Estimation of life time in fatigue analysis of horn structures

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Abstract

In the article the problem of estimation life time of the structures for magnetic lens (horns) is discussed. Due to pulse-type excitation by current flow, the relatively broad frequency band of stress component function is obtained. Moreover due to repetition the problem of pulse resonance can be obtained. The lifetime prediction is done based on the spectral attempt. The analysis were performed for two type of horn strictures: the CERN NuFact one and the EUROnu designed one.

Keywords: horn, fatigue analysis, life time

1. Introduction

Horn is a magnetic lens which focuses particles in a beam. Horn consists of two concentric conductors which delimit a closed volume. The current flow of the order of a few hundred of kA, and having a form of sequence of half-sine short time pulses repeated with a given frequency (in last projects about 50 Hz) due to need of cooling of the structure. It generates in the considered volume a toroidal magnetic field with intensity decreasing proportionally to the distance from the horn axis. [10]. The magnetic field is generating the magnetic force, which is the external excitation acting on the horn structure, usually made of aluminum. Due to oscillating (cyclic) form of the current flow, the magnetic force has the same form in time domain, therefore it is the source of the structure vibrations. The vibrations generates changing in time stresses in the material of the horn. Therefore due to nature of the process the problem of fatigue of material arises. Hence the question of the life time of the structure is open.

2. Attempts to fatigue analysis of horns

The realistic mechanical structures, or their parts, are commonly subjected to repeated loads, which are also named as cyc1ic loads. As the results of their action, there are obtained the cyc1e stresses, which can lead to physical material damage. Even at stresses below the ultimate strength, the microscopic damages can accumulate in the form of crack or the other form of macroscopic damage that leads to failure of the element. This process of damage and failure due to cyc1ic loading is called as fatigue [3]. Due to characteristic features of applied methods and the level of complication, the fatigue analysis is understood as an independent part of the strength of materials. The complexity of the analysis comes from the existences of a few problems, which have an important view on their results. Let us briefly classify them:

- Method of analysis: stress-based approach, strain-based approach, crack propagation method / fracture mechanics (Griffith criterion, crack opening displacement - COD, J-integral).
- Zones on the S-N curve (existence of the plastic strains regions) - fatigue strength: quasi-static, low-cycle, high-cycle.
- Methods of description of non-symmetric cyc1es - diagrams of: Smith, Haigh, Heywood; equivalent completely reversed stress.
- Methods of description of multiaxial stress: effective stress amplitude, effective mean stress.
- Description of the cumulative fatigue damage; methods of: Palmgren-Miner, Serensen, Haibach, Henry, Corten-Dolan, and the other ones.
- Methods of description of the realistic construction's effects of: geometry (notch effect, size effect), material machining (cutting, welding etc.), surface (surface roughness, changing of surface properties, residual stress, corrosion), material structures (thermal machining, residual stress).
- Methods of determination of the environmental effects: stress amplitude, thermal loadings, frequency and stress form, corrosion, freeting, prestressing.
- Methods for estimation of the material damage due to irradiation.

Vibration of engineering structures produces time variable displacements functions. Hence, the components of stress tensor are the time function too. The form of vibrations is determined by structure geometry and applied boundary conditions. They determine the modal characteristic of the system. For complex structures relatively high modal density is often observed. The other important parameter influencing the solution is the type of external excitation, and its spectrum in particular. For short time excitation, as pulses, the relatively broad frequency band of excitation is observed. The most important role plays values of natural frequencies of the system. Thus often in the transient case, the time history of displacements and stress components have irregular form with respect to time. It means that the vibrations have the form of quasi periodic vibrations. But they are still not of random type from nature of the process (if not chaotic ones).

The known in literature fatigue analysis of such cases can generally takes the following form:

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- Analysis in time domain superposition of harmonically variable stress components [3].
- Cycle counting of irregular stress functions in time domain (e.g. rain-flow method [3]).
- Spectral method in frequency domain based on PSD analysis (e.g. [8]).
- Direct spectral method in frequency domain based on FFT analysis for a few-modal spectrum (preferable uni-modal or bi-modal) [6].

3. Fatigue analysis of CERN NuFact short horn

The geometry of analysed structure is axisymmetric. The magnetic field is generated by current flow of pulse form. It has a form of sequence of half-sine pulses with time duration of 93 μs, repeated every 20 ms (50 Hz), with amplitude of 400 kA. The requested number of pules is equal to repetitions, i.e. five months of operation.

The analysis of dynamical behaviour of a structure is based on the finite element modelling of the structure. Due to almost axisymmetric geometry, and axisymmetric excitation (magnetic force), the FEM analysis has been done as an axisymmetric one, by applying the Ansys solid 42 type elements. Only the solid structure, without cooling medium (water) has been modelled. The gravity effect was not taken into account. Nodal temperature values come from the thermal estimation given in [7]. The temperature distribution is assumed to be linearly varying vs. radius (distance from the axis), between fourth characteristic points. Due to geometry of the horn, the pressure values can be estimated from the simplified formula [10]. The magnetic pressure is varying in time domain in the same way as the current flow. The stress distribution in the structure has the form of multi-axial ones. The standard S-N fatigue curves are used for uni-axial and usually alternate stress. Therefore the equivalent completely reversed uniaxial stress was calculated. Analysis of obtained values of dynamic stress distribution in time domain and static thermal stress have made possible to choose the most danger regions in the structure. The obtained values of the equivalent completely reversed stresses show, that the structure can work on safety level about 1.63 (experimental S-N curves, assumption of the completely reversed bending nature of stress variation).

4. Fatigue analysis of the EUROnu single separated horn

Estimation of life time for EUROnu horn was made for preliminary estimated thermal stress and dynamic stress coming only one magnetic pulse response assuming the proposed geometry [1,2,4]. In FEM simulation there was no observed effect of stress and displacement increasing in time. Life time prediction was estimated for three models of probability density: Rayleigh, Dirlik and Benasciutti-Tovo [8]. Moreover each estimation were done for three values of probability for S-N curve. The estimated values of lifetime are given in a Table 1. Number of pulses per second is equal to 12,5.

Table 1: Lifetime estimation.

S-N CURVE PROBABILITY	LIFETIME [s]
95%	8,6 E+7
50%	1,9 E+7
5%	6,6 E+6

5. Effect of corrosion and welding

Generally the welds in AlMgSi alloys have good resistance to corrosion. But in some corrosive environments localised corrosion can occur. Possible sites for crevice corrosion and possible weld defects that might lead to subsequent corrosion process are discussed in [9]. Therefore the welding process must be done carefully and with high quality.

6. Conclusions

Analysis of life time for the horn structures are necessary and possible nowadays.

Due to many assumptions, which must be taking into account the analysis is not easy to realization and has a form of estimation.

The structural analysis of horn is usually performed by finite element method. Some computer packages have implemented a specially oriented modulus for fatigue analysis.

It is necessary to take directly into account the effect of thermal and magnetic pulses in the analysis. The horn structure is subjected to various types of heat loadings coming from current pulses, magnetic field and in some cases of kinetic energy of beam (if the target is located inside horn).

The other problem is degradation of material properties due to radiation. The number of cycles to failure depends on accumulation of micro-damage due to irradiation.

References

[1] Baussan E. et al., Neutrino Super Beam Based on a Superconducting Proton Linac, *Physical Review Special Topics – Accelerators and Beams*, 14, 021002 (1-18), 2014.

[2] Bielski J., Cupiał P., Kozień M.S., Łacny Ł., Skoczeń B., Szybiński B., Ustrzycka A., Wróblewski A., Superbeam single horn thermo-mechanical and Multiphysics study and integration of 4-horns, *Report on the Cracow team contribution to EUROnu project in 2010-2011*, 14, 2012.

[3] Dowling N.E., Mechanical Behaviour of Materials. Engineering Methods for Deformations, Fracture and Fatigue, Prentice-Hall International Editors Inc, Englewood Cliffs, 1993.

[4] Edgecock T.R. et al., High intensity neutrino oscillation facilities in Europe, *Physical Review Special Topics – Accelerators and Beams*, 13, 021002 (1-18), 2013.

[5] Kocańda S. and Szala J., *Bassis of fatigue computations* (in Polish), PWN, Warsaw, 1999.

[6] Kozień M.S. and Szybiński B., Method of time-life estimation of vibrating engineering structures with irregular time history response, *Abstracts of the 5th International Conf. on Very High Cycle Fatigue*, Berlin, 2011, 539-544.

[7] Maugain J.-M., Rangod S. and Voelker F., Study of a horn with integrated target for a neutrino factory, *NuFact note 80*, CERN, May 21st, 2001.

[8] Niesłony A. and Macha E., *Spectral Method in Multiaxial Random Fatigue*, Springer, Berlin-Heidelberg, 2007.

[9] Sheir L.L., *Corrosion*, Newnes-Butterworths, Oxford, 2000.

[10] Wertelaers P., *Magnetic pressure and mechanical considerations on a new design for the Gran Sasso neutrino beam*, Ep 99-135, CERN, 30 August 1999.