

Vpliv zareze v zobnem korenju pastorka na frekvenčni odziv gonila

Influence of the Pinion Tooth Root Notch on the Frequency Spectrum of a Gear Drive

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Članek obravnava analizo vpliva globine zareze v zobnem korenju na frekvenčni odziv zobiškega gonila z uporabo vibroakustične analize. Različne globine zareze v zobnem korenju pastorka so bile narejene z žično erozijo, s katero se je simulirala utrujenostna razpoka, do katere prihaja pri zobiških gonilih zaradi prevelikih obremenitev, napačne konstrukcije ali napak v materialu.

Preizkusi so bili izdelani za različne vrtilne frekvence in momente. Časovni signali, ki so bili zajeti z uporabo dveh mikrofonov, so bili obdelani s Fourierjevo transformacijo. Tako dobljeni močnostni frekvenčni spektri so se za različne globine zareze, različne momente in različni vrtilni frekvenci, značilno razlikovali tako v številu amplitud kakor tudi v stranskih frekvencah. To dokazuje, da je omenjena metoda za diagnosticiranje zobiških gonil primerna oziroma uporabna.

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(Ključne besede: gonila zobiška, poškodbe gonil, diagnoze, signali časov, analize frekvenčne)

In the paper the influence of tooth root notch and its depth on the frequency response of the gear drive by the vibroacoustic method has been treated. Different notch depths were made by the wire erosion and represented a perfect substitute for real cracks. It is well known that cracks occur due to overloads, wrong design of overloads or defects in the base material.

Tests were made for different rotation speeds and torque. Dynamic signals were captured by two microphones and analysed by Fourier transform. A frequency power spectrum was found with significantly varying amplitudes depending on changing notch depth, torque, rotation speed, and also with varying number of side-band frequencies. This fact proves that the above mentioned method is suitable for diagnosing gear drives.

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(Key words: gear drives, gear faults, diagnostics, time-signal, frequency analysis)

0 UVOD

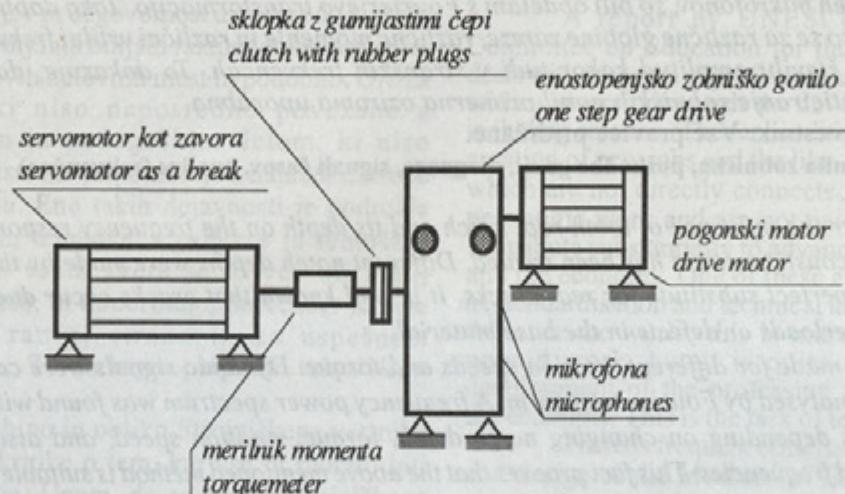
Zobiško gonilo je treba, tako kakor vse druge dele določenega sklopa, redno preverjati, da ne pride do resnejših okvar ali, v najslabšem primeru, do loma zoba, kar pomeni zaustavitev sistema. Morebitne poškodbe zobiškov so vir dodatnih vibracij, ki se prenašajo na preostale elemente sistema. Tako so dodatno obremenjeni tudi drugi elementi zobiškega gonila, kar lahko povzroči poškodbe tudi na njih. Zaradi doseganja proizvodnih norm je pomembno čim bolj nemoten tehnološki proces. Temu primerno je treba razviti obliko vzdrževanja, ki dopušča ugotavljanje stanja sistema med samim obratovanjem [4]. Temeljiti mora na načelu pravočasnega odkrivanja napak že med samim obratovanjem, kar pomeni načrtovanje zamenjave poškodovanega dela že takrat, ko je napaka oziroma poškodba šele na začetku nastajanja. To ne pomeni samo znatnih prihrankov, ampak, kar je mogoče še pomembnejše, redno in zanesljivo obratovanje tehnološkega procesa, pomeni pa tudi, da je treba imeti pravočasno na zalogi elemente, ki jih bomo morali zamenjati.

0 INTRODUCTION

Like all others components of an assembly, the gear drive must be supervised regularly in order to prevent serious damage. The worst case which can take place is a tooth fracture, meaning a complete breakdown. Eventual gear damages are sources of additional vibrations transmitted from one part to another. In this way, all other components of the gear drive are additionally affected and damages can appear on them also. Undisturbed manufacturing is necessary for achievement of the production norms. In order to ensure continuous operation, a maintenance has to be established enabling on line system monitoring [4]. The way it works is in time finding out faults and damages. This means that the planning of the exchange of the damaged part can be taken already at the moment when the damage starts to grow from its initial point. Acting in this way, considerable expenses can be saved, and also the regular and reliable operation of the manufacturing can be ensured. Those parts, which have to be exchanged should be available on time.

1 OPIS MERILNE VERIGE

Postavitev merilne verige s sestavnimi elementi prikazuje slika 1. Enostopenjsko zobjniško gonilo je nameščeno v sredino merilne verige. Na vstopni strani gonila je pogonski motor, na izstopni strani pa je servomotor, uporabljen kot zavora. Moment se meri na izstopni strani z merilno napravo za merjenje momenta. Morebitna osna odstopanja se korigirajo z gumijasto elastično sklopko, ki je nameščena med merilno napravo za moment in izstopno gredjo gonila. S frekvenčno regulacijo pogonskega motorja se dosegajo različni obremenilni pogoji [1].



Sl. 1. Merilna veriga
Fig. 1. Testing rig

2 PRIPRAVA PASTORKA ZA PRESKUŠANJE

Zaradi prevelikih obremenitev, napačne konstrukcije ali napak v materialu lahko pride med obratovanjem v korenu zobjnika do utrujenostne razpoke. Obremenitev zob je usmerjena pravokotno na zobjni bok. Opazovati vpliv globine razpoke na frekvenčni spekter je bil prvi namen preskušanja. Ker je utrujenostno razpoko z natančno globino zelo težko narediti, je bil sprejet kompromis, da se naredi zareza različnih globin v zobjnem korenju z žično erozijo, z debelino žičke $d=0,3\text{ mm}$ [1]. Zareza se od utrujenostne razpoke razlikuje po obliki, debelini, smeri širjenja v notranjost zoba, vendar obe v enaki meri vplivata na spremembo zobjne togosti, ki pa zelo močno vpliva na frekvenčni spekter. Če je zareza globlja, je zob bolj deformljiv, kar ima vpliv na frekvenčno sliko zobjnega para.

Globina zarezov v zobjnem korenju pastorka je bila stopnjevana kakor prikazujeta preglednica 1 in slika 2.

1 SETTING UP THE TESTING RIG

The measurement set up is shown in figure 1. In the middle of the testing rig a one step gear drive is installed. At both sides of the gear drive the motors are situated; at the input side the drive motor is situated and at the output side of the gear drive the servomotor, which is used as a break. The torque is measured on the output shaft by a special torquemeter. For correction of the shaft axes misalignment, a rubber elastic clutch was installed between the torquemeter and the output shaft of the gear drive. To achieve different conditions, the frequency control of the driving motor was used [1].

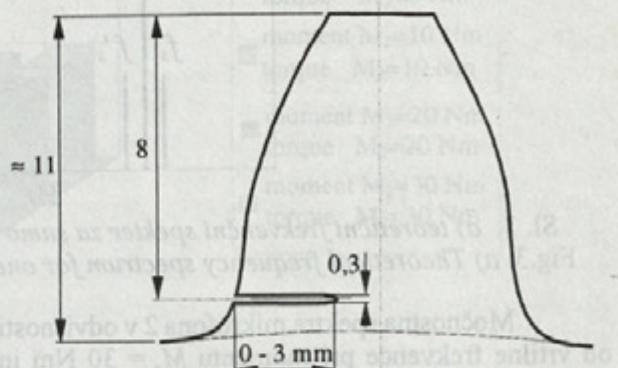
2 PINION PREPARATION FOR TESTS

Owing to overloads, faulty design or material defects, a fatigue crack may appear in the tooth root during system operation. The load on the tooth is oriented perpendicularly to it. The main purpose of the experiment was initially to try to establish the influence of the notch depth. Due to difficulties when producing a fatigue crack with the exact depth in the tooth root, it was decided to make a notch with wire erosion. In order to make the notch as similar as possible to the fatigue crack, a wire with thickness $d=0,3\text{ mm}$ was chosen [1]. The differences between the notch made by wire erosion and the fatigue crack occur in the form, thickness and direction of the crack spreading. It is interesting that both the fatigue crack and the notch have approximately the same influence on the tooth stiffness, which by itself remarkably affects the frequency spectrum. When the notch depth is bigger, than the tooth is more deformable, and this influences the frequency spectrum.

The notch depth in the pinion tooth root was graduated as shown in table 1 and figure 2.

Pregl. 1. Globina zareze v zobnem korenju pastorka
Tab. 1. Notch depth in the tooth root of the pinion

	Globina zareze Notch depth mm
Pastorek št. 1 Pinion No. 1	0
Pastorek št. 2 Pinion No. 2	1
Pastorek št. 3 Pinion No. 3	2
Pastorek št. 4 Pinion No. 4	3



Sl. 2 Globina razpoke v zobnem korenju
Fig. 2. Notch depth in the tooth root

3 OBREMENITVENI KOLEKTIV

Zobniško gonilo je bilo obremenjeno z različnimi obremenilnimi momenti (Nm) pri različnih vrtilnih frekvencah (ms^{-1}). Vrtilna frekvenca na izstopni gredi se je stopnjevala v zaporedju 100, 200, 400, 600 in 800 vrt/min. Zaradi tehničnih omejitev frekvenčnega krmilja je bilo le pri 800 vrt/min mogoče gonilo obremeniti tudi s 60 in 90 Nm, pri preostalih vrtilnih frekvencah je bilo gonilo obremenjeno z 0, 10, 20 in 30 Nm na izstopni gredi [1].

4 ANALIZA GONILA NA PODLAGI STRANSKIH FREKVENC

Karakteristične zobne frekvence in njihove višje harmoniske se preprosto izračunajo po enačbi:

$$f_N = (N+1) \cdot \frac{n_1 \cdot z_1}{60} = (N+1) \cdot \frac{n_2 \cdot z_2}{60} \quad \text{Hz} \quad (1)$$

pri čemer so: f_N – zobna frekvenca, N – 0, 1, 2, 3, ... osnovna frekvenca in višje harmoniske, n_1 – vrtilna frekvenca vstopne gredi (min^{-1}), n_2 – vrtilna frekvenca izstopne gredi (min^{-1}), z_1 – število zob pastorka, z_2 – število zob zobjnika.

Zaradi napak na zobjeh zobjnikov se okrog osnovne zobne frekvence in njenih višjih harmoniskih pojavijo tako imenovane stranske frekvence [3]. Te so lahko bolj ali manj izražene, resnica pa je, več ko ima zobjnik napak po številu ter velikosti, več je stranskih frekvenc in bolj je spekter "kosmat". Več ko je napak, več je teh stranskih frekvenc – zato je tudi površina pod krivuljo močnostnega frekvenčnega spektra večja (sl. 3) [2]. Prav ta površina definira enega izmed kriterijev, po katerem se ocenjuje velikost napak v gonilu [1].

3 LOAD ENSEMBLE

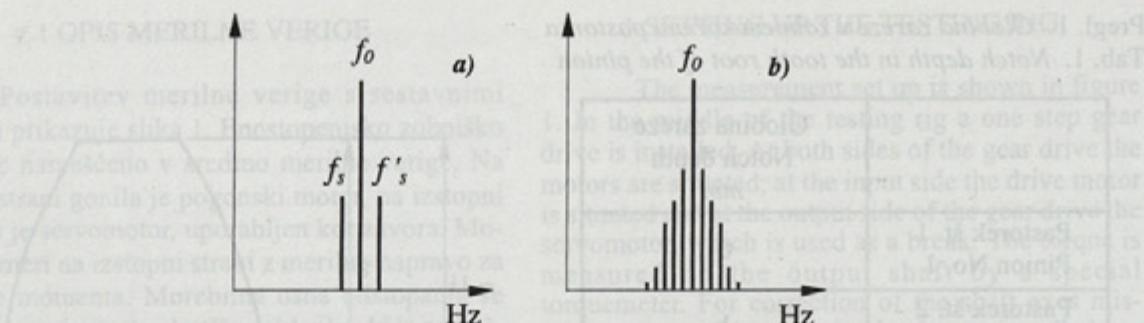
The gear drive was loaded with different torques (Nm) at different rotation speeds (ms^{-1}). The revolutions per minute of the output shaft of the gear drive were graduated in the following sequence: 100, 200, 400, 600, and 800. At 800 rev/min the gear drive was loaded with torques of 60 and 90 Nm, due to the technical limitation of the frequency controller. At other rotation speeds the gear drive was loaded with torques 0, 10, 20 and 30 Nm on the output shaft [1].

4 GEAR DRIVE ANALYSIS ON THE BASE OF THE SIDE-BAND FREQUENCIES

The characteristic tooth frequencies and their higher harmonics can be simply calculated by the equation:

where: f_N – the tooth frequency, N – 0, 1, 2, 3, ... the basic frequency and its higher harmonics, n_1 – the rotation speed of the input shaft (min^{-1}), n_2 – the rotation speed of output shaft (min^{-1}), z_1 – the tooth number on the pinion, z_2 – the tooth number of the driven gear.

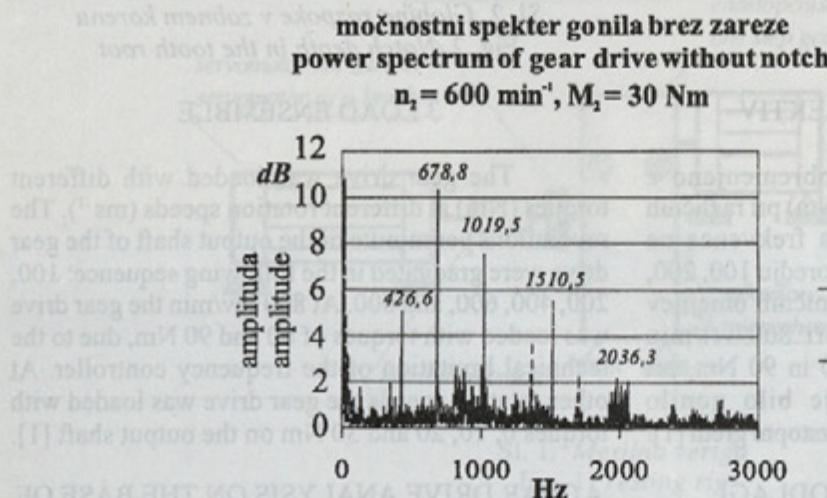
Because of defects on the both gear wheels, the side-band frequencies appear around the base frequency and their higher harmonics [3]. These new frequencies are more or less expressed within the spectrum. The more defects the gear drive has, the more side-band frequencies occur. Following the area under the power frequency increases for each next defect, figure 3 [2]. That is why these kinds of frequencies are so suitable for fault gear drive diagnostics. The area under the spectrum curve becomes a significant criterion for estimating the amount of the gear drive defects [1].



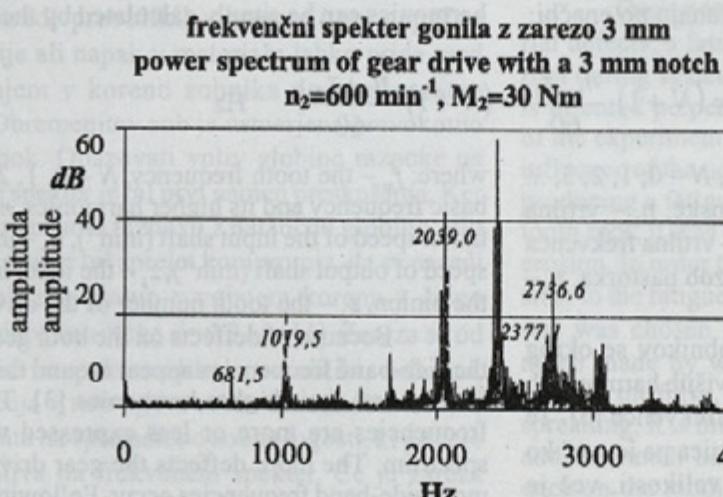
Sl. 3. a) teoretični frekvenčni spekter za samo en poškodovan zob; b) dejanski frekvenčni spekter
Fig. 3. a) Theoretical frequency spectrum for one damaged tooth only; b) Actual frequency spectrum

Močnostna spektra mikrofona 2 v odvisnosti od vrtilne frekvence pri momentu $M_2 = 30 \text{ Nm}$ in dolžini zareze 0 in 3 mm prikazujeta slike 4 in 5:

The power spectra of the microphone 2 in dependence of the rotation frequency at torque $M_2 = 30 \text{ Nm}$ and notch depth 0 in 3 mm are shown in figures 4 and 5:



Sl. 4. Frekvenčni spekter za zarezo 0 mm pri $M_2=30 \text{ Nm}$
Fig. 4. Frequency spectrum for a 0 mm notch at $M_2=30 \text{ Nm}$

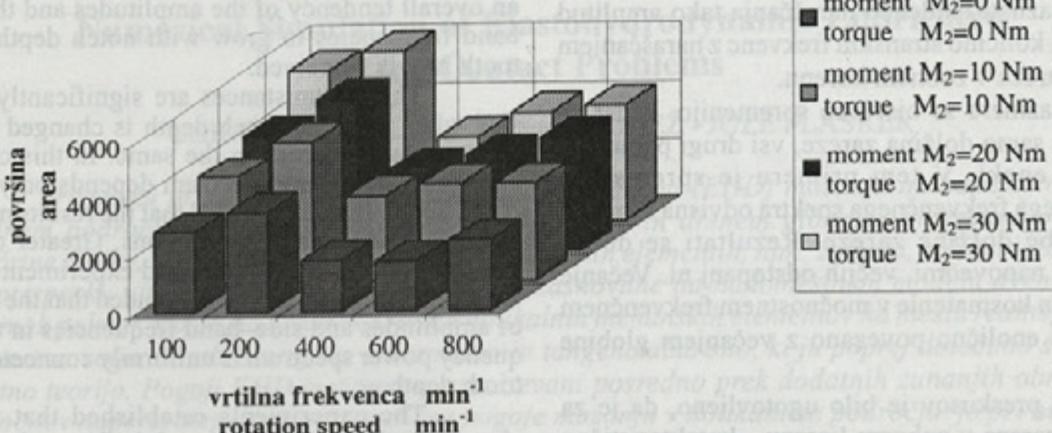


Sl. 5. Frekvenčni spekter za zarezo 3 mm pri $M_2=30 \text{ Nm}$
Fig. 5. Frequency spectrum for a 3 mm notch at $M_2=30 \text{ Nm}$

Nekaj površin pod krivuljami močnostnih spektrov za določeno globino zareze, pri različnih vrtilnih frekvencah prikazujeta slike 6 in 7.

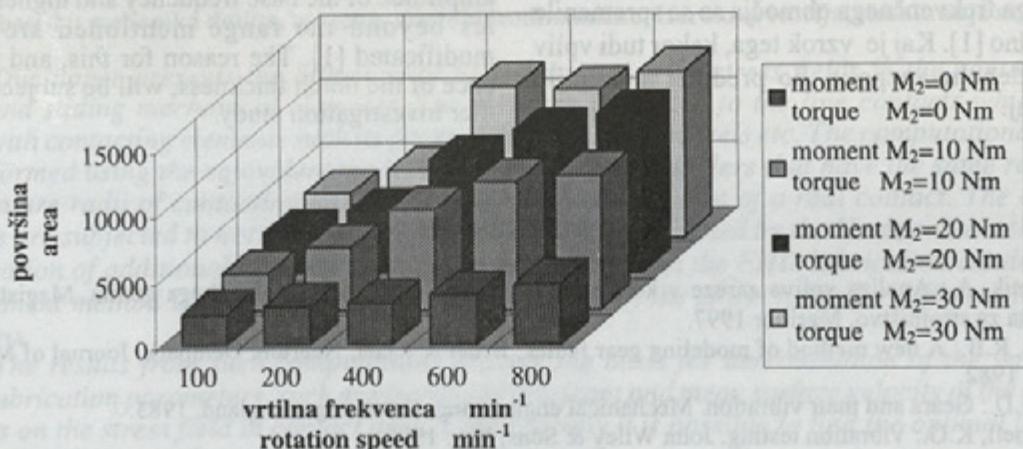
Some areas under the curves of the power spectra for a defined notch depth, at different rotation speeds are shown in figures 6 and 7.

površina pod spektrom za mikrofon 1 pri zarezi 0 mm
area under spectrum curve for microphone 1 for a 0 mm notch



Sl. 6 Površina pod frekvenčnim močnostnim spektrom z globino zareze 0 mm, pri različnih vrtilnih frekvencah n_2
Fig. 6. Area under power frequency spectrum for a 0 mm notch at different rotation speeds n_2

površina pod spektrom za mikrofon 1 pri zarezi 3 mm
area under spectrum curve for microphone 1 for a 3 mm notch



Sl. 7 Površina pod frekvenčnim močnostnim spektrom za globino zareze 3 mm, pri različnih vrtilnih frekvencah n_2
Fig. 7. Area under power frequency spectrum for a 3 mm notch at different rotation speeds n_2

5 SKLEP

Zobne frekvence, osnovna in njene višje harmonike, ostanejo nespremenjeni glede na os x, se pa bistveno spremeni njihove amplitudne, kakor tudi količina stranskih frekvenc, če se spremeni globina zareze.

Nesporno je bilo tudi ugotovljeno, da na rezultate zelo močno vplivata slika nošenja in soosnost gredi [1]. Slika nošenja in soosnost gredi se spremenita v primerih, kadar je treba zobnike v gonilu zamenjati, kar je bil primer pri našem preskusu. Pri ponovnem sestavljanju gonila enakih pogojev skorajda ni mogoče doseči. V primeru, da se ta parametra spremeni, potem mnogo močnejše vplivata na potek močnostnega frekvenčnega spektra kakor samo podaljšanje zareze v zobnem korenju. V tem primeru natančnih napovedi ni mogoče podati.

5 CONCLUSION

The tooth frequencies-the base and its higher harmonics remain unchanged on the x-axis, but their amplitudes significantly change. Also the quantity of the side-band frequencies depends on the notch depth.

It is undoubtedly established that the results are strongly dependent on the contact area of the meshing gear's teeth and shaft misalignment [1]. Both the contact area of the meshing gears teeth and the shaft's misalignment are modified in cases when a gear wheel needs to be substituted with another one. Such a case happened within our experiment. It was impossible to assure identical conditions when the gear drive was taken apart and then reassembled with another gear wheel. In the case when the contact of the area of the meshing gear's teeth and shaft's misalignment significantly change, then these two parameters much more influent the power spectrum in comparison with the notch depths. When such a case occurs, an accurate prediction is impossible. But it

Do določene mere je primerjavo med različnimi dolžinami zareze mogoče narediti, saj je globalno mogoče zaznati tendenco naraščanja tako amplitud kakor tudi količino stranskih frekvenc z naraščanjem globine zareze v zobnem korenju.

Razmere se bistveno spremenijo, kadar se spreminja samo dolžina zareze, vsi drugi parametri ostanejo enaki. V tem primeru je spremembu močnostnega frekvenčnega spektra odvisna samo od spremembe dolžine zareze. Rezultati se dobro ujemajo z napovedmi, večjih odstopanj ni. Večanje amplitud in kosmatenje v močnostnem frekvenčnem spektru je enolično povezano z večanjem globine zareze.

Iz preskusov je bilo ugotovljeno, da je za napako - zareza v zobnem korenju - karakteristično to, da prihaja do največjih povečanj amplitude in stranskih frekvenc v območju med 1500 Hz in 3200 Hz, kamor spadajo nekateri višji harmoniki (sl. 4, 5). Amplituda osnovne frekvence in harmonike zunaj omenjenega frekvenčnega območja so se spremenile le minimalno [1]. Kaj je vzrok tega, kakor tudi vpliv različnih debelin razpoke, bo predmet nadaljnjih raziskovanj.

can be said that comparison between the different notch depths can be made in general, also because of an overall tendency of the amplitudes and the side-band frequencies to grow with notch depth in the tooth root is perceived.

The circumstances are significantly modified when only the notch depth is changed and all other parameters remain the same. In this case the change of frequency spectrum depends only on the notch depth. It must be stated that the results matched very well with earlier predictions. Greater disparities between the predictions and experiment results were not noticed. It can be concluded that the growth of amplitudes and side-band frequencies in the frequency power spectrum is uniformly connected with tooth depth.

The experiments established that for the characteristic effect - the notch in the tooth root the biggest increase of the amplitudes and the side-band frequencies was found in the range between the frequencies 1500 Hz and 3200 Hz. Some higher harmonics appear in this range also (fig. 4 and 5). The amplitude of the base frequency and higher harmonics beyond the range mentioned are slightly modified [1]. The reason for this, and the influence of the notch thickness, will be subject of a further investigation study.

6 LITERATURA 6 REFERENCES

- [1] Globevnik, A.: Analiza vpliva zareze v korenju zoba na frekvenčni odziv zobniškega gonila. Magistrsko delo, Fakulteta za strojništvo, Maribor 1997.
- [2] Randall, R.B.: A new method of modeling gear faults., Brüel & Kjaer, Naerum, Denmark, Journal of Mechanical Design, 1982.
- [3] Smith, J.D.: Gears and their vibration. Mechanical engineering, Cambridge, England, 1983.
- [4] McConnell, K.G.: Vibration testing. John Wiley & Sons, Inc., 1995.

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