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1st INTERNATIONAL SCIENTIFIC CONFERENCE

28th - 30th November 2012.

Jahorina, B&H, Republic of Srpska



University of East Sarajevo

Faculty of Mechanical Engineering

Conference on Mechanical Engineering Technologies and Applications

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PREFACE

Production in developed countries is based on the modernization and optimization of the production processes with the application of new technologies that are the result of scientific research. The application of new technology enables companies efficient production and competitiveness in the world market.

Faculty of Mechanical Engineering, University of East Sarajevo, organizes the First international conference "COMETa2012 - Conference on Mechanical Engineering Technologies and Application", which has tasks: to increase economic competitiveness in the region and the create a unique European Research Area.

Globally, the worldwide we are witnessing a rapid development and a host of new technological solutions, which occur primarily in the multidisciplinary development (mechatronics) but also in development of completely new technologies, such as nanotechnology, new energy sources, intelligent machines and processes, micro-technique, etc. All of this puts researchers and engineers in the new challenges and creates opportunities for products and technologies that provide a precondition for economic recovery and creation of new jobs.

COMETa2012 conference program structure is consisted of the following thematic areas: Production technologies and advanced materials, Applied mechanics and mechatronics, Development of products and mechanical systems, Energetics and thermo - technique, Renewable energy and environmental protection, Quality, management and organization, Maintenance and technical diagnostics.

Participation in international conference COMETa2012 was achieved by: 182 authors from 9 countries, with a total of 90 papers, including 4 plenary and 3 of introductory, 4 leading commercial companies and many small and medium enterprises. Bruel & Kjeaar Workshop: "Measurement of noise and vibration", was also organized at the conference, as well as a round table discussion: "The importance of quality infrastructure of B&H within the European integration".

The presence of a large number of participants from Bosnia and Herzegovina and abroad as well as the problems which are processed at the conference, coincide with the themes promoted by the European Union in its development programs.

On the basis of previous exposure, a gathering of scientists and researchers at the international conference COMETa should be understood not only as an exchange of knowledge and achievements of the narrower set of scientists and researchers, but also as a constant and serious attempt to focus social consciousness and social life on activities that ensures progress and prosperity of any society, and that is productive work, creating new knowledge and economic development.

On behalf of the Organizing Committee of the Conference COMETa2012, thank all authors, reviewers, as well as institutions, companies and individuals who contributed to realization of the Conference.

East Sarajevo, October 28th, 2012.

President of the Organizing Committee

Prof. dr Ranko Antunović



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PRORAČUN NOSIVOSTI OSOVINA I VRATILA PREMA DIN 743

Dragan Milčić¹, Miroslav Mijajlović², Dragoljub Živković³, Slobodan Miladinović⁴

Rezime: DIN 743 [1] postoji već 12 godina. Ovaj standard je namenjen za proveru nosivosti štapnih oblika konstrukcionih elemenata- osovina i vratila. Zasniva se na proverenim osnovama, pre svega na nekadašnjem standardu TGL 19340 i brojne istraživačke i razvojne radove. Ovaj standard daje preporuke za proračun statičkog i dinamičkog stepena sigurnosti osovina i vratila, koji su opterećeni različitim opterećenjima. U radu je dat predlog proračuna stepena sigurnosti osovina i vratila, kada je opterećenje dato u vidu spektra opterećenja.

Ključne riječi: Proračun nosivosti, Osovine, Vratila, DIN 743, Spektr opterećenja

CALCULATION OF LOAD CAPACITY OF AXLES AND SHAFTS ACCORDING TO DIN 743

Abstract: DIN 743 [1] has been introduced 12 years ago and it defines the procedure of estimating load capacity of the rod-shaped structural elements – axles and shafts. The standard is primarily based on the former standard TGL 19340, numerous researches and engineering projects. It gives recommendations for the calculation of static and dynamic safety factors of axles and shafts, loaded with variant loads. The paper presents a novel procedure of safety factor calculation of an axle or a shaft, when the load is given as a load spectrum.

Keywords: Calculation of load capacity, Axle, Shaft, DIN 743, Load spectrum

1. UVOD

Najčešći problem inženjera u procesu konstruisanja je određivanje stepena sigurnosti za određenu konstrukciju.

Pitanje koje se najčešće postavlja je: koje opterećenje i pod kojim uslovima određena konstrukcijamože izdržati a, da ne dođe do njenog deformisanja.

Sveopštim razvojem znanja i informacija svakodnevno se pronalaze nove

¹ Prof. dr Dragan Milčić, Univerzitet u Nišu Mašinski fakultet, Aleksandra Medvedeva 14, 18000 Niš, Srbija, milcic@masfak.ni.ac.rs

² Dr Miroslav Mijajlović, Univerzitet u Nišu Mašinski fakultet, Aleksandra Medvedeva 14, 18000 Niš, Srbija, mijajlom@masfak.ni.ac.rs

³ Prof. Dr Dragoljub Živković, Univerzitet u Nišu Mašinski fakultet, Aleksandra Medvedeva 14, 18000 Niš, Srbija, dzivkovic@masfak.ni.ac.rs

⁴ Dr Slobodan Miladinović, Visoka tehnička škola strukovnih studija iz Uroševca sa privremenim sedištem u Zvečanu, Branislava Nušića 6, Zvečan, Srbija, miladinovicslobodan21@gmail.com

metode za proračun stepena sigurnosti. Često su te metode specijalizovane za određeni tip konstrukcije. Inženjeri koji se bave konstruisanjem i oblikovanjem osovina i vratila, nakon tzv. „projektnog proračuna“, imaju zadatak da odrede stepen sigurnosti na kritičnim preseccima tj. na mestima geometrijskih diskontinuiteta gde dolazi do velikog porasta napreznja.

DIN 743 standard obuhvata izraze i jednačine za određivanje stepena sigurnosti na kritičnim preseccima osovina i vratila i to prema dva kriterijuma:

- sigurnost u odnosu na plastičnu deformaciju dela (statički stepen sigurnosti).
- sigurnost u odnosu na dinamičku izdržljivost materijala (dinamički stepen sigurnosti)

Proračun razmatra opterećenja na zatezanje/pritisak, savijanje i uvijanje. Napreznja na smicanje nije uzeto u obzir.

Rezultati dobijeni po standardu DIN 743 otklanjaju nedoumice po pitanju sigurnosti na kritičnim mestima osovina i vratila i time omogućuju inženjerima uspešnije i preciznije, dimenzionisanje osovina i vratila.

2. PRORAČUN STEPENA SIGURNOSTI

2.1. Statički stepen sigurnosti

Statički stepen sigurnosti izračunava se pri maksimalnom opterećenju vratila. Ova opterećenja se uglavnom javljaju prilikom pokretanja ili zaustavljanja vratila. Ova retka ali vrlo visoka opterećenja izazivaju maksimalna napreznjana na kritičnim preseccima osovina i vratila.

Izračunata vrednost statičkog stepena sigurnosti treba biti veća ili jednaka minimalnoj sigurnosti S_{\min} ($S \geq S_{\min}=1,2$).

U slučaju istovremenog opterećenja osovina i vratila na zatezanje/pritisak, savijanje i uvijanje statički stepen sigurnosti se određuje prema izrazu (1):

$$S = \frac{1}{\sqrt{\left(\frac{\sigma_{zd \max} + \sigma_{b \max}}{\sigma_{zdFK} + \sigma_{bFK}}\right)^2 + \left(\frac{\tau_{t \max}}{\tau_{tFK}}\right)^2}} \quad (1)$$

gde su:

$\sigma_{zd \max}$ - maksimalni normalni napon pri opterećenju na zatezanje/pritisak;

$\sigma_{b \max}$ - maksimalni normalni napon pri opterećenju na savijanje;

$\tau_{t \max}$ - maksimalni tangencijalni napon pri opterećenju na uvijanje;

σ_{zdFK} - granica tečenja mašinskog dela pri opterećenju na zatezanje/pritisak;

σ_{bFK} - granica tečenja mašinskog dela pri opterećenju na savijanje;

τ_{tFK} - granica tečenja mašinskog dela pri opterećenju na uvijanje;

Granice tečenja određuju se prema, izrazu (2) za slučaj opterećenja na zatezanje/pritisak, i prema izrazu (3) za slučaj opterećenja na uvijanje:

$$\sigma_{zd, bFK} = K_1(d_{eff}) \cdot K_{2F} \cdot \gamma_F \cdot \sigma_S(d_B) \quad (2)$$

$$\tau_{tFK} = K_1(d_{eff}) \cdot K_{2F} \cdot \gamma_F \cdot \sigma_S(d_B) / \sqrt{3}, \quad (3)$$

gde su:

$K_1(d_{eff})$ - tehnološki faktor uticaja veličine;

- K_{2F} - faktor statičke izdržljivosti;
 γ_F - faktor povećanja granice tečenja;
 $\sigma_{s(dB)}$ - granica tečenja materijala (pobne epruvete).

Prema standardu DIN 743 faktor statičke izdržljivosti K_{2F} ima vrednost od 1 do 1,2, dok faktor povećanja granice tečenja γ_F ima vrednost od 1 do 1,15. Ove vrednosti mogu povećati statički stepen sigurnosti za 10 do 20%. Važno je napomenuti da na statički stepen sigurnosti bitno utiče tehnološki faktor veličine $K_1(d_{eff})$.

2.2. Dinamički stepen sigurnosti

Dinamički stepen sigurnosti određuje se iz odnosa amplituda dinamičkih izdržljivosti i amplitudnog napona u kritičnim presecima vratila. Kao i kod statičkog stepena sigurnosti potrebno je tačno odrediti koja naprezanja deluju na kritičnim presecima kao i njihove srednje i amplitudne vrednosti. Pri naprezanju na zatezanje/pritisak ili savijanje je:

$$S = \frac{\sigma_{zd,bADK}}{\sigma_{zd,ba}} \quad (4)$$

Izračunata vrednost dinamičkog stepena sigurnosti treba biti veća ili jednaka minimalnoj sigurnosti $S \geq S_{min}=1,2$.

U slučaju istovremenog opterećenja osovina i vratila na zatezanje/pritisak, savijanje i uvijanje dinamički stepen sigurnosti se određuje prema izrazu (5):

$$S = \frac{1}{\sqrt{\left(\frac{\sigma_{zda}}{\sigma_{zADK}} + \frac{\sigma_{ba}}{\sigma_{bADK}}\right)^2 + \left(\frac{\tau_{ta}}{\tau_{tADK}}\right)^2}} \quad (5)$$

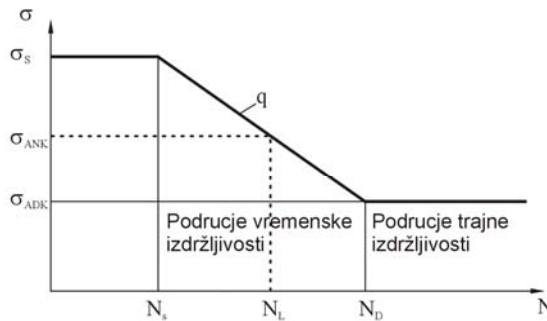
gde su:

- σ_{zda} - amplitudni napon pri opterećenju na zatezanje/pritisak;
 σ_{ba} - amplitudni napon pri opterećenju na savijanje;
 τ_{ta} - amplitudni napon pri opterećenju na uvijanje;
 σ_{zADK} - amplituda dinamičke izdržljivosti pri opterećenju na zatezanje/pritisak;
 σ_{bADK} - amplituda dinamičke izdržljivosti pri opterećenju na savijanje;
 τ_{tADK} - amplituda dinamičke izdržljivosti pri opterećenju na uvijanje.

2.3. Proračun stepena sigurnosti u području vremenske dinamičke izdržljivosti

U području vremenske izdržljivosti vremenska dinamička izdržljivost se proračunava koristeći podatak o trajnoj dinamičkoj izdržljivosti na osnovu jednačine SN krive (Slika 1)

$$\sigma_{ANK} = q \sqrt{\frac{N_D}{N_L}} \cdot \sigma_{ADK} \quad (\sigma_{ANK} \leq \sigma_{FK}) \quad (6)$$



Sl.1 Velerova kriva u koordinatnom sistemu $(\log)\sigma-(\log)N$

Osim ako nije drugačije navedeno, može se uzeti $q = 5$ za savijanje, odnosno zatezanje/pritisak i $q=8$ za uvijanje. Jednačina (6) važi za $N_L \leq N_D$. (Pri proračunu prema metodi Palmgrin-Miner-osnovna, područje trajne dinamičke izdržljivosti ne postoji. Ovde važi jednačina (6) i za $N_L > N_D$.) Za prelomne tačke Velerove linije pretpostavlja se $N_D=10^6$ odnosno $N_S=10^3$ ($10^2 \dots 10^4$) (slika 1).

Stvarna opterećenja mašina u eksploatacionim uslovima nisu uvek jednaka nominalnim. Uslovi u kojima mašine rade mogu biti stacionarni i nestacionarni uslovi. Mašine uglavnom rade u nestacionarnim uslovima eksploatacije, pa su i opterećenja takvih mašina nestacionarno promenljiva. Naponi koji se javljaju u delovima mašina u toku eksploatacije su često veća od trajne dinamičke izdržljivosti, što dovodi do akumulacije oštećenja u materijalu, a posle određenog vremena do preloma.

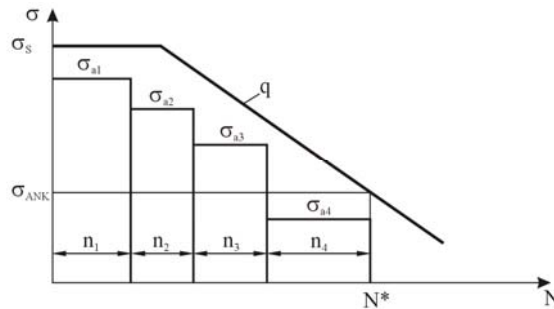
Visok stepen tačnosti pri dimenzionisanju i proveru sigurnosti protiv razaranja može se postići merenjem eksploatacionih opterećenja i identifikacijom spektra opterećenja vitalnih elemenata mašina. Spektri opterećenja dobijaju se na osnovu eksploatacionih merenja mašinskog sistema u procesu rada za određene uslove, pa prema tome svaki spektar opterećenja ima svoju verovatnoću pojave. Izbor merodavnog spektra rešava se uvođenjem više spektara reprezentata za određene radne uslove, čime se omogućuje dovoljno tačna procena za sve među uslove.

Najpogodnija forma prikaza karakteristika slučajnih procesa radnih opterećenja, kakav je obrtni moment na vratilu prenosnika je eksploataciono merenje obrtnog momenta i njegova diskretizacija, a zatim i statistička obrada u cilju dobijanja spektra opterećenja.

Na osnovu spektra opterećenja proračunava se i dobija spektra napona. Kada se poseduje spektar napona vrši se izaberu hipoteze između: Palmgrin-Miner-elementarna, Palmgrin-Miner-originalna, Palmgrin-Miner-proširena i Palmgrin-Miner konsekvantna.

2.3.1. Hipoteza Palmgrin-Miner-elementarna

Kod hipoteze Palmgrin-Miner-elementarna pretpostavlja se da ne postoji trajna izdržljivost, odnosno da svi blokovi spektra doprinose oštećenju. Dakle, moraju da se uzmu u obzir svi blokovi spektra. Ova pretpostavka se često ocenjuje kao suviše pesimistička. Sa ovom metodom određena ekvivalentna amplituda napona smatra se količinski (po kvantitetu) suviše velikom, a time određeni stepen sigurnosti prema DIN 743 će biti manji u odnosu na sračunate stepene sigurnosti drugim ovde spomenutim postupcima.



Sl.2 Palmgrin-Miner-elementarna

Kod hipoteze Palmgrin-Miner-elementarna pretpostavlja se da, svi blokovi spektra doprinose oštećenju odnosno trajna dinamička izdržljivost ne igra ulogu. Stepen sigurnosti se određuje prema jednačini:

$$S = \frac{\sigma_{ANK}}{\sigma_a}, \quad (7)$$

gde je σ_a - ekvivalentni amplitudni napon određen prema jednačini:

$$\sigma_a = \frac{\sigma_{a1}}{K_{Koll}} \quad (8)$$

Pri čemu je:

σ_{a1} – amplitudni napon koji odgovara delu spektra koji reprezentuje najveće opterećenje,

K_{Koll} – faktor spektra koji se određuje prema izrazu:

$$K_{Koll} = \sqrt[q]{\left(\frac{1}{v^q} - 1\right) \cdot D_M + 1}. \quad (9)$$

Stepen punoće v se određuje prema izrazu:

$$v = \sqrt[q]{\sum_{i=1}^j \left(\frac{n_i}{N^*}\right) \cdot \left(\frac{\sigma_{ai}}{\sigma_{a1}}\right)^q} \quad (10)$$

gde ako nije drugačije navedeno ili poznato: $q = 5$ za zatezanje / pritisak ili savijanjem, odnosno $q = 8$ za uvijanje.

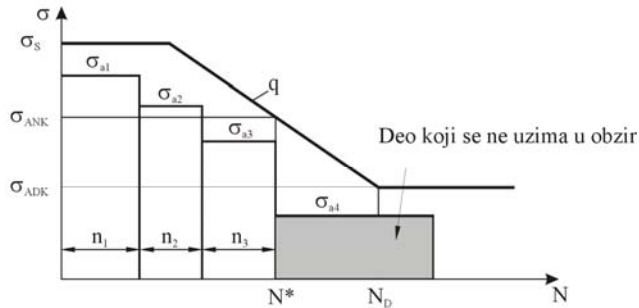
Kod ove hipoteze važi:

$$N^* = \sum_{i=1}^j n_i \quad (11)$$

Pri čemu je j poslednji blok datog spektra. Ova metoda se preporučuje kod agresivnih medija i otvrdnutih čelika, npr. čelika za kotrljajne ležaje i slično.

2.3.2. Hipoteza Palmgrin-Miner-originalna

Hipotezom Miner-originalna se pretpostavlja da se bilo koje naprezanje ispod trajne dinamičke izdržljivosti može izdržati bez loma (slika 3). Sa ovom pretpostavkom dati blok spektra ispod trajne dinamičke izdržljivosti nema udeo u oštećenju. To znači da se svi blokovi opterećenja datog spektra opterećenja kod kojih $\sigma_{ai} < \sigma_{ADK}$ (i-broj bloka spektra) zanemaruju.



Sl.3 Palmgrin-Miner-originalna

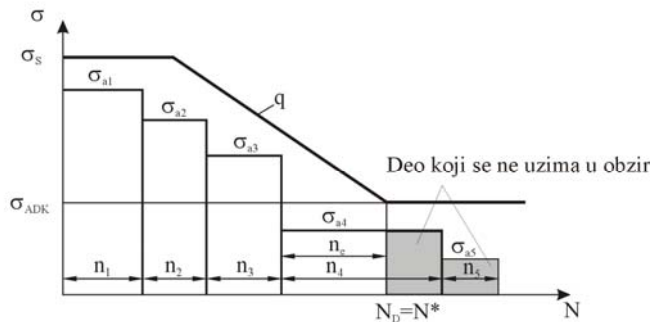
Stepen punoće je:

$$v = \sqrt[q]{\sum_{i=1}^{j^*} \left(\frac{n_i}{N^*}\right) \cdot \left(\frac{\sigma_{ai}}{\sigma_{a1}}\right)^q} \quad (12)$$

gde je $N^* = \sum_{i=1}^{j^*} n_i$ sa $j^* = p-1$ (kada je $N^* > N_D$ onda je $N^* = N_D$), a pri čemu je p prvi blok spektra ispod trajne dinamičke izdržljivosti.

2.3.3. Hipoteza Palmgrin-Miner-proširena

Za razliku od hipoteze Palmgrin-Miner-original ovde se polazi od činjenice, da samo blokovi spektra čija suma je manja ili jednaka N_D doprinose oštećenju. Blokovi spektra koji prevazilaze granicu N_D se odbacuju (slika 4).



Sl.4 Palmgrin-Miner-proširena

Onda se umesto n_i poslednjeg bloka spektra koristi n_e (slika 4).

$$n_e = N_D - \sum_{i=1}^{k-1} n_i \quad (13)$$

Poslednji blok spektra k je prvi koji prelazi preko prelomne tačke Velerove linije (primer na slici 4a, stepen 4; $k=4$). Za K_{koll} važi jednačina (9), v se određuje prema jednačini (10) sa

$$N^* = \sum_{i=1}^j n_i \text{ kada je } \sum_{i=1}^j n_i < N_D$$

odnosno

$$N^* = N_D \text{ i } j^* = k \text{ kod } \sum_{i=1}^j n_i \geq N_D.$$

2.3.4. Hipoteza Palmgrin-Miner- konsekventna

Postupkom Palmgrin-Miner-konsekventna se direktno uzima u obzir da se smanjenje udela trajne dinamičke izdržljivosti događa sa povećanjem oštećenja [1]. Prema [2] i novijim istraživanjima treba ovaj postupak da daje bolje rezultate u smislu podudaranja sa stvarnim ponašanjem komponenti.

Stepen sigurnosti se mora odrediti ovde iterativnim postupkom. Počevši od početne vrednosti S_{step0} , varira se stepen sigurnosti S_{step} kao zamišljeno povećanje opterećenja, do dobijanja broja promene opterećenja \tilde{N} , koji odgovara zahtevanom broju promena opterećenja N^* .

$$\tilde{N} = [(A_{kon} - 1) \cdot D_M + 1] \cdot \left(\frac{\sigma_{ADK}}{S_{Step} \cdot \sigma_{a1}} \right)^q \cdot N_D \quad (14)$$

Sa

$$A_{kon} = \left(\frac{S_{Step} \cdot \sigma_{a1}}{\sigma_{ADK}} \right)^{q-1} \cdot \left(\frac{Z1}{N1} + \sum_{\lambda=p}^j \frac{Z2}{N2} \right) \quad (15)$$

$$Z1 = \left(\frac{\sigma_{ADK}}{S_{Step} \cdot \sigma_{a1}} \right)^{q-1} - \left(\frac{\sigma_{ap}}{\sigma_{a1}} \right)^{q-1} \quad (16)$$

$$Z2 = \left(\frac{\sigma_{a\lambda}}{\sigma_{a1}} \right)^{q-1} - \left(\frac{\sigma_{a(\lambda-1)}}{\sigma_{a1}} \right)^{q-1} \quad (17)$$

$$N1 = \sum_{i=1}^{p-1} \frac{n_i}{N^*} \cdot \left(\frac{\sigma_{ai}}{\sigma_{a1}} \right)^q \quad (18)$$

$$N2 = \sum_{i=1}^{\lambda} \frac{n_i}{N^*} \cdot \left(\frac{\sigma_{ai}}{\sigma_{a1}} \right)^q \quad (19)$$

Pri tom je j broj blokova spektra, a p broj blokova spektra ispod σ_{ADK} . Pri svakom iteracionom koraku određuje se novo p , pošto se svi blokovi spektra povećavaju sa faktorom S_{Step} . U jednačinama (14) do (19) koriste se blokovi napona σ_{ai} (izlazni podaci). Za iteracioni ciklus neophodno je σ_{aj+1} . S toga je preporučeno da se dodatno uvede stepen napona $(j+1)$ sa $n_{j+1}=0$ i $\sigma_{aj+1}=0$.

Za zahtevani radni vek uzimaju se u obzir svi blokovi spektra:

$$N^* = \sum_{i=1}^j n_i$$

3. ZAKLJUČAK

Na osnovu napred navedenog može se zaključiti sledeće:

- DIN 743-1-3 postoji već 12 godina. Ovaj standard je namenjen za proveru nosivosti osovina i vratila. Ovaj standard je 2008 godine dopunjen 4. delom koji se odnosi na proračun nosivosti osovina i vratila za slučaj opterećenja definisanog spektrom opterećenja. Standard još uvek nije usvojen, već je varijanta draft.
- Visok stepen tačnosti pri dimenzionisanju i proveru sigurnosti protiv razaranja može se postići merenjem eksploatacionih opterećenja. Najpogodnija forma prikaza karakteristika slučajnih procesa radnih opterećenja, kakav je obrtni moment na vratilu prenosnika je eksploataciono merenje obrtnog momenta i njegova diskretizacija, a zatim i statistička obrada u cilju dobijanja spektra opterećenja.
- Na bazi definisanog spektra opterećenja sračunava se spektar napona, a zatim primenom izabrane hipoteze Palmgrin-Miner vrši provera stepena sigurnosti vratila i osovina.

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