Journal of Polish CIMAC
Gdansk University of Technology
The Faculty of Ocean Engineering and Ship Technology

SELECTED PROBLEMS OF SERVICE LOAD ANALYSIS OF MACHINE COMPONENTS

Bogdan Ligaj

University of Technology and Life Sciences in Bydgoszcz
ul. Prof. S. Kaliskiego 7, 85-789 Bydgoszcz, Poland
tel.: +48 52 340 82 53, fax: +48 52 340 82 71
e-mail: bogdanj@utp.edu.pl

Abstract

Design of engineering structures is associated with making of series of calculations, including the ones on fatigue life. Appropriate assumptions about the number of load cycles allows to determine the extent of fatigue, what affects the method of calculating and developing the methodology of experimental tests.

The paper provides general comments on the analysis of service loads of machine components in the context of the conducted tests and fatigue life calculations.

***Keywords**: fatigue life, random service load*

1. Introduction

Design of machines is connected with adopting the assumptions about among others working time. The assumption during the life design of objects results in such technical solutions that meet the formulated criteria. They require to carry out various tests and calculations, including these on fatigue.

Effect of factors associated with the geometry of objects, properties of construction materials, manufacturing technology and the nature of the loads makes the problems of machine components life calculations extremely difficult. The probabilistic nature of the load courses also affects the raise of the complexity of the issue level. It results from the conditions of machine maintenance.

Tests and calculations of fatigue life of the construction components, operating under specified servicing conditions, require knowledge of the nature of service loads, which usually are random. By making measurements of stress (strain) variation in representative working conditions, the timings reflecting the nature of the measurand variations are determined. Consequently, they constitute a basis to develop a one-or two-parametric spectra loads. These spectra allow to conduct the calculations and fatigue tests of machine components for the service period.

The aim of this study is to formulate general comments on the analysis of service loads of machine components in the context of the conducted tests and fatigue life calculations involving: assessment of the ranges of low, high and gigacycle fatigue, assessment of the type of load with reference to the nature of the force and assessment of the proposed fatigue life of sample components.

2. Projected objects life

Measurement and analysis of service loads reveals the properties in the field of values, time and frequency. Depending on working conditions loads show a large variation, which is revealed by parameters and statistical functions [4, 5].

Figure 1 presents examples of courses of load changes of significantly different structural components. Their visual assessment indicates the diverse nature and extent of the stress variations that results from the different operating conditions. Figure 1a presents the course of fighter wing loads during one flight, during which certain tasks were performed. Figure 1b relates to changes in the value of torque driving so-called finishing stand per unit of time or technological cycle. Figure 1c presents the changes in the value of the bending moment in the rod of stub axle, while figure 1d changes in pressure in the pipeline. Knowledge of the stress variation course in the elements of machines allows the development of load spectra used in the calculations with reference to fatigue life.

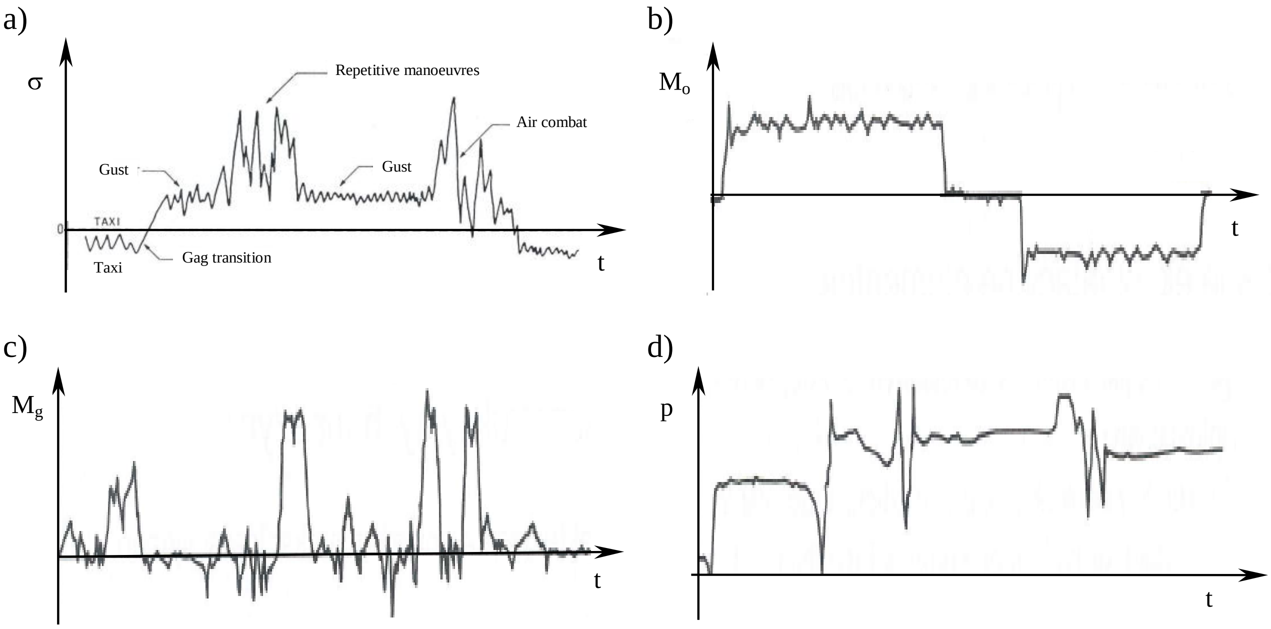

Fig. 1. Examples of time changes course: a – stress in the wing of a fighter aircraft [1], b – driving torque of so-called finishing stand [2], c – the bending moment in the rod of car stub axle [2], d – the pressure in the pipeline [2]

Machine design is associated with the selection of design features due to the adopted criteria, which include design life. Depending on the class of objects mentioned life can be expressed: in time unit (hours, years of operation), the number of flights (maneuvers, activations), mileage (in kilometers), the number of revolutions or technological cycles.

Precise formulation of design life in cycles for engineering structures working in variable load conditions is difficult. Therefore it is based on estimating the number of cycles for loads courses corresponding to the representative operating conditions.

Definition of the number of load cycles per unit in which the design life was expressed allows to specify the total number of cycles. Consequently, it enables to determine the range of fatigue to which the element will be subjected during the operation. This results in the selection of appropriate methods of calculations and tests with reference to fatigue life.

3. Ranges of low, high and gigacycle fatigue

Calculations of fatigue life of machine components are carried out with the usage of methods that apply fatigue life Wöhler curve. On its background three areas corresponding with ranges: Low-Cycle Fatigue (LCF), high-cycle fatigue (HCF) and gigacycle fatigue (GCF) can be distinguished (fig. 2). The division into these ranges results from the changes in properties of material occurring through operation of the load of a variable character. For loads level above the flexibility limit (for LCF) significant plastic strain is observed leading to the occurrence of adverse effects in the structure of the material. Consequently, they lead to the formation of fatigue cracks in a small number of load cycles. Hysteresis loops for a range of LCF have a much larger field for a loop of other ranges, what results in significant plastic strain. High-cycle fatigue includes a range of load variations between the flexibility limit and fatigue limit Z_G. The limit of fatigue is determined by experimental studies or adopted for the base number of cycles N_0 at the known form of equation describing the gradient of fatigue life curve**.** Depending on the type of material or structural elements fatigue category N_0 value is assumed in the range from $10^6 \div 5 \cdot 10^6$ cycles [7]. In range of high – cycle fatigue in the area of limited life the hysteresis loop field size decreases with decreasing amplitude of the load. It is assumed that the high-cycle fatigue area covers a range up to 10^8 cycles. Above a given number mentioned the occurrence of gigacycle fatigue area (GCF) is assumed. Amplitude load cycles value, which affect the fatigue life, shall be at the level $k \cdot Zg$, where k is a factor including the impact of stress that lie below the limit of fatigue. Its value is in the range $k = 0.4 \div 0.6$. Stress amplitude lying below $k \cdot Zg$ are within the area of unlimited life [10].

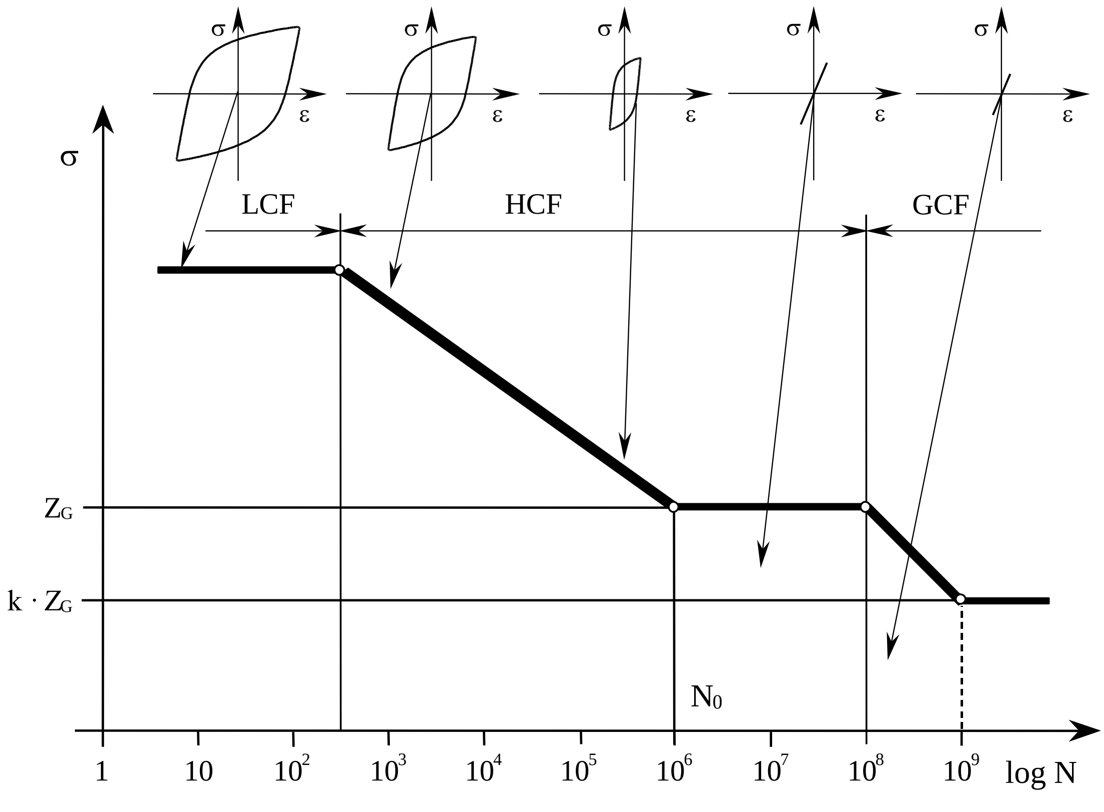

Fig. 2. Schematic presentation of the ranges: LCF – low-cycle fatigue, WCF – high-cycle fatigue, GCF – gigacycle fatigue

Assuming at the stage of the fatigue life design expressed with the number of load cycles for the construction element allows to specify the nature of the predicted fatigue effects and the level of maximum stress. Such knowledge enables the appropriate selection of calculation methods and experimental research program.

4. Type of service loads

The nature of the service load of machine components is affected by many factors associated with the operating conditions. Taking into consideration, for example the suspension parts of wheeled vehicles, the course of stress changes is influenced by type of surface, driving speed, steering maneuvers performed, acceleration, braking, etc. These types of maneuvers generate forces (moments) of loading elements and, consequently, their strain. The level of strain depends on the value of working force. This type of loads are associated with dynamic forcing. For most elements of engineering structures i.e. aircrafts, ships, machines, etc. we also deal with the mentioned dynamic forcing. The second type of forcing is kinematic forcing. An example of such a force can be non-coaxially located machine shafts connected to a rigid coupling. Lack of coaxiality causes constant deflection value, which corresponds to the specified value of stress. During rotation of the shaft rotating bending occurs and what is characteristic the value of the strain is constant during the entire period of operation while the value of the stress varies.

In order to illustrate the differences resulting from the method of forcing, in figure 3 there are presented sample test results in the conditions of the constant amplitude loads with controlled stress (dynamic force) and strain (kinematic force). Test results relate to steel S355J0 (by old standards 18G2A steel) in conditions of loads characterized by asymmetry coefficient cycle R = -1 (fig. 3a and 3b). Hysteresis loops (fig. 3c), recorded with controlled stress show a cyclic weakening of the material resulting from an increase of their area with the number of cycles. Additionally a cyclic creep effect is observed and it is associated with the movement of the loop along the axis of strain. Presented in figure 3d hysteresis loops recorded in a control strain conditions show no cyclic creep. For the initial period of life loops are characterized by the largest field, which, together with the growth of the cycles number decreases. In the final period of life the shape of the hysteresis loop is changing. The characteristic crease related to the growing fatigue crack is visible. Analysis of test results allowed for the designation of graphs illustrating the cyclic variations of the total strain amplitude ε_{ac} (fig. 3e) and the stress amplitude σ_a (fig. 3f). For the dynamic force (fig. 3e) on the graph there is no stabilization period of the analyzed loop parameter, which is noticeable for the kinematic force [10].

It can therefore be concluded that depending on the force method hysteresis loops are characterized by different parameters of stress, strain and dissipation energy for similar periods of life.

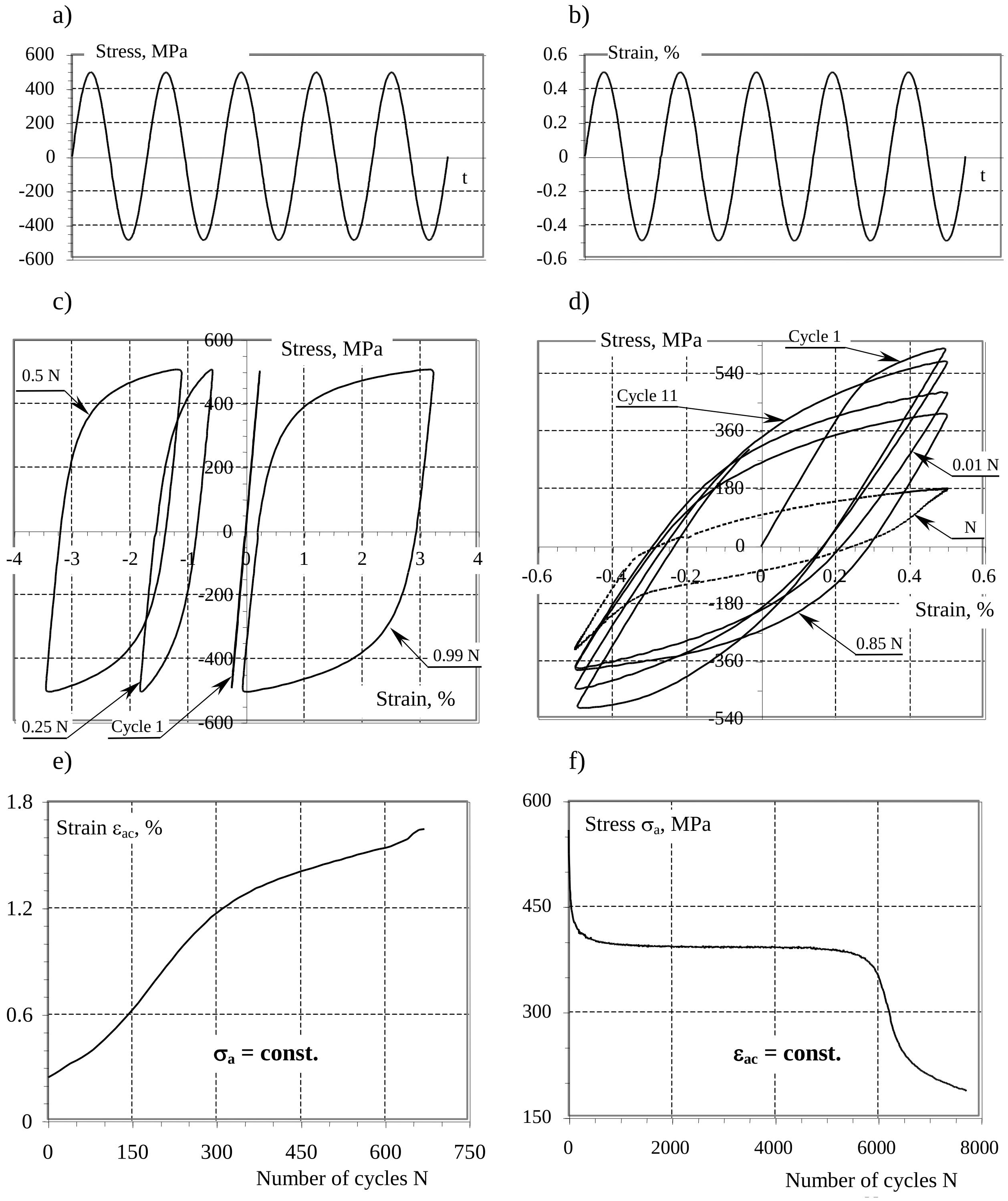

Fig. 3. The test results of S355J0 steel in conditions of stress and strain control: a - variation course of the loads with controlled stress (R = -1, σ_a = 500 MPa), *b - variation course of the strain with controlled strain* (R = -1, ε_{ac} = 0.5%), *c - selected hysteresis loops recorded under conditions of stress control, d - selected hysteresis loops recorded under conditions of strain control, e - graph of cyclic weakening for* σ_a = *const., f - graph of cyclic weakening for* ε_{ac} = *const.*

5. Examples of service load analysis in terms of fatigue life

Knowledge of the nature of the loads and number of cycles per unit distance of the assumed operation allows to determine the components life. This is important because of the indication of the extent of fatigue and the choice of research methods and calculations.

In papers [3, 6, 8, 9, 11, 12] the values of fatigue life of components of selected machinery and equipment (fig. 4) are presented. Expected design life was converted from hours of work, the number of kilometers, etc. on the number of load cycles. This allows to compare the values of life.

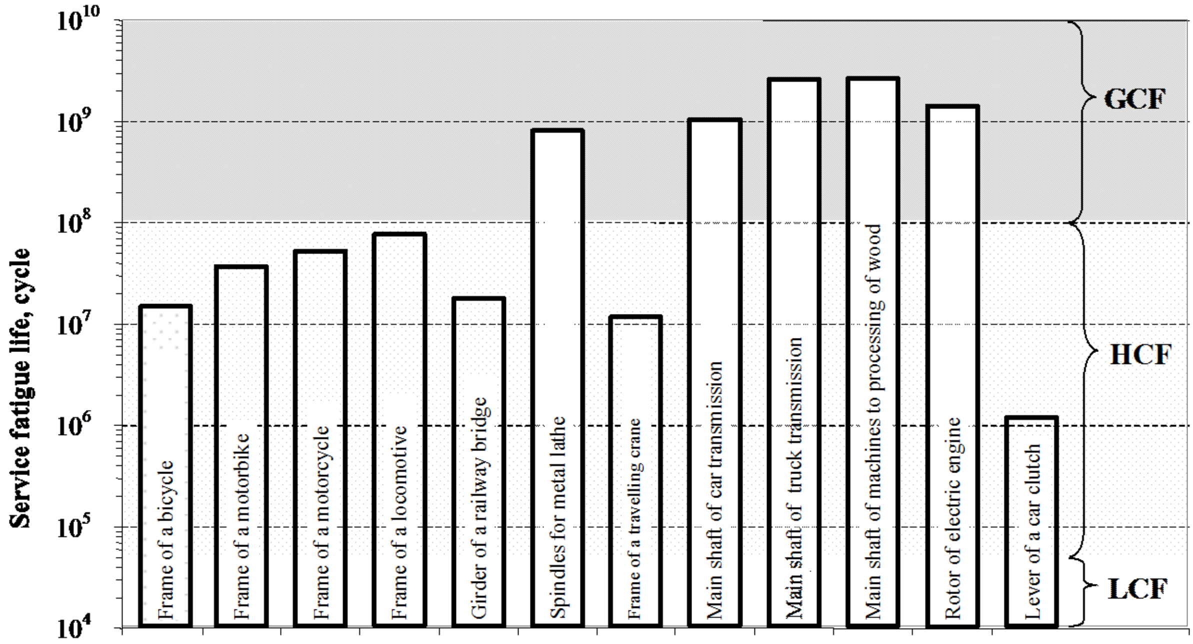

Fig. 4. Life ranges of selected objects elements

The performed analysis of life reveals that expected life expressed in number of cycles is within the range of high-and gigacycle fatigue.

Examples of machinery and equipment, whose elements work in the field of low-cycle fatigue may be given. These include the chemical industry equipment, energetic, engineering design, where the load variation results from the temperature cycles (eg. daily, annual), technological cycles (eg. filling and emptying of tankers), etc.

6. Summary

Expected life of machinery components at the design stage should be expressed in the number of changing load cycles. It allows to determine the fatigue range to which will be subjected the elements during operation and the level of maximum stress at points of stress concentration. Definition of the fatigue range results in the adoption of appropriate methods of calculation and experimental studies methods of fatigue life.

When assessing the fatigue life of machine components the nature of the load force must be taken into account. Depending on whether they are dynamic load or change the kinematic the variation of the nature of fatigue process follows, which in consequence may lead to different life results.

The presented examples of components and their corresponding life values indicate that the dominant fatigue ranges in mechanical engineering are high and gigacycle fatigue ranges. It is therefore necessary to develop calculation and research methods that correspond with mentioned ranges of designed life.

References

[1] Aalt A. Ten Have (Research engineer, National Aerospace Laboratory NLR, Amsterdam, The Netherlands), *European approaches in standard spectrum development, Development of Fatigue Loading Spectra*, STP 1006, ASTM, Philadelphia, 1989.

[2] Broichhausen J., *Schadenskunde*, Munchen, Wien, Carl Hanser Varlag, 1985.

[3] Gurney T. R., *Zmęczenie konstrukcji spawanych*, WNT, Warszawa, 1973.

[4] Heuler P., Klatschke H., *Generation and use of standardised load spectra and load–time histories*, International Journal of Fatigue 27 (2005), pp. 974–990

[5] Kocańda S., Szala J., *Fundamentals of fatigue calculations, (in Polish),* PWN, Warszawa 1997.

[6] Kugiel R.W., *Trwałość samochodów,* WKiŁ, Warszawa, 1965.

[7] Polska norma PN-EN 1993-1-9, Eurokod 3: *Projektowanie konstrukcji stalowych*, Warszawa, 2007.

[8] Serensen S.V., Kogaev V.P., Snejderovic R.M., *Nesuscaja sposobnost i razcety detalej masinna procnost*, Masinostroenie, Moskva, 1975.

[9] Sobczykiewicz W., *Wrażliwość zmęczeniowa spawanych stali o podwyższonej wytrzymałości na statystyczne widmo obciążeń występujące w wysięgnikach karatowych żurawi jezdniowych*, Rozprawa doktorska, Politechnika Warszawska, 1972.

[10] Szala J., *Hypotheses of fatigue damage accumulation, (in Polish)*, Monographs, University of Technology and Agriculture, Bydgoszcz 1998.

[11] Szala J., Przybyliński B., Zawiślak S., *Wybrane zagadnienia z analizyobciążeń zmęczeniowych elementów maszyn*, Zeszyty naukowe ATR, 1988.

[12] Wiśniewski Z., *Badanie widma naprężeń w konstrukcjach nośnych,* Przegląd Mechaniczny, nr 6, 1983 r.

Note: This work has been elaborated in the frame of the project No. 0715/B/T02/2008/35 financed by Polish Ministry of Sciences and Higher Education.