The subject of these studies are high manoeuvrability jet engine fan WT9 titanium rotor blades.

Below are presented the natural vibration frequencies of rotor blades in four fan stages. Three blades were selected from the 2nd, 3rd and 4th stages of the fan, and respectively numbered 2 (W2), 3 (W3) and 4 (W4). These blades were damaged all along their leading and trailing edges (Fig. 1-3). After 370 hours of operation, four more blades were taken from the 1st, 2nd, 3rd and 4th stages and respectively numbered 1n (W1n), 2n (W2n), 3n (W3n), 4n (W4n). The damage on these blades is presented in Fig. 4-7. None of the blades had previously undergone any repairs.

The natural frequencies of rotor damaged blades 2, 3 and 4 were measured, as were their vibration modes and logarithmic decrement of damping *d* (see Tab. 1). The blades were measured in their initial state, i.e. as they were delivered, and also after the damaged material had been removed. The damaged material was successively removed from each blade according to its numerical order, as presented in Fig. 1-3. After this treatment each blade's natural frequency was measured again and its vibration mode determined. Tab. 1 presents the natural vibration values of the blades before the damaged material was removed. The natural frequency vibration values measured according to the sequence the damage from the blades was removed (see Fig. 1-3) differ very little from each other.

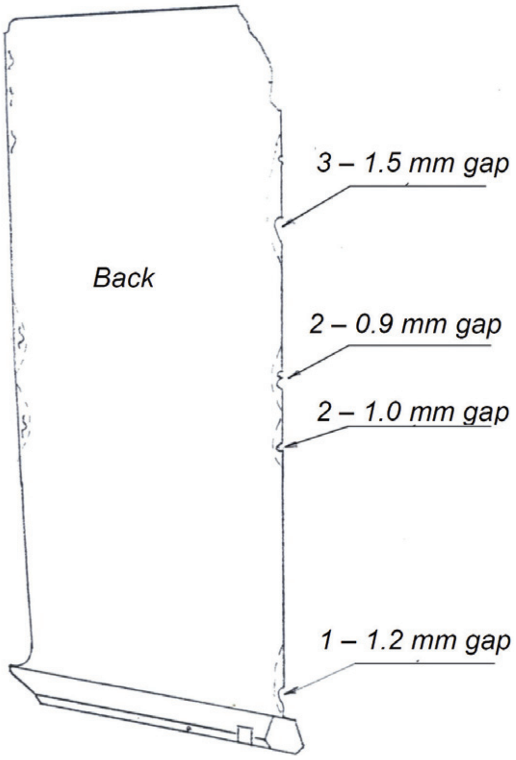

Fig. 1. Damaged high manoeuvrability aircraft fan 2nd stage rotor blade 2

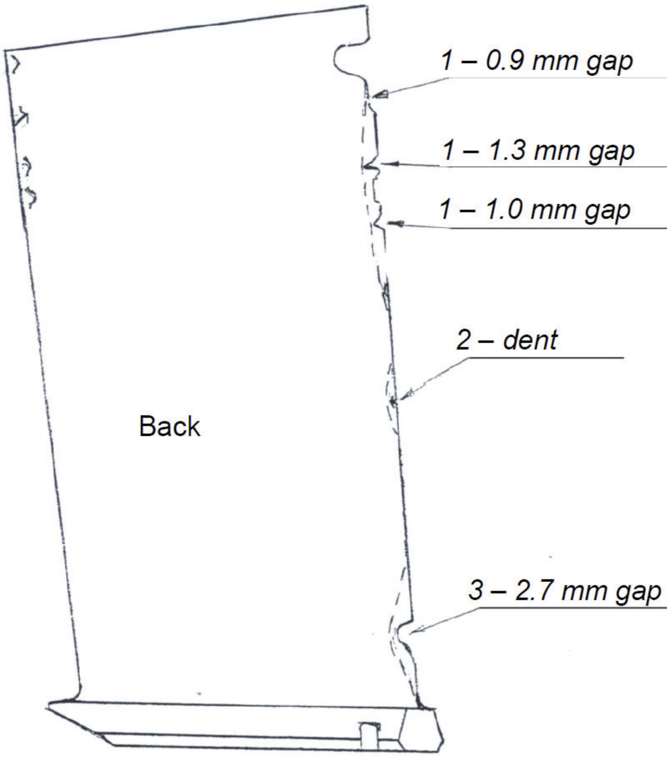

Fig. 2. Damaged high manoeuvrability aircraft fan 3rd stage rotor blade 3

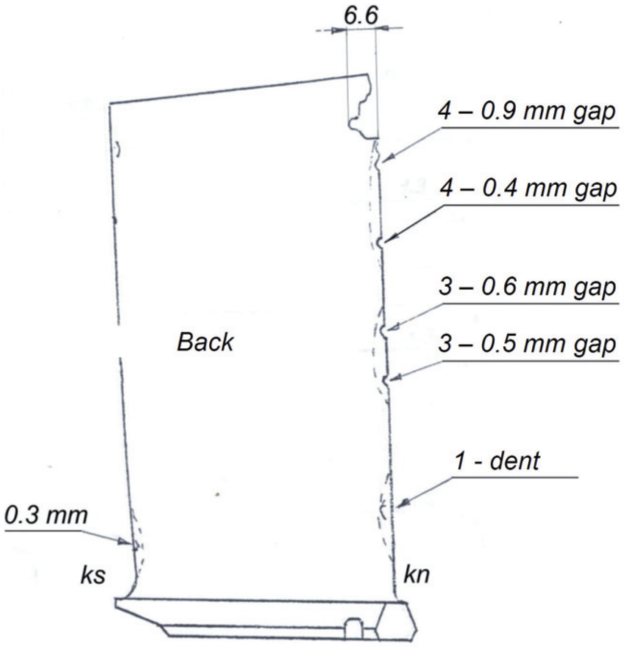

Fig. 3. Damaged high manoeuvrability aircraft fan 4th stage rotor blade 4

Measured were the natural vibration frequencies of blades damaged by foreign objects, numbered 1n, 2n, 3n and 4n. Each free vibration frequency was then associated with a particular vibration mode and corresponding logarithmic decrement of damping (*d*). Additionally, an imitation of an incurred 3 mm dent was removed from blade 1n, as shown in Fig. 4, after which the natural frequency was measured.

The test results are presented in Tab. 1. The natural vibration frequencies of the three blades that had had 0.3 mm to 3 mm of blade edge damaged material removed (i.e. blades 2, 3 and 4) did not

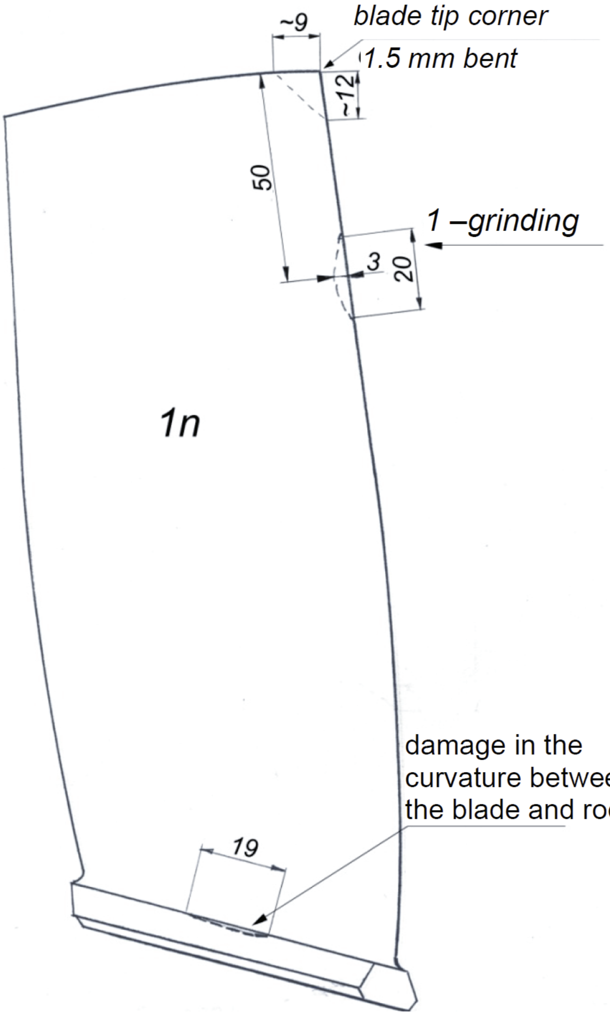

Fig. 4. Damaged high manoeuvrability aircraft fan 1st stage blade 1n

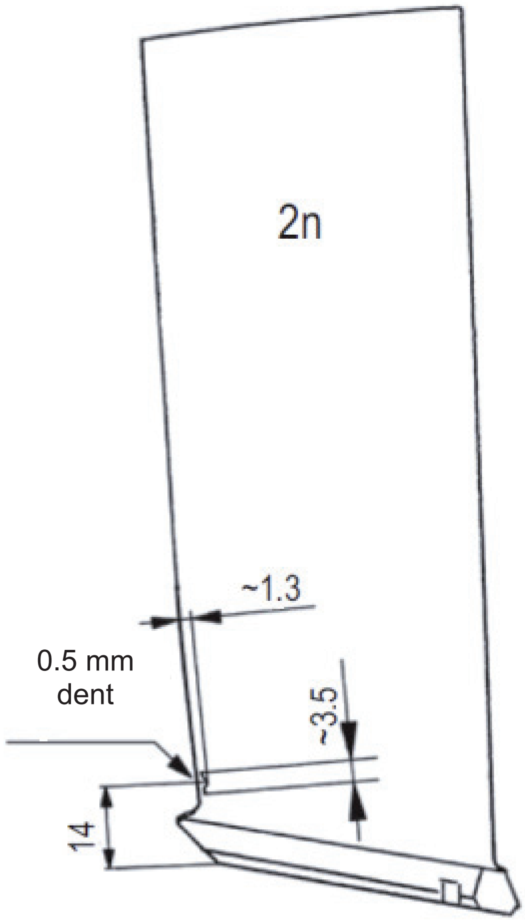

Fig. 5. Damaged high manoeuvrability aircraft fan 2nd stage blade 2n

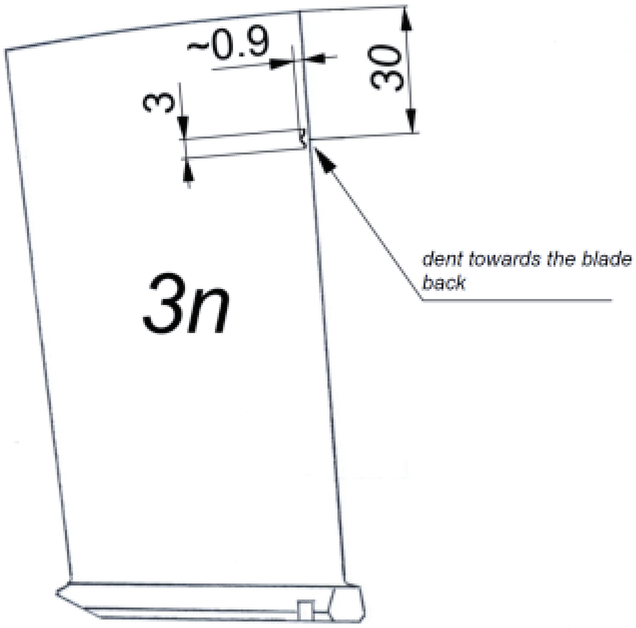

Fig. 6. Damaged high manoeuvrability aircraft fan 3rd stage blade 3n

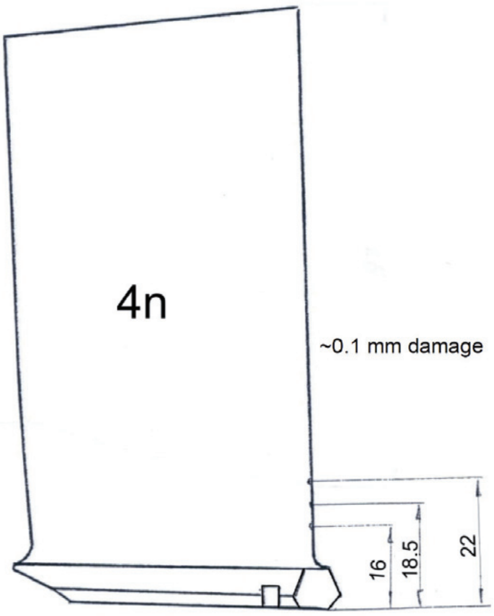

Fig. 7. Damaged high manoeuvrability aircraft fan 4th stage blade 4n

Tab. 1. Measured natural vibration frequencies and logarithmic decrement of damping (d) of high manoeuvrability aircraft fan titanium blades

Blade stage No.	*f* [Hz] and logarithmic decrement of damping (*d*)										
W1n	*f* [Hz]	192	492	1006	2362	2875	3833	4362	5332		
	d		0.004		0.0019	0.0027	0.0026	0.0022	0.0032		
W2	*f* [Hz]	172	638	923	1517	2275	3270	3557	3917	5633	7133
	d		0.0094		0.0039	0.0017	0.0079	0.0016	0.004	0.0069	0.081
W2n	*f* [Hz]	169	629	863	1514	2248	3303	3453	3825	5555	
	d		0.0031		0.0059	0.0008	0.0027	0.0005	0.0005	0.001	
W3	*f* [Hz]	244	574	914	1147	2709	3042	3554	5135	6773	
	d					0.0051	0.0138	0.0005	0.0003	0.0033	
W3n	*f* [Hz]	239	571	905	1141	2693	3049	3484	5225	6598	
	d					0.0118	0.0186	0.0018	0.0007	0.0012	
W4	*f* [Hz]	292	1064	1354	2563	3140	4178	5969	7803		
	d		0.0018	0.0014	0.012	0.0063	0.0007	0.001	0.0017		
W4n	*f* [Hz]	296	1066	1374		3119	4000	5997	7184	8028	
	d		0.0018	0.0131		0.0256	0.0067	0.0216		0.057	

significantly change. Fluctuations in the first five vibration modes of rotor blades in all the three stages were very small, regardless of which part of the blade the damage had been removed (ground away). Differences in the higher natural vibration frequency modes ranged from around a dozen to several dozen Hz, with the greatest natural frequency change being only ca. 1%. Even in the case of 1st stage rotor blade, which had damage ground away to the depth of 3 mm, no significant changes in the natural vibration frequency was noted.

Table 1 presents the logarithmic decrements of damping for the analysis blades of high manoeuvrability aircraft engine compressor titanium blades. In the case of 1st stage rotor blade W_{1n} (Fig. 4) the damping decrement of the second frequency mode is 0.004, in the 4th mode, at 2362 Hz, it slightly decreases to 0.0019, in the next mode, at 2875 Hz, it increases to 0.0027 and then at 5332 Hz rises further still to 0.0032. The damage of 2nd stage rotor blade W_2 is presented in Fig. 1, while the damage of blade W_{2n} is shown in Fig. 5. The logarithmic damping decrement of blade W_2 in the 2nd natural vibration mode at 639 Hz is 0.0094, while that of blade W_{2n} at 629 Hz is 0.0031. At 1517 Hz the blade W_2 damping decrement is 0.0039, which is less than in the second frequency mode. At 1514 Hz the W_{2n} blade damping decrement exceeds that of the second frequency mode and is equal to 0.0059. Other W_{2n} blade frequencies have considerably lower damping decrement values than blade W_2. The W_{2n} blade has 0.5 mm long and 3.5 mm deep dents (Fig. 5), which substantially alters damping decrement values as compared to the W_2 blade (Fig. 1), which has up to 1.2 mm deep gaps on its leading edge. The W_3 blade (Fig. 2), with a number of up to 2.7 mm deep defects on its leading edge, has much lower damping decrements than the W_{3n} blade (Fig. 6), which only has dents 0.9 mm deep and 3 mm long. The W_4 blade (Fig. 3) with a badly damaged leading edge and also a defect on the trailing edge has much lower damping decrements at given frequencies than the W_{4n} blade with only small, 0.1 mm deep defects on its leading edge.

The above analysis shows that the larger blade defects, the greater the damping decrement changes. Each damaged blade in a given compressor stage a different damping decrement, even if there are only negligible natural vibration frequency differences.

Therefore in deciding whether or not a damage in a rotor blade may be removed one should consider not only the natural frequency changes, but also altered damping coefficients in several of the first vibration modes.

Studied was the effect of damage removal on the fatigue strength of titanium rotor blades (2, 3, 4, 1n, 2n, 3n and 4n) in the first four stages of a high manoeuvrability aircraft engine compressor. It was found that the fatigue strength of blades damaged during engine operation as well as blades with such damage partly removed did not significantly change. It has been estimated that the fatigue strength for these blades after 10^7 cycles was ca. 340 MPa.

Conclusions

1. The removal of damaged material from a rotor blade as well as the distribution of such removals on the blade edges does not significantly alter the blade's natural vibration frequency.
2. The removal of damage from a rotor blade did reveal damping decrement changes, which is significant in the analysis of stress in blades.
3. The fatigue strength of damaged fan blades practically remains unaltered.

The rotor blades in the low pressure compressor of a high manoeuvrability aircraft engine are made of BT9 titanium alloy with $R_m = 1200$ MPa strength. When the blade mechanically damaged, its fatigue strength may be impaired on account of the low $\delta = 1.2\text{-}1.7$ safety coefficient to which such blades are usually manufactured as well as the properties of titanium itself.

The analysis presented in this paper regarding damage sustained by such blades during engine operation has little effect on their natural frequencies or fatigue strength. High manoeuvrability aircraft engines are very reliable and so far no fan rotor blade failures have been recorded.

The fatigue strength of titanium alloys is defined by the phases of crack initiation and development in places where internal stress builds up (the damaged area). Such alloys feature 'crack development discontinuity' in the form of numerous, local changes of crack development direction.

Generally speaking, cracking in titanium alloys is a mixed process where all possible mechanisms of crack development intertwine. It occurs when a foreign object is sucked into the engine, damaging blades and thus cause local build-ups of stress. These are the areas where fatigue cracks may be initiated and then develop.

In order to avoid engine failures it is necessary to define a method for the detection and measurement of defects as well as the permissible size of blade defects.

It should be emphasized that research into the possibility of extending the technical requirements to permit damaged supersonic aircraft rotor blades to be repaired by grinding was first conducted in the years 1982 to 1983. At the time extensive studies were carried out into the distribution of vibration modes in rotor blades of all stages in both low pressure and high pressure compressors. A large number of compressor rotor blades from particular stages were studied in terms of fatigue strength as well as stress distribution along blade leading edges, trailing blade edges and backs associated with particular vibration modes. It is important to note that the measurements of low pressure compressor rotor blades were taken in a running engine on a test bench at ITWL. On the basis of these studies technical requirements were determined with regard to the possibility of grinding away and polishing damaged parts of rotor blades from all six stages (three from the low-pressure and three from the high-pressure compressor) of supersonic aircraft engines. Thanks to this research the number of engines that had to undergo major overhauls on account of blade damage by foreign bodies was significantly reduced. Blades repaired by grinding continued to work in the engine for many thousands of flight hours without failure.

From the developed technical requirements concerning various types of aircraft engine, which define the scale and nature of repairable damage to compressor rotor blade leading and trailing edges as well as the technology of damage removal, the following general rules stand out:

1. Blade edges with damaged areas, dents and gaps that do not exceed values determined during the blade's examination can be removed by polishing or ground away.
2. First stage blades may be repeatedly ground and polished the removed damage is less than 0.05 mm deep.
3. In practically all engine types and compressor stages rotor blades with damage below 1/3 of the blade's length should be removed and exchanged in overhauls.

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