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COMPARISON OF AIRCRAFT ENGINE COMPRESSOR BLADE FINITE LIFE FATIGUE STRENGTH DETERMINATION METHODS

**Wojciech Obrocki, Amadeusz Setkowicz,
Maciej Masłyk, Jan Sieniawski**

S u m m a r y

The paper presents a comparison of selected fatigue strength test methods to determine the average finite life fatigue strength. The tests were performed on aircraft engine compressor blades. The paper covers blades fatigue tests results performed using electrodynamic shaker.

Keywords: compressor blade, fatigue tests, fatigue testing methods

Analiza porównawcza metodyki badań trwałej wytrzymałości zmęczeniowej łopatek sprężarki silnika lotniczego

S t r e s z c z e n i e

W pracy przedstawiono analizę porównawczą wybranych metod ustalania wytrzymałości zmęczeniowej łopatek wirnika sprężarki silnika lotniczego – określenia średniej trwałości i wytrzymałość zmęczeniową. Próby zmęczeniowe sprężarki wykonano za pomocą elektrodynamicznego wzbudnika drgań.

Słowa kluczowe: łopatki sprężarki, badania zmęczeniowe, metody badań zmęczeniowych

1. Introduction

High cycle fatigue tests are very time-consuming processes. The method used to assess the engine blade fatigue strength affects their production cost [1]. Optimizing this process, especially specimens number reducing is a full economic justification.

The materials fatigue strength is most often determined using Wöhler's curve based on conducted fatigue tests results with various number of methods. For full Wöhler's curve development the staircase method is most commonly used. This method requires test performance for a specified specimens number (at least 25) and statistical analysis fulfillment of its results. For this reason, other fatigue strength determination methods are also in use [2]. One of them is the

Address: Prof. Jan SIENIAWSKI, Wojciech OBROCKI, MSc. Eng., Amadeusz SETKOWICZ, MSc. Eng., Maciej MASŁYK, MSc. Eng., Rzeszow University of Technology, Faculty of Mechanical Engineering and Aeronautics, Department of Materials Science, Powstancow Warszawy 12, 35-959 Rzeszow, e-mail: jansien@prz.edu.pl

progressively specimen load increasing method. This method allows for specimens sample reduction to 15 pieces. Methodology can be applied for fatigue strength control of individual products in series production [3].

The paper presents a tests methodology comparison of blades fatigue strength determination with varying cross-sectional dimensions and complex curvilinear surfaces in a high cycle fatigue test conditions.

2. Methodology, test stand and material

The test stand for fatigue tests consist of the following elements: LDS V830 air-cooled electrodynamic shaker – 4 (Fig. 1, Tab. 1), climatic chamber – 1, power amplifier – 2 and computer aided system for test control – 3. The research was conducted in the Research and Development Laboratory for Aerospace Materials in Material Science Department of Rzeszow University of Technology.

Fig. 1. Test stand for conducting fatigue tests

Table 1. Technical specification of the LDS V830 electrodynamic shaker

Sine Force (peak)	6,78 kN
Random Force (rms)	5,77 kN
Armature Resonance (f_n)	3100 Hz
Velocity (sine peak_ – full-field	2 m/s
Max. Acceleration	1176,7 m/s (120g)
Max. Displacement (peak)	25,4 mm
Shaker Body Mass (M_b)	616 kg
Internal Load Support Capacity	160 kg
Usable Frequency Range	5 – 3500 Hz

Computer aided system for fatigue test control was developed with National Instruments Compact Data Acquisition modules application and the LabView software environment. The system controls the operation of electrodynamic shaker and provides required head amplitude and vibration frequency [4]. The software allows the specimen be tested in resonant vibration [5]. The condition for constant blade dynamic load during fatigue tests is constant value of vibration amplitude.

Measurements performed during blades fatigue tests:

- shaker head vibration amplitude and frequency
- specimen tip displacement
- blade surface stress using strain gauge

Shaker head vibration amplitude and frequency were determined by a piezoelectric accelerometer, attached to the specimen holder [6]. Amplitude measurement of vibrating blade tip displacement was performed with the optical method using a measuring microscope, whereas a laser head was used for constant displacement monitoring. Adopt fixed position of a laser spot at 1 mm distance from blade tip on its surface (Fig. 2).

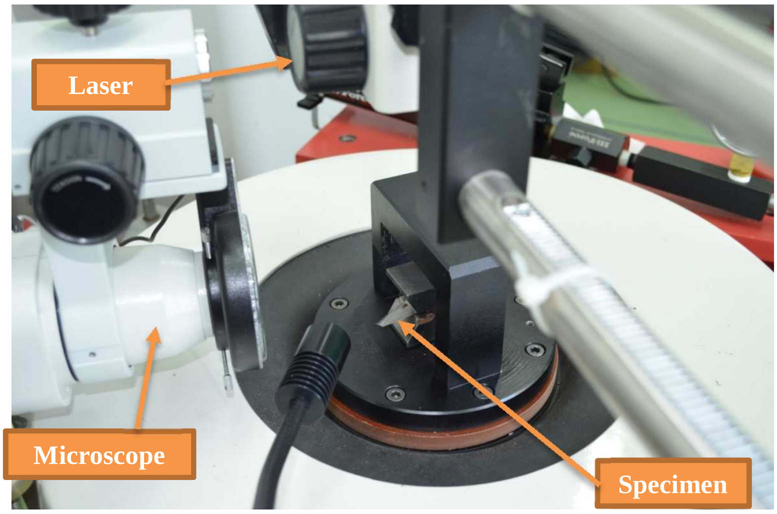

Fig. 2. The specimen secured in the electrodynamic shaker holder

Strain measurement on the blade surface was performed with strain gauge application with foil area l = 2 mm (Fig. 4) [7, 8]. Specimens stress values in the elastic range were determined in accordance with Hooke law. The specimen fall within cyclic bending load during fatigue test to acquired proper intersection stress value [9]. Shaker force value was controlled by adjusting the shaker head vibration parameters. Adopt that the shaker head vibration frequency is equal to tested specimen natural frequency. Beginning of specimen natural frequency dropping indicates the micro-crack initiation and its propagation [10].

Technical specification of tested specimens (Fig. 3):

- blade height – 55 mm
- blade width – 20,5 mm
- material –- alloy EI-961, constitution: 11% Ce; 1,6% W; 1,5% Ni; 0,35% Mo; 0,18% V; 0,11% C; 0,03% P; 0,025% S
- R_m – 1050 MPa
- R_e – 850 MPa
- coating – cadmium or Al/AlN
- Young's module – 196 GPa

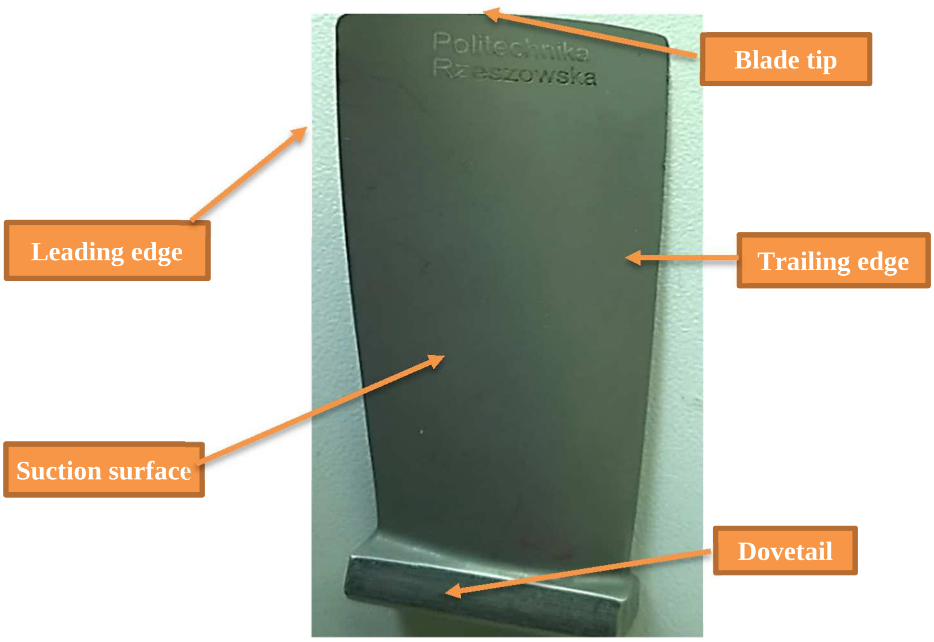

Fig. 3. The specimen – aircraft engine compressor blade

The average engine compressor blade finite life fatigue strength at a room temperature was determined with two methods application: staircase and progressively specimen load increasing.

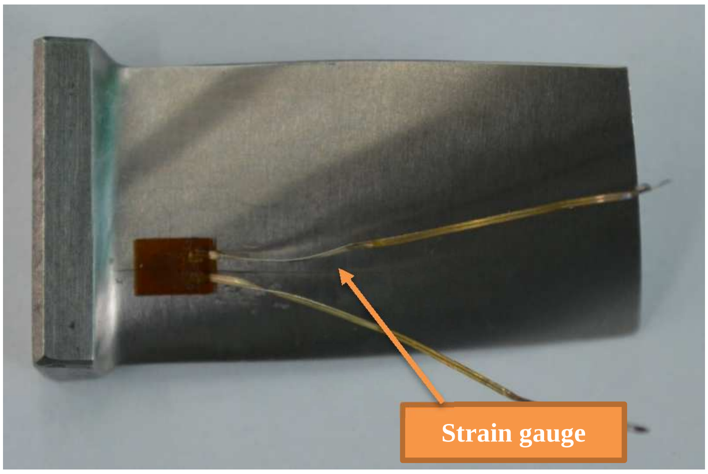

Fig. 4. The specimen with resistance strain gauge

Staircase method

The staircase method based on subjecting each specimen to cyclic bending with a specified stress value σ_1 at a predetermined base cycle number *n* [11]. If the specimen does not break at assumed cycles number *n* during the test, another specimen is tested at stress value $\sigma_2 = \sigma_1 + \Delta\sigma$. In the case where during test the specimen breaks, another one is set at stress value $\sigma_2 = \sigma_1 - \Delta\sigma$.

- Fatigue test base cycle number $N_G = 1 * 10^7$
- Stress step value $\Delta\sigma = 29{,}4$ MPa
- Basic stress value $\sigma_1 = 363$ MPa

For the research an amount of 25 specimens were used. The average compressor blade finite life fatigue strength using the staircase method calculated basis on the equation:

$$\bar{S} = S' + \left(\frac{\sum_{i=0}^{q} i n_i}{n} \pm 0{,}5\right)\Delta S$$

where: $\bar{S}$ – average finite life fatigue strength, S' – max strength value of less frequent occurrences, ΔS – strength step value, n_i – amount of specimen load changes, *n* – specimens sum value from selected occurrences, *i* – amount of stress increase, q – load levels number, +0,5 for not occurred events, –0,5 for damaged specimens.

Applied an amount of events in which frequency occurrences *n* is lower. Standard deviation was calculated in accordance with dependence:

$$S = 1{,}62\left(\frac{n\sum_{i=0}^{q} i^2 n_i - \left(\sum_{i=0}^{q} i n_i\right)^2}{n^2} + 0{,}29\right)\Delta S$$

Progressively load increasing method

The method based on subjecting each specimen to cyclic bending with a specified stress value σ_1 at a predetermined base cycle number n [12]. If the specimen does not break at assumed cycles number n during the test, another specimen is tested at stress value $\sigma_2 = \sigma_1 + \Delta\sigma$. The stress value increases until the specimen breaks. When the specimen breaks while being tested another one is tested at the initial stress value σ_1.

- Fatigue test base cycle number $N_G = 1 * 10^7$
- Stress step value $\Delta\sigma = 29{,}4$ MPa
- Basic stress value $\sigma_1 = 363$ MPa

The average finite life fatigue strength determined using an amount of 15 specimens.

$$\bar{S} = \frac{\sum_{i=0}^{n}\left(\sigma_{ip}^{y} - 0{,}5\Delta\sigma\right)}{n}$$

where: $\bar{S}$ – average finite life fatigue strength, ΔS – strength step value, n – specimens sum value from selected occurrences, q – load levels number, σ_{ip}^{y} – specimen destructive stress value.

Standard deviation was calculated in accordance with dependence:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(\sigma_{ip}^{y} - \bar{\sigma}_{ip}^{y}\right)^2}{n-1}}$$

3. Results

The fatigue test results of 25 specimens tested using a staircase method are presented in table 2. Performed calculations of average finite life fatigue strength $\bar{S}$ and standard deviation S.

The average finite life fatigue strength of tested specimens using staircase method equals $\bar{S}$ = 418 MPa and standard deviation S = 14,3 MPa.

Table 2. Staircase method fatigue test results

Specimens No.	Load σ, MPa	Cycle number *n*
L21	370	$1 * 10^7$
L22	400	$1 * 10^7$
L23	430	$0,09 * 10^7$
L24	400	$1 * 10^7$
L25	430	$0,08 * 10^7$
L26	400	$1 * 10^7$
L27	430	$1 * 10^7$
L28	460	$0,075 * 10^7$
L29	430	$0,322 * 10^7$
L30	400	$1 * 10^7$
L31	430	$0,11 * 10^7$
L32	400	$1 * 10^7$
L33	430	$0,62 * 10^7$
L34	400	$1 * 10^7$
L14	430	$0,13 * 10^7$
L35	400	$1 * 10^7$
L36	430	$0,13 * 10^7$
L37	400	$0,77 * 10^7$
L38	370	$1 * 10^7$
L39	400	$1 * 10^7$
L40	430	$0,12 * 10^7$
L41	400	$1 * 10^7$
L42	430	$1 * 10^7$
L43	460	$0,05 * 10^7$
L44	430	$1 * 10^7$

The fatigue test results of 15 specimens tested using progressively load increasing method are presented in table 3. Performed calculations of average finite life fatigue strength $\overline{S}$ and standard deviation S.

The average finite life fatigue strength of tested specimens using progressively load increasing method equals $\overline{S}$ = 415 MPa and standard deviation S = 23,6 MPa.

4. Conclusion

The fatigue tests results of the aircraft engine compressor blades performed on 40 specimens using two different methods i.e. staircase method and progressively load increasing method have determined that the average finite life fatigue strength does not depend on research method. In the case of staircase method, the standard deviation value is almost two times lower. Application of a staircase method allows for significant research time consuming reduction in comparison to progressively load increasing method.

Table 3. Progressively load increasing method fatigue test results

Specimens No.	**Load σ, MPa**	**Cycle number *n***
L16	400	$1 * 10^7$
L16	430	$0,23 * 10^7$
L17	370	$1 * 10^7$
L17	400	$1 * 10^7$
L17	430	$1 * 10^7$
L17	460	$0,14 * 10^7$
L18	370	$1 * 10^7$
L18	400	$0,24 * 10^7$
L7	370	$1 * 10^7$
L7	400	$1 * 10^7$
L7	430	$1 * 10^7$
L7	460	$0,245 * 10^7$
L8	370	$1 * 10^7$
L8	400	$1 * 10^7$
L8	430	$1 * 10^7$
L8	460	$0,008 * 10^7$
L9	370	$1 * 10^7$
L9	400	$1 * 10^7$
L9	430	$1 * 10^7$
L9	460	$0,047 * 10^7$
L10	370	$1 * 10^7$
L10	400	$1 * 10^7$
L10	430	$0,22 * 10^7$
L11	370	$1 * 10^7$
L11	400	$1 * 10^7$
L11	430	$0,25 * 10^7$
L12	370	$1 * 10^7$
L12	400	$1 * 10^7$
L12	430	$0,32 * 10^7$
L15	370	$1 * 10^7$
L15	400	$0,59 * 10^7$
L16	370	$1 * 10^7$
L16	400	$1 * 10^7$
L16	430	$0,23 * 10^7$
L17	370	$1 * 10^7$
L17	400	$1 * 10^7$
L17	430	$1 * 10^7$
L17	460	$0,14 * 10^7$
L18	370	$1 * 10^7$
L18	400	$0,24 * 10^7$
L19	370	$1 * 10^7$
L19	400	$1 * 10^7$
L19	430	$1 * 10^7$
L19	460	$0,45 * 10^7$
L20	370	$1 * 10^7$
L20	400	$1 * 10^7$
L20	430	$1 * 10^7$
L20	460	$0,26 * 10^7$

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References

[1] H.S. LAFTA: Finite element analysis of a gas turbine rotor blade. *International Journal of Scientific Engineering and Technology Research.* Semar groups technical society 2014.
[2] A. ADEYINKA AZEEZ: Fatigue failure and testing methods, Riihimaki 2013.
[3] M. MASŁYK, W. OBROCKI, A. SETKOWICZ, J. SIENIAWSKI: Experimental fatigue strength determination of damaged aircraft engine blades. *Advances in Manufacturing Science and Technology*, **40**(2017)4.
[4] W. OBROCKI, K. KRUPA, J. SIENIAWSKI: Metodyka eksperymentalnych badań wytrzymałości zmęczeniowej łopatek sprężarki silnika lotniczego. *Mechanik*, **87**(2014)2.
[5] B. SZUMIELEWICZ, B. SŁOMSKI, W. STYBURSKI: Pomiary elektroniczne w technice. WNT, Warszawa 1982.
[6] A. SETKOWICZ, W. OBROCKI, J. SIENIAWSKI, W. ZIAJA: Strain distribution of aircraft engine compressor blade surface applying numerical and experimental methods. *Advances in Manufacturing Science and Technology*, **41**(2017)2.
[7] Strain-gage Instrumentation. Vishay Precision Group Micro-Measurements
[8] E.J. WILSON: Strain gauge instrumentation. Harris' shock and vibration handbook. Library of Congress Cataloging-in-Publication Data 2002.
[9] D. RADAJ: Design and analysis of fatigue resistant welded structures. Abington, Cambridge 1990.
[10] J.W. WYRZYKOWSKI, E. PLESZAKOW, J. SIENIAWSKI: Odkształcanie i pękanie metali. WNT, Warszawa 1999.
[11] R. POLLAS, A. PALAZOTTO, T. NICHOLAS: A simulation-based investigation of the staircase method for fatigue strength testing. *Mechanics of Materials.* OH 45433 2005.
[12] A guide for fatigue testing and the statistical analysis of fatigue data, ASTM E09 Committee 1963.

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