Name of the project: (2002-2004)

The influence of a random multiaxial nonproportional stress on the fatigue life of machine parts

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Characteristic of the project

State of the art of knowledge of fatigue damaging caused by a multiaxial stress with nonproportional random components is low up to now. This fact does not enable reliable dimensioning machine parts, and determining their service lives. The proposed project sets oneself the goal to remove the drawback, and, on the base of the own theoretical and experimental research, to judge critically existing procedures, and to develop own algorithms and a program for calculating fatigue lives of the complex loaded machine parts. Testing will run in modernized laboratories of both cooperating institutions with the use of computer-controlled electrohydraulic testing machines. During the whole time of the project solution, the experimental results will serve both as an information source for setting material parameters influencing fatigue life, and as a criterion of acceptability of project solutions. In the final of the project solution, a real machine part will be tested on a rig equipped by two free actuators for generating the above mentioned complex stress. Both the known loading processes and the correponding results of the real experiment will serve for testing the new program product. The successfull solution, in forms of verified algorithms, the program for calculating fatigue life, and an experimental data base, will enable future users to optimize new machine structures for guaranteed service lives even in such complicated conditions of loading

A survey of the state of art

Demands concerning strength dimensioning of dynamically stressed structures like chassis, bogies and bodies of road and railway vehicles increase, in order to ensure their reliability during prescribed lifetime. Most of these structures are loaded by a complex spatial force systems, generating complex, time-variable stress-state in their individual parts. The effort to decrease the mass, coming out of economic reasons, leads to better material property utilisation and, thus, to safety factor reduction.

The introduction of computers and advanced computational methods (like FEM) enables now to obtain reliable information on distributions and levels of stresses in particular structures. However, it doesn't solve the problem of structure fatigue life prediction connected to no less important information on fatigue properties of used materials or external factors influencing these properties, respectively. Consequently, the problem of fatigue life is necessary to be solved as a complex one from the viewpoint of both the stress-state and the failure process knowledge. This approach is the aim of relative great number of researchers engaged in the effect of multiaxial loading on the life of dynamically stressed structures.

The character of loading may be from harmonic to random, with stress components either proportional or non-proportional. The computational method solving the mentioned problem for all loading combinations hasn't been found yet up to now. Number of hypotheses has been formulated; the review of them is summed up in the report [1]. The development of criteria applied to a life prediction under multiaxial fatigue has been presented based on results of the grant project GA 101/99/1668. Approaches utilising the criteria of static strength even in the field of dynamic loading belong among historically the oldest ones. The same holds for successive criteria derived on their basis using the combination of the first and the second stress-state tensor invariant [3], [5], [7] as a damage parameter. Their application, however, needn't lead to satisfactory agreement between computations and experiments in case of non-proportional loading. Even in the proportional case, the evaluation ought to be acceded rather thoughtfully. The most commonly adopted procedures in the Czech Republic were those, starting from the strength theory [8]. The A.S.I. codification for needs of nuclear engineering form the base for evaluations by the program STATE

[9]. However, any detailed information concerning experimental verification of these procedures hasn't been obtained from literature.

In the eighties and nineties, the research group around Brown and Miller [10] and Socie [11]-[14] formed the criterion belonging to those which has been spread as first into testing even in computational applications in multiaxial fatigue. It is so called critical plane criterion. The authors dealt with processes leading to crack initiation and development in detail, and present interesting information on this area with introducing several types of solutions for different loading cases and materials as well. In the framework of carried out and here commented experiments, the criterion seams to be also acceptable for simpler cases of non-proportional loading. However, it would be useful to try to apply the criterion to more complex loading conditions.

Next, so-called McDiarmid criterion [15], described also in the report [1], belongs to the family of critical plane criteria. It has come through long development and experimental verification. The results described are rather not clearly mapped and don't allow uniqueness of conclusions. The criterion seams not to be sufficiently flexible (in contrast to previous one) in reaction to those different loading conditions, which can occur in this field. The criterion appears often in other authors works.

The work of Wang and Brown has recently lead to further re-evaluation of their earlier damage criteria (in the year 1996). The first version of their criterion [16] is described in published papers as a relative realistic one, incorporated into some of software products for fatigue solution. Nevertheless, the authors themselves prefer a new method. The idea of fundamental effects on damage development has remained preserved. Owning to changes in decomposition of a loading process, a significant shift appeared, from rigorous criteria of single critical plane towards the proposal enabling more realistic view on the damage principle [17]-[20]. The critical plane is here joined to each cycle separately. Both presented criterion versions reach very good results in studied papers.

So called integral accesses form next group of methods. They start from the knowledge that the critical plane criteria, which assume a "vector" (directional) damage, need not be a suitable physical model, and present the damage by a scalar quantity independent on stress tensor direction. One of attempts to solve this question is the work of Kenmeugne, Vidal, Robert and Bahuauda [21], [22]. Also Esderts and Zinner [23] apply the integration with the aim of reaching the interaction of individual damage planes. To integral approaches belongs the Papadopoulos criterion [6], [24], [25] described in details in the report [1], which, compared to experiments shows a good agreement. Nevertheless, the emphasis ought to be paid to rather narrow field of the criterion applicability in an algebraic form. In other applications that are not of Papadopoulos concern, the solution is applied in the integral form, which makes computational problems. This mesoscopic approach of Papadopoulos has been followed by Morel in his works [26] and [27]. However, this author only transferred given criterion into family of critical plane criterions.

The crucial damage parameter for following analysed criteria of multiaxial fatigue is the product of stress and relative strain on a critical plane. Due to the character of such product they can be considered as energy criterions, maybe even partial-energetic criterions. A fundamental energy criterion has published the research group around Ellyin [29]. Incorporating the plastic creep into this hypothesis can be considered as a huge contribution of this concept.

The Stefanov's criterion, firstly published in his PhD thesis in 1980 [30], is quite beyond all previous approaches. It was formulated with the goal to explain extreme deviations between some experimental results and prediction methods used for judgment of different effects, which other authors tried to avoid during computations. Stefanov considers just the way of loading as the most significant damage parameter. Remaining parameters considered in some other criteria are included in his proposal as well. The author develops his theory in four papers [30]-[34] published up now, and describes several practical solutions with outstanding results. It is necessary to admit that, in spite of a certain empiricism of the procedure, the criterion can be evaluated both as very attractive with good agreement with prediction, and as acceptable to further development. Unfortunately, some substantial information essential for building computational program the author hasn't published yet. Similarly, the criterion mentioned by Borodia, et all [35] is analogously dependent on a loading trajectory. He starts from so-called non-proportionality parameter, the value of which influences the intensity of an equivalent stress linearly. The results presented here by the authors seam to be very prospectus, but the demand for further verification again arises.

It is clear from the given survey that the problem of machine part fatigue under multiaxial random loading with non-proportional components is rather complicated and, thus, it hasn't been solved satisfactorily up to this time. It results from a relative small number of published theoretical and namely experimental results, nevertheless, the way of the mentioned loading is more often encountered in service than the harmonic one. The reason is probably in the fact that the life prediction hasn't been quite satisfactorily solved yet even for the case of random loading with plane stress state and proportional stress components, what is the subject of the grant project GA 101/99/0103. The project is being finished at present on the workplace of the proposer [2] yielding interesting results.

A complexity of the newly proposed grant project is the reason, why any engineering applicable computational method predicting the fatigue lifetime of machine parts for given loading way with satisfactory precision doesn't exist up to now. Solution of the proposed project would change this situation.

The aims of the project

The aim of suggested project is to make an investigation of principles of machine part fatigue failure under combined loading with a random character of non-proportional components of stress, and to design the methodology for lifetime prediction. The problem will be solved both theoretically, and experimentally.

The goal of experimental works will be in ensuring the reliable data of fatigue lives, origins of cracks and their propagation, measured under defined conditions on samples exposed to different non-proportional random combined loading. The data will be engaged as a comparison material for theoretical works.

The aim of theoretical works will lay in designing, developing and testing of computational methods of machine part life prediction under combined loading. Besides, own experimental data and experimental results accessible in literature will be used too. The selected methods of lifetime computation yielding the best results will then be programmed.

Concept and methods

It can be inferred from formulation of the aims that the project is basic-research oriented on the up to now little explored field of machine part fatigue under complex multiaxial loading with random stress-state character. The study will be carried out on tube-form samples, both smooth, and notched (with a transverse hole, necessary for easier identification of the point of a fatigue crack origin and propagation). The place of assumed crack origin will be followed in detail during tests, and the velocity and direction of crack propagation dependent on loading parameters will be measured. All these tests with combined loading will be performed on the computer controlled electro-hydraulic testing machine Inova ZUZ 200-1, which enables simultaneous independent loading of a tested sample in push-pull and torsion regimes. Auxiliary tests with uniaxial stress will run on simpler machines Inova and Instron, where both loading and measurements are controlled by computer as well.

Analysis and testing methods for estimating fatigue life taken from literature sources will be performed in parallel to experiments, both accompanied with building up the program modules for dimensioning machine parts exposed to a danger of damaging by a multiaxial fatigue process. The new program will complete the system created at present, which is based on uniaxial approaches. A selection of relevant multiaxial methods will come out of above described results of experiments under non-proportional loading performed in the proposer's laboratory, and from literature sources. Parallel testing of several criteria will enable mutual comparison of life prediction results and experimental results, and will allow to test the sensitivities of methods to initial parameters, and to cover possible further factors, which might influence the damage process.

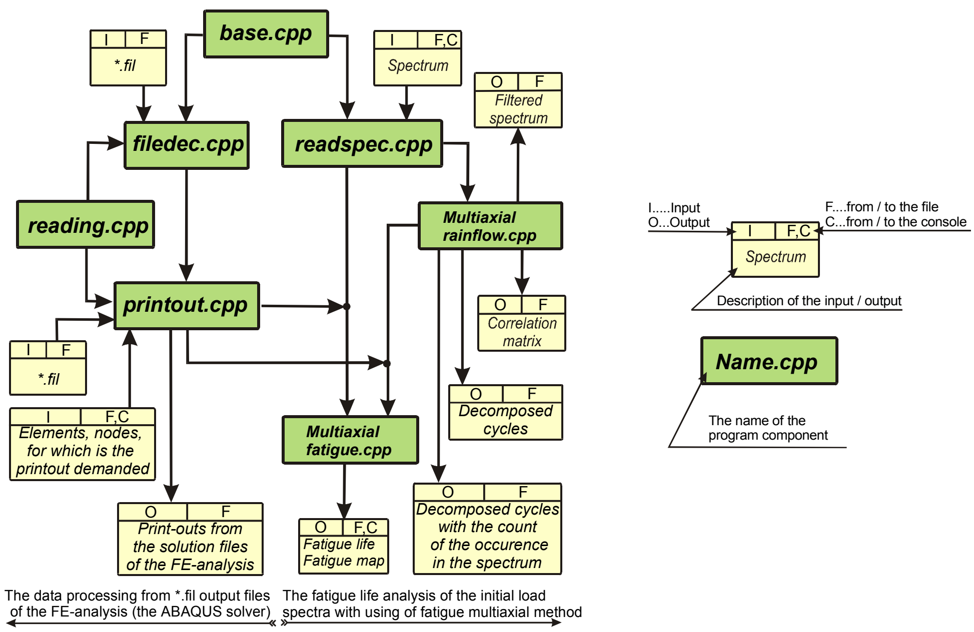
Nevertheless, the consideration should come out of complexity of individual application processes (from simple to difficult solvable ones). In addition, it is necessary to take into account the existence of common program units in order to exploit the already programmed algorithms into new method developments. This analysis brought us to a conclusion to analyse and apply the methods described by a group of authors around Socie [11]-[14] as first ones. They enable, to a considerable extent, both to exploit current algorithms for loading decomposition, and in the best way worked up methods of selection of anticipated damage planes. Within the framework of the method, programming functional units is expected both for stress state description in a point of a body and for finding a normal line to outside surface in a given point and rotation of estimated planes. All these partial algorithms are useful also for development of other proposed methods.

A next stage is represented by program versions of both criteria of Wang and Brown [17]-[20]. The first criterion is, from programmer viewpoint, largely analogous to the Socie algorithm. The other criterion results from the first one. However, it requires to design and to program the methods of loading spectrum decomposition. In this project stage, the extent of algorithms concerning the methods of critical plane, and thus the possibility to program further modifications of critical plane, will be covered.

Further special programming activities will be focused at integral criteria. The choice is directed on utilisation of some of "classical" versions (e.g. Kenmeugne et all [21] [22]), and on mesoscopic criteria (Papadopoulos [6], [24], [25]). It will be necessary to solve a numerically key integration operation related to damages evaluated in individual planes. In next stage, the design of a selective integration mostly loaded planes. For the present, any published and verified solution doesn't exist, and the method would represent a real novelty.

As far as energy methods are concerned, they all belong to a family of the above-mentioned integral criteria or to critical plane criteria; with the difference that damage parameter is here considered as a form of deformation energy. The applications will thus be derived from designed algorithms of critical plane methods. It is assumed, the Ellyin criterion [28] and its modifications will give interesting results.

The final aim of the theoretical part of the grant project solution is a program for mapping a damage of machine part subject to stochastic multi-axial fatigue stress. It will significantly widen abilities of the existing program for calculating fatigue life under uniaxial loading, created in the grant project GA 101/99/1668.The program will be a self-standing macro-block, the first part of which will process results of FEM computations of different partial loading states. The program will evaluate fatigue damages and display their mapping in critical planes for multi-component service loading of the part in the second stage of computations. The total diagram of programs is given on the following figure:



At the present, a collection of procedures for input and editing FEM (ABAQUS, ANSYS, COSMOS, etc.) outputs of the type **.fil* are operational. Even the module *base.cpp* for transferring FEM results into the fatigue branch of computing is finished

On the base of careful testing, the optimum method will be selected for predicting fatigue lives of machine parts and verified by the experimental data. A testing of several criteria will enable a mutual comparison of predicted lives with experimentally obtained ones. It enables to find sensitivities of methods on input parameters, and, if necessary, to involve additional, up to the time unknown, parameters can influence the damaging process in different stages of the damage.

In final stage, the selected optimum method will be verified on the problem of fatigue life prediction of a chosen machine part, which will be also determined experimentally by using the pair of free actuators Instron-Schenck Testing in the fatigue laboratory of the proposer's workplace. All knowledge and experience resulting from earlier projects dealing with fatigue will be used in an experiment design, investigations of connections between loading, fatigue failure and the resulting fatigue lifetime, as well as in the course of programming.

Expected result and its application

The solution of the project is assumed to bring the improving of contemporary state-of-art in following directions:

- giving precision to information on fatigue failure mechanisms of machine parts subjected to combined non-proportional random loading,
- progress in development of existing methods, and possible a new method for predicting the service life of machine parts under above mentioned loading character,
- development and formulation of corresponding program modules and their incorporating into a general program for life prediction of machine parts.

Application of this project results is expected in engineering, namely in vehicle developments, strength dimensioning of dynamically loaded structures and their lifetime verifications. The non-negligible will be the utilisation of obtained results in an educational process and in PhD studies, at least by two technical universities (The Czech Technical University in Prague and The University of West Bohemia in Plzeň).

References

[1] RŮŽIČKA, M.; PAPUGA, J.: Aspects of fatigue damaging under multi-axial loading (In Czech). Res. Rept. No.:. 2051/00/11. ČVUT in Prague, Prague 2000, 35 pages

[2] VÁCLAVÍK, M.; SVOBODA, J.: Fatigue properties of steels under multiaxial loading. In: Diagnostika a aktivní řízení. Proc. Colloq. IT CAS, Třešť, 2000

[3] RŮŽIČKA, M.; HANKE, M.; ROST, M.: Dynamic strength and lifetime. (In Czech), Prague, ČVUT ,1992.

[4] FATEMI, A.; SOCIE, D. F.: A critical plane approach to multiaxial fatigue damage including out-of-phase loading. Fatigue Fract. Engng. Mater. Struct., *11*, 1988, č. 3, s. 149-165.

[5] AKRACHE, R.; LU, J.: Three-dimensional calculations of high cycle fatigue life under out-of-phase multiaxial loading. Fatigue Fract. Engng. Mater. Struct., 22, 1999, č. 6, s. 527-534.

[6] PAPADOPOULOS, I. V.; DAVOLI, P.; GORLA, C.; FILIPPINI, M.; BERNASCONI, A.: A comparative study of multiaxial high-cycle fatigue criteria for metals. International Journal of Fatigue, *19*, 1997, č. 3, s. 219-235.

[7] ALTENBACH, H.; ZOLOCHEVSKY, A.: A generalized fatigue limit criterion and a unified theory of low-cycle fatigue damage. Fatigue Fract. Engng. Mater. Struct., 19, 1996, č. 10, s. 1207-1219.

[8] SOUKUP, J.: Less usual application of the rain-flow method (In Czech). Brno, EGV Ltd. 1993.

[9] Standartized technical documentation A. S. I. for stress calculation of equipment and piping in nuclear power plants of the type VVER. Section III. (In Czech), Prague, State office for nuclear safety and Institut of technical inspection, 1995.

[10] BROWN, M. W.; MILLER, K. J.: A theory for fatigue under multiaxial stress-strain conditions. Proc. Inst. Mech. Engrs 187, 1973, s. 745-755.

[11] SOCIE, D. F.; KURATH, P.; KOCH, J.: A multiaxial fatigue damage parameter. In: Biaxial and Multiaxial Fatigue, EGF 3. Red. M. W. Brown a K. J. Miller, London, Mechanical Engineering Publications 1989, s. 535-549.

[12] BANNANTINE, J. A.; SOCIE, D. F.: A multiaxial fatigue life estimation technique. In: Advances in Fatigue Lifetime Predictive Techniques, ASTM STP 1122. Red M. R. Mitchell a R. W. Landgraf. Philadelphia, American Society for Testing and Materials 1992, s. 249-275.

[13] SOCIE, D. F.: Critical plane approaches for multiaxial fatigue damage assessment. In: Advances in Multiaxial Fatigue, ASTM STP 1191. Red. D. L. Dowell a R. Ellis, Philadelphia, American Society for Testing and Materials 1993, s. 7-36.

[14] KIM, K.S.; PARK, J. C.: Shear strain based multiaxial fatigue parameters applied to variable amplitude loading. Int. Journal of Fatigue, 21, 1999, 5, s. 475-483.

[15] MCDIARMID, D. L.: A general criterion for high cycle multiaxial fatigue failure. Fatigue Fract. Engng. Mater. Struct., 14, 1991, č. 4, s. 429-453.

[16] WANG, C. H.; BROWN, M. W.: A path-independent parametr for fatigue under proportional and nonproportional loading.

Fatigue Fract. Engng. Mater. Struct., *16, 1993*, č. 12, s. 1285-1298.

[17] KIM, K.S.; PARK, J. C.; LEE, J. W.: Multiaxial fatigue under variable amplitude loads. J. of Engng. Mater. Tech., Transactions of the ASME, 121, 1999, s. 286-293.

[18] KIM, K.S.; PARK, J. C.: Shear strain based multiaxial fatigue parameters applied to variable amplitude loading. Int. Journal of Fatigue, 21, 1999, 5, s. 475-483.

[19] WANG, C. H.; BROWN, M. W.: Life prediction techniques for variable amplitude multiaxial fatigue-Part 1: Theories, Part 2: Comparison with experimental results. J. of Engng. Mater. Tech., Transactions of the ASME, 118, 1996, s. 367-374.

[20] BROWN, M. W.; SUKER, D. K.; WANG, C. H.: An analysis of mean stress in multiaxial random fatigue. Fatigue Fract. Engng. Mater. Struct., 19, 1996, č. 2/3, s. 323-333.

[21] VIDAL-SALLE, E; KENMEUGNE, J. L.; BAHUAUD, R. J.: Multiaxial fatigue under variable amplitude loading. In:Fatigue '96, Proc. of the Sixth Int. Fatigue Congress., Vol. II. Red. Lütjering, G. Berlin, Pergamon 1996.

[22] KENMEUGNE, B.; VIDAL-SALLÉ, E.; ROBERT, J. L.; BAHUAUD, J.: On a new multiaxial fatigue criterion based on a selective integration approach. In: Fatigue '96, Proc. of the Sixth Int. Fatigue Congress, Vol. II. Red. G. Lütjering, Berlin, Pergamon 1996, s. 1013-1018.

[23] ESDERTS, A.; ZENNER, H.: Multiaxial fatigue under random loading: experiments and lifetime prediction. In:Fatigue '96, Proc. of the Sixth Int. Fatigue Congress., Vol. II. Red. Lütjering, G. Berlin, Pergamon 1996.

[24] PAPADOPOULOS, I. V.: A new criterion of fatigue strength for out-of-phase bending and torsion of hard metals. Int. Journal of Fatigue, 16, 1994, s. 377-384.

[25] PAPADOPOULOS, I. V.: Critical plane approaches in high-cycle fatigue on the definition of the amplitude and mean value of the shear stress acting on the critical plane. Fatigue Fract. Engng. Mater. Struct., 21, 1998, č. 3, s. 269-285.

[26] MOREL, F.: A fatigue life prediction method based on a mesoscopic approach in constant amplitude multiaxial loading. Fatigue Fract. Engng. Mater. Struct., 21, 1998, č. 3, s. 241-256.

[27] MOREL, F.: Fatigue multiaxiale sous chargement d´amplitude variable. [Disertační práce.], Université de Poitiers 1996.

[28] ELLYIN, F.; XIA, Z.: A general fatigue theory and its applications to out-of-phase cyclic loading. Journal of Engng. Mater. Technol., Transactions of the ASME, *115*, 1993, s. 411-416.

[29] ELLYIN, F.: Fatigue Damage, Crack Growth and Life Prediction. Chapman & Hall 1997.

[30] STEFANOV, S. H.: Fatigue life at a critical location of real structure under cyclic or random non-proportional loadings. [PhD disertation.] (In Bulgarian), Sofia, Sofia Technical University 1980

[31] STEFANOV, S. H.: A curvilinear integral method for multiaxial fatigue life computing under non-proportional, arbitrary or random stressing. Int. Journal of Fatigue, 15, 1993, č. 6, s. 467-472.

[32] STEFANOV, S. H.: The curvilinear integral method: computer realization and testing 1 (under non-proportional reversed axial force and torque). Int. Journal of Fatigue, *17*, 1995, č. 8, s. 567-575.

[33] STEFANOV, S. H.: The curvilinear integral method: Testing 2 (under non-proportional pulsating axial force and internal pressure). Int. Journal of Fatigue, 18, 1996, č. 1, s. 41-48.

[34] STEFANOV, S. H.: The curvilinear integral method: a question to the critical plane concept. Int. Journal of Fatigue, *19*, 1997, č. 2, s. 101-107.

[35] BORODII, M. V.; KUCHER, N. K; STRIZHALO, V. A.: Development of a constitutive model for biaxial low-cycle fatigue. Fatigue Fract. Engng, Mater. Struct., 19, 1996, No 10, pp 1169-1179