

Vibroakustično modeliranje alternatorja

Vibro-Acoustic Modelling of an Alternator

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V prispevku so predstavljeni osnovni prijemi pri izdelavi sklopljenega modela alternatorja za ovrednotenje vibroakustičnega odziva kot posledice različnih vzbujanj alternatorja; vibracij motorja z notranjim zgorevanjem, neuravnoteženosti rotorja ter magnetnih sil. Prikazani sta izdelava in preverjanje strukturnih trirazsežnih (3D) modelov metode končnih elementov (MKE) za osnovne sestavne dele; posamezne povezane sklope in za alternator kot celoto. Preverjanje strukturnih modelov je izvedeno z eksperimentalno modalno analizo (EMA), ki je obenem namenjena za ovrednotenje dušenja ter posodobitev strukturnega modela alternatorja. Natančneje je opisan poseben primer izračuna vibroakustičnega odziva kot posledice vzbujanja magnetnih sil. Pri tem je bil za ovrednotenje magnetnih sil izdelan trirazsežni model MKE za magnetno polje, tako da je omogočal harmonsko analizo magnetnih sil in njihov neposreden prenos v strukturni model MKE alternatorja. Na podlagi poznanega vzbujanja alternatorja, tj. magnetnih sil v določenih obratovalnih razmerah, je bil ovrednoten in analiziran strukturni in akustični odziv alternatorja.
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(Ključne besede: alternatorji, vibracije, metode končnih elementov, metode robnih elementov, analize modalne)

In this paper we present the basic approaches to building a sequentially coupled model of an alternator to evaluate the vibro-acoustic response resulting from different excitations, such as engine vibration, rotor unbalance and magnetic forces. Special emphasis is given to the set-up and verification of the three-dimensional (3D) structural finite-element (FE) model for the whole alternator and for the alternator components. The verification of the structural model was carried out using experimental modal analysis (EMA), which was also applied for the estimation of the modal damping and for the structural FE model updating. Special emphasis is given to the evaluation of magnetic noise, generated due to the magnetic force excitation in the alternator. To estimate the magnetic forces and their harmonic components a 3D magnetic FE model of the alternator was prepared. Finally, the exciting magnetic forces, calculated for the specific operation conditions of the alternator, were transferred into a structural FE model, where the structural and acoustic responses were calculated and analysed.

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(Keywords: alternators, vibrations, finite element methods, boundary element methods, modal analysis)

0 UVOD

Osnovni cilj izdelave sklopljenega numeričnega modela alternatorja za ovrednotenje vibroakustičnega odziva sta optimizacija in razvoj novih konstrukcij alternatorjev z notranjim ventilatorjem, ki naj po tehničnih značilnostih dosegajo ali celo presežajo primerljive konkurenčne izdelke. Slednje pomeni, da pri alternatorju dosežemo zadovoljiv odvod toplote oz. povečamo izkoristek pri majhni stopnji

0 INTRODUCTION

The optimisation of an alternator with an internal ventilator was the major driving force for setting up a coupled numerical model of the alternator intended to evaluate its vibro-acoustic response. Additionally, this model will be used in the development process of new designs of alternators, helping to improve their technical characteristics and make them comparable or even better than their competitors. In the case of the alternator,

aerodinamičnega hrupa ventilatorja ter pri tem ne ogrozimo dobe trajanja alternatorja ali povečamo njegovega vibracijskega in akustičnega odziva. Enako pomembna je optimizacija konstrukcije alternatorja z vidika magnetike, ki prav tako omogoča izboljšanje izkoristka ter zmanjšanje magnetnega hrupa alternatorja, povzročena z magnetnimi silami, ki vzbujajo strukturo alternatorja.

Pri doseganju omenjenega cilja se srečujemo z izključujočimi se zahtevami in omejitvami, ki iskanje optimalne rešitve zelo otežujejo. Pri iskanju takih rešitev so v veliko pomoč računalniška tehnologija in numerične metode. Predvsem razmah računalniške tehnologije v zadnjem času je omogočil, da se zahtevni večdisciplinarni problemi, npr. nastajanje hrupa, v doglednem času rešijo z numeričnimi simulacijami. Bistvena prednost, ki jo omogočajo numerične simulacije, je možnost uporabe optimizacije, kar zmanjša število prototipov in posledično količino eksperimentalnega dela. Skupno se to kaže v krajšem razvojnem času in večji kakovosti izdelka.

improvements could be achieved with better heat transfer, which corresponds to higher efficiency, where the aerodynamic noise of the ventilators needs to be kept under control. Besides this, the alternator's durability should not be threatened by either an increase in the alternator's vibration and/or acoustic response. Optimising the design of the alternator from the thermal and structural dynamic points of view is not enough.

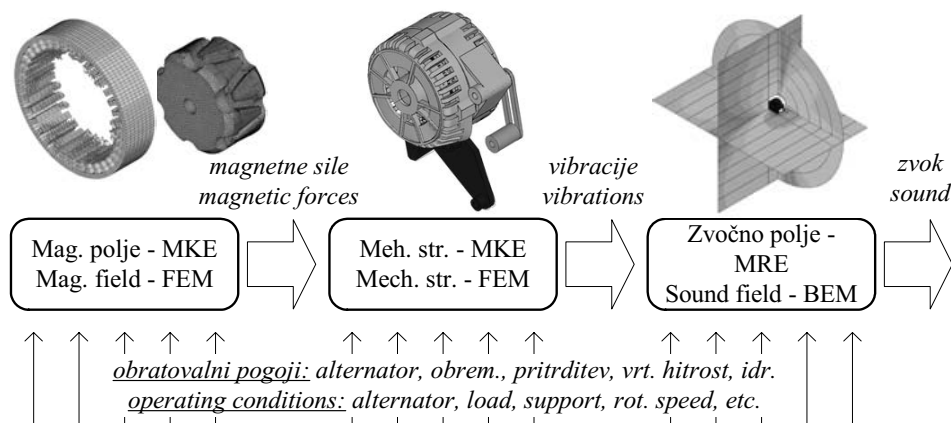
When achieving the above-mentioned goal one can meet many limitations and contradictory demands that make the search for the optimum design of the alternator very difficult. At this point numerical simulations can be applied as a very effective tool to help the engineer. The recent development of computer technology and numerical methods have also made it possible to simulate very demanding multidisciplinary problems such as the generation of the magnetic noise in a reasonable time. The major advantage of the computer technology and numerical methods is the possibility to make the optimisation and the evaluation in a virtual environment. This significantly decreases the number of prototypes and the quantity of the experimental work and finally shortens the development time and increases the quality of the product.

1 SKLOPLJENI VIBROAKUSTIČNI MODEL ALTERNATORJA

V splošnem vibroakustični model alternatorja združuje tri fizikalne probleme, tj. magnetni, strukturalni in akustični problem, in njim pripadajoče modele, ki jih lahko predstavimo kot celovit – zaporedno

1 A COUPLED VIBRO-ACOUSTIC MODEL OF THE ALTERNATOR

In general, the vibro-acoustic model of the alternator unites three physical problems, i.e., the magnetic, the structural dynamic and the acoustic. With regard to the physical nature of the alternator,



Sl. 1. Zaporedno povezani magnetni, strukturalni in akustični problem alternatorja
 Fig. 1. The sequentially coupled magnetic, structural dynamic and acoustic problem of the alternator



Sl. 2. *Obravnavani alternator*
 Fig. 2. *The investigated alternator*

sklopljeni problem. Značilnost takega problema je, da ga lahko obravnavamo v treh ločenih zaporednih korakih (sl. 1).

Da bi potrdili verodostojnost tako postavljenega modela, je potrebno preverjanje na dejanskih modelih. Zaradi omenjenega smo se pri gradnji sklopljenega modela alternatorja odločili, da ga izvedemo za že obstoječi alternator (sl. 2).

Z uporabo MKE za magnetno polje izračunamo velikosti in porazdelitev magnetnih sil, ki delujejo na zunanje površine rotorja in statorja alternatorja. Ker vrtenje rotorja vpliva na spreminjanje gostote magnetnega pretoka v zračni reži alternatorja, ima to za posledico periodičen značaj magnetnih sil.

Da bi tako zahteven model magnetnega polja lahko rešili, smo predpostavili, da je porazdelitev magnetnih sil neodvisna od same obremenitve alternatorja. To pomeni, da v magnetni model nismo vnesli statorskih tokov, ampak le nespremenljiv rotorski tok, ki pomeni magnetno vzbujanje alternatorja. Porazdelitev magnetnih sil smo izračunali z magnetostatičnim modelom za različne medsebojne lege rotorja in statorja. Tako dobimo potek spreminjanja magnetnih sil pri vrtenju rotorja alternatorja, na katerem izvedemo harmonsko razdružitev.

Rezultate spremenljivih magnetnih sil pri vrtenju rotorja, izračunanih z MKE za magnetno polje, smo uporabili kot vzbujevalne sile v strukturnem modelu po MKE. Temeljna naloga pri določitvi strukturnega odziva sta bili gradnja in ovrednotenje strukturnega modela po MKE. Strukturni model po MKE smo preverili z eksperimentalno modalno analizo (EMA), ki smo jo izvedli za različne sklope in

each problem can be treated independently, and then they can all be linked into one sequentially coupled problem, Figure 1.

To validate the presented model of the alternator it is necessary to verify it with real cases. For this reason we decided to set-up the vibro-acoustic model for the existing alternator, Figure 2.

The magnetic forces and their distribution, acting on the exterior surfaces of the rotor and stators, are calculated using the finite-element method (FEM) for the magnetic field. In this case it is assumed that a consequence of the stationary rotation of the rotor is a periodic varying of the magnetic forces caused by changes of the magnetic flux densities in the air gap of the alternator.

To simplify the solution of the magnetic problem of the alternator it was necessary to make a few assumptions. The major one relates to the stator excitation. Here we assumed that the distribution of the magnetic forces is load independent. By assuming this, we avoid having to take into account the stator currents, so the rotor current was considered as the only magnetic excitation in the magnetic model. The distribution of the magnetic forces was calculated using a magneto-static model for different rotor positions which describes the changing of the magnetic forces during the rotation and finally allows a calculation of their harmonic components.

The results of the changing magnetic forces during the rotor rotation, calculated using FEM for the magnetic field, are used as the excitation forces in the structural FEM model. The basic job in the process of the evaluation of the structural dynamic response is to build and to verify the structural FEM model. The verification of the structural FEM model was done using experimental modal analysis (EMA)

podsklope alternatorja ter za alternator v celoti. Ovrednotenje strukturnega odziva modela po MKE alternatorja na vzbujanje z magnetnimi silami smo obravnavali kot problem harmonskega vzbujanja, pri čemer je vzbujanje podano s harmonskimi komponentami magnetnih sil.

Zadnji korak v postopku vibroakustičnega modeliranja alternatorja obravnava zvočno polje kot posledico strukturnega odziva. Zvočno polje, ki je rešitev Helmholtzove valovne enačbe, smo obravnavali z metodo robnih elementov (MRE). Glede na numerično zahtevnost omenjenega problema [1] smo numerične simulacije izvedli le za omejeno število diskretnih vrednosti valovnih števil oz. frekvenc. Pri tem smo se omejili na frekvence z največjim prispevkom k magnetnemu hrupu oz. na frekvence prvih nekaj harmonskih komponent, ki nastanejo zaradi harmonske razdružitve magnetnih sil.

2 MAGNETNE SILE V ALTERNATORJU

Ovrednotenje magnetnih sil v alternatorju smo izvedli z uporabo MKE. Zaradi oblike rotorja oz. rotorskih krempljastih polov smo morali ovrednotenje sil izvesti na trirazsežnem modelu, saj je omenjeno geometrijsko lastnost neposredno nemogoče opisati z dvorazsežnim modelom. Glede na simetrično obliko rotorja, ki ima 6 polovih parov, smo zgradili model, ki obsega le eno šestino celotnega alternatorja (sl. 3).

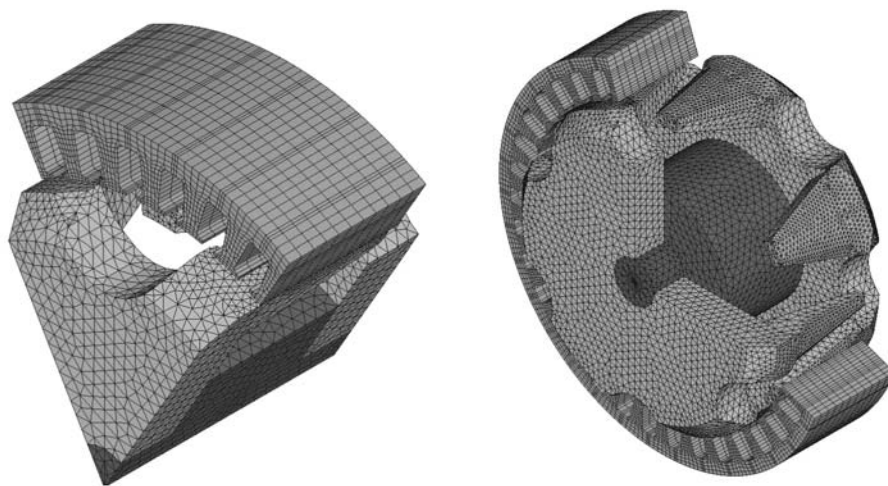
on every single part of the alternator and its substructures as well as on the whole structure of the alternator. The evaluation of the structural response of the alternator FEM model, as a consequence of the magnetic force excitation, is considered as a harmonic problem.

The last step in the process of the vibro-acoustic modelling of the alternator deals with the sound field as a result of the structural response, i.e., vibrations on the alternator structure. The sound field, governing by the Helmholtz wave equation, is evaluated by the boundary-element method (BEM). Due to the numerical extensiveness of the mentioned problem [1], we limited the simulations of the sound field to only a few wave numbers or discrete frequencies. Only the frequencies with a significant contribution to the magnetic noise or a few first harmonics of the magnetic forces are taken into account for the sound-field calculation.

2 MAGNETIC FORCES IN THE ALTERNATOR

The evaluation of the magnetic forces was carried out using the FEM. Because of the claw pole shape of the rotor it was necessary to build up a three-dimensional (3D) FEM model for the magnetic field. For that reason a two-dimensional FEM model cannot be used. As a result of the cyclic symmetry of the rotor with six pole pairs, only one sixth of the complete alternator was modelled, Figure 3.

Taking into account the cyclic symmetry of



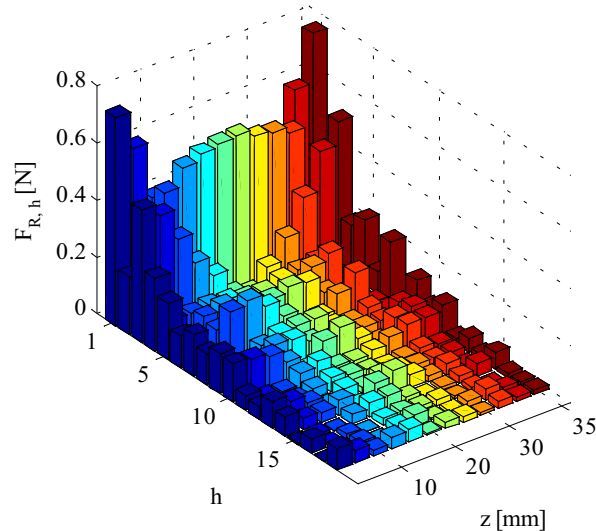
Sl. 3. Pogled v trirazsežni model po MKE alternatorja za magnetno polje (levo) in celoten alternator (desno)
Fig. 3. The 3D FEM magnetic model of the alternator (left) and the complete alternator (right)

Zaradi simetrije alternatorja smo vrtenje izvedli za 60° v enakomerno razporejenih korakih. Pri izbiri velikosti koraka smo se odločili na podlagi potrebe po razločevanju harmonskih komponent, ki nastanejo pri razvoju magnetnih sil v Fourierjevo vrsto. Glede na predhodne izkušnje in poznavanje karakterja magnetnega hrupa ([1], [5] in [6]), pri katerem se vpliv višjih harmonskih komponent zmanjšuje in njihove frekvence segajo v frekvenčna področja, ki so glede vibroakustičnega odziva manj zanimiva, smo za ovrednotenje izbrali le prvih 12 harmonskih komponent. Iz omenjenega izhaja, da je treba izpeljati izračun magnetnih sil za vsaj 24 korakov, da izpolnimo Nyquistov pogoj. V našem primeru so bili izračuni sil izvedeni za vrtenje v 60 korakih po 1° . To omogoča, da ovrednotimo tudi višje harmonske komponente, kar pripomore k natančnejšemu ovrednotenju magnetnih sil. Slika 4 prikazuje harmonsko analizo za magnetne sile, ki delujejo v vzdolžnih vzdolž sredine statorskega zoba.

Poleg vpliva vrtenja na magnetne sile je bilo treba ovrednotiti tudi vpliv razmer pri obratovanju. Zaradi zahtevnosti smo se na tem mestu omejili na obratovanje neobremenjenega alternatorja, ko ni statorskega vzbujanja. Glede na naravo delovanja obravnavanega alternatorja smo razmere obratovanja opredelili s tokom v rotorskem navitju. Tako smo ovrednotenje magnetnih sil pri vrtenju rotorja izvedli za različne rotorske tokove. Pri izbiri velikosti tokov smo izhajali iz poznavanja obratovalnih razmer alternatorja in upoštevali dejstvo, da se v običajnih razmerah vrednosti tokov gibljejo med 2A in 4,2A.

the rotor, the magnetic forces calculation was performed in evenly distributed steps in a rotation over 60 degrees. The step size was chosen on the basis of distinguishing the harmonic components that arise from the discrete Fourier transform. Based on previous practice and expertise in the modelling of electric machine noise ([1], [5] and [6]), where the influence of higher harmonics decrease and their frequencies range out of vibro-acoustic interest, for the evaluation of magnetic forces only the first 12 harmonics were chosen. From those facts it follows that at least 24 steps must be executed to fulfil the Nyquist criterion. In our case the magnetic forces calculations during the rotation was performed in steps of 1 degree. This enables us to evaluate the higher harmonics that contribute to a precise presentation of the magnetic forces. Figure 4 shows the harmonic decomposition of the magnetic forces acting on nodes along the centre of the stator tooth.

Besides the influence of rotation on the magnetic forces, the evaluation of the operating conditions of the alternator is also important. For the sake of simplicity we have studied only the unloaded alternator so there is no magnetic excitation on the stator side. Regarding the physical nature of the alternator, the operating conditions were defined with current in the rotor winding. Finally, the magnetic forces calculation was performed for different rotor currents. Knowing that under normal operating conditions the rotor current is generally between 2A and 4.2A, the appropriate rotor current was determined.



Sl. 4. Harmonске komponente magnetnih sil vzdolž statorskega zoba

Fig. 4. Harmonic components of the magnetic forces along the centre of stator tooth

Prenos magnetnih sil iz modela po MKE za magnetiko v strukturni model po MKE je lahko zelo zahteven predvsem zaradi različnih postopkov reševanja magnetnega problema na eni in strukturnega problema na drugi strani. Različne zahteve po diskretizaciji pri obravnavi magnetike na eni strani in mehanske strukture na drugi strani onemogočajo uporabo enotne diskretizacije trirazsežnega modela po MKE za reševanje sklopljenega magnetomehanskega problema. Gostota mreže trirazsežnega modela po MKE, ki jo zahteva obravnavna problema magnetike, je namreč preveliko breme pri reševanju strukturnega problema. Nasprotno lahko rečemo, da je diskretizacija strukturnega modela neprimerna ali celo neuporabna za reševanje magnetike.

Glede na značaj magnetnih sil, predvsem v smislu krajevne in časovne porazdelitve na površini statorja in krempljastih polov rotorja, je njihov učinek nemogoče v celoti nadomestiti z rezultirajočimi silami in momenti ([1], [5] in [6]). Slednje smo predpostavili le za učinek magnetnih sil, ki delujejo na krempljaste pole rotorja in so znotraj zelo toge strukture krempljastih polov zaradi simetrije vedno v ravnotežju. Nasprotno je za resničen prenos magnetnih sil, ki vzbujajo "elastičen" stator, potrebno ohraniti njihov krajevni značaj. Časovni značaj magnetnih sil pa je opredeljen s harmonskimi komponentami.

3 STRUKTURNI ODZIV ALTERNATORJA

V drugi fazi vibroakustičnega modeliranja alternatorja je treba določiti strukturni odziv kot posledico vzbujanja alternatorja, tj. vibracij motorja z notranjim zgorevanjem, neuravnoveženosti rotorja ali magnetnih sil. Predstavljena je gradnja strukturnega modela po MKE, čemur je namenjen največji poudarek. Opisano je preverjanje modela ter končno ovrednotenje strukturnega odziva, pri čemer smo se omejili le na odziv kot posledico vzbujanja magnetnih sil. Z najmanjšimi dopolnitvami strukturnega modela je mogoče priti tudi do odziva kot posledice vibracij motorja z notranjim zgorevanjem ali neuravnoveženosti rotorja.

Pri ovrednotenju strukturnega odziva se omejimo na ustaljeno delovanje alternatorja. Magnetne sile, ki v takem načinu obratovanja vzbujajo strukturo alternatorja, imajo periodičen značaj. Ob predpostavki, da je mehanska struktura linearen sistem z majhnim dušenjem, lahko obravnavani problem prevedemo na problem

The transfer of magnetic forces from the magnetic FEM model to the structural FEM model can be very difficult to carry out because of there being one way to solve the magnetic model and another way to solve the structural model. A dissimilar requirement for the mesh density of the magnetic and structural problems is the reason why the same mesh cannot be used for the 3D FEM coupled magneto-structural problem. The mesh density required in the 3D FEM magnetic problem is too dense for solving 3D FEM structural problem. Put another way, the mesh density of the 3D FEM structural problem is too coarse to be used in the 3D FEM magnetic problem.

Observing the character of the magnetic forces in terms of time and space distribution over the surface of the stator and the rotor claw pole it is impossible to entirely substitute their effect with the resulting magnetic forces and moments ([1], [5] and [6]). The latter is assumed for the affect of the magnetic forces acting on the rotor claw poles, which are a very rigid structure, and because of their symmetry the magnetic forces are always in counterbalance. In contrast to the credible transfer of magnetic forces, which excite the "elastic" stator, the preservation of their space distribution is required. Meanwhile, their time distribution is characterized with harmonic components.

3 STRUCTURAL RESPONSE OF THE ALTERNATOR

In the second phase of the vibro-acoustic modelling of the alternator it is necessary to determine its structural response as a consequence of the excitation of the alternator, i.e., vibrations due to the operation of an internal combustion engine, rotor unbalance or magnetic forces. Great stress is laid on building a structural FEM model, which is introduced here. The model checking and the final verification of the structural response are described with the assumption that only the response as a consequence of the magnetic forces excitation was taken into account. With a minimum of modal updating it would also be possible to describe the response due to vibrations of an internal combustion engine and rotor unbalance.

The steady state operation of the alternator was assumed during the verification of the structural response. The magnetic forces, which excite the structure, are in this case periodic. Taking into consideration the mechanical structure as a low-damped linear system, our problem can be

vsiljenega nihanja za celoten spekter harmonskih komponent magnetnih vzbujevalnih sil. Nazadnje iz znanega odziva posameznih harmonskih komponent obnovimo celotni strukturni odziv.

V našem primeru smo za ovrednotenje strukturnega odziva na izbranem alternatorju uporabili MKE. Prvotno je bilo treba strukturni model po MKE zgraditi ter preveriti njegovo skladnost na dejanski izvedbi. Gradnje strukturnega modela smo se lotili korakoma. Strukturo alternatorja smo obravnavali po delih, ki smo jih na koncu združili v celoto. Za vsak posamezni del alternatorja smo izdelali model po MKE in ga tudi preverili. Sklepno dejanje pri gradnji strukturnega modela po MKE je bilo povezovanje posameznih delov v celoto. Za potrebe ovrednotenja smo izvedli različne meritve strukturnega odziva, tako posameznih delov kakor celotnega alternatorja, pri čemer smo uporabili eksperimentalno modalno analizo (EMA). To je poleg ovrednotenja strukturnega modela po MKE omogočilo tudi ovrednotenje dušenja za posamezne sklope alternatorja.

3.1 Gradnja strukturnega modela alternatorja

Glede na zapletenost strukture obravnavanega alternatorja smo strukturni model po MKE gradili postopoma. Pri tem smo izhajali iz razdelitve obravnavanega alternatorja, ki se ponuja sama po sebi. Celotno strukturo smo razdelili v štiri sklope: *prednji ležajni pokrov (PLP)*, *zadnji ležajni pokrov (ZLP)*, *stator* in *rotor* (sl. 5). Ker je že vsak sklop sam po sebi dovolj zahteven, je bilo treba tudi pri gradnji strukturnega modela po MKE posamezni sklop graditi v več korakih, kolikor je pač konstrukcija to dopuščala. Tako smo pri gradnji strukturnega modela MKE za posamezen sklop izhajali iz osnovnih podsestavov, ki jih lahko z MKE preprosto modeliramo in v nadaljevanju s preizkusi preverimo. Postopoma smo model sklopa dopolnjevali in ga sproti večkrat preverili. Lahko rečemo, da smo pri gradnji strukturnega modela in njegovih sklopov sledili tehnološkemu postopku izdelave alternatorja. Tak postopek je zahteval veliko število prototipov in preizkusnega dela.

Sklepno dejanje v izgradnji strukturnega modela po MKE obravnavanega alternatorja je povezava predhodno izdelanih sklopov v celoto. Zato da bi lahko čimbolj prepričljivo izvedli mehanske povezave v strukturnem modelu po MKE, moramo spoje dobro poznati. Glede na naravo spojev oz. mehanskih povezav, ki se pojavljajo med PLP, ZLP, statorjem in rotorjem, smo delali s tremi različnimi

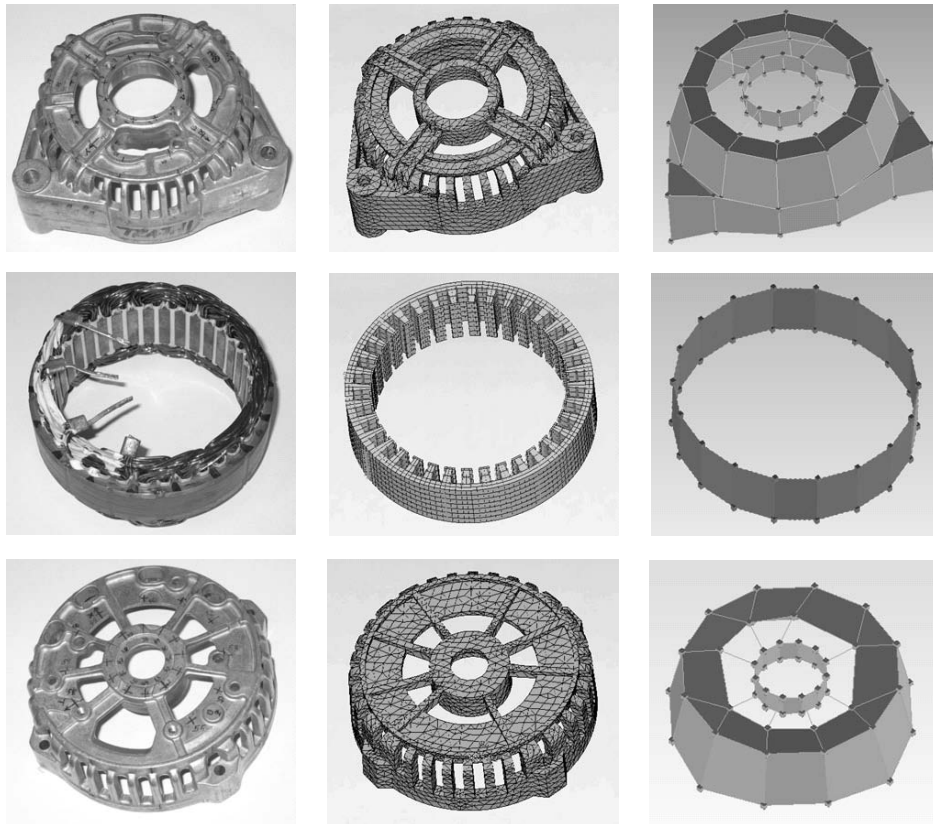
transformirano v prisiljeno vibracijo problem za celoten spekter vzbujevalnih sil, magnetnih sil. Nazadnje iz znanega odziva posameznih harmonskih komponent obnovimo celotni strukturni odziv.

Za ovrednotenje strukturnega odziva na izbranem alternatorju uporabili MKE. Prvotno je bilo treba strukturni model po MKE zgraditi ter preveriti njegovo skladnost na dejanski izvedbi. Gradnje strukturnega modela smo se lotili korakoma. Strukturo alternatorja smo obravnavali po delih, ki smo jih na koncu združili v celoto. Za vsak posamezni del alternatorja smo izdelali model po MKE in ga tudi preverili. Sklepno dejanje pri gradnji strukturnega modela po MKE je bilo povezovanje posameznih delov v celoto. Za potrebe ovrednotenja smo izvedli različne meritve strukturnega odziva, tako posameznih delov kakor celotnega alternatorja, pri čemer smo uporabili eksperimentalno modalno analizo (EMA). To je poleg ovrednotenja strukturnega modela po MKE omogočilo tudi ovrednotenje dušenja za posamezne sklope alternatorja.

3.1 Structural model of the alternator

With regard to the complexity of the alternator's structure the structural FEM model was built up gradually. In this case we used alternator subpart definitions as they are defined in production, so the structure was divided into four basic subparts: the drive-end bracket (DEB), the rear-end bracket (REB), the stator and the rotor (Figure 5). Due to the great complexity of the subpart FEM models, some of them had to be built gradually, as the design so allowed. In this way we proceeded from the construction of very basic element FEM models, the characteristics of which were then experimentally verified. The main FEM model was progressively built and experimentally verified at every coupling step. We can say that we followed the technological production process during the building up of the FEM model of the alternator. This kind of process required many different prototypes and types of experimental work.

The final action in the structural FEM model construction of the investigated alternator is the coupling of the previously made subassemblies into an integrity. To design the structural FEM model connections as realistically as possible, we should know them very well. Regarding the nature of the connection that occurs between the DEB, the REB, the stator and the rotor, we applied three different



Sl. 5. Sklopi alternatorja: PLP (zgornja vrsta), stator (srednja vrsta) in ZLP (spodnja vrsta) ter njim pripadajoča dejanska struktura (stolpec levo), strukturni model po MKE (stolpec sredina) in model EMA (stolpec desno)

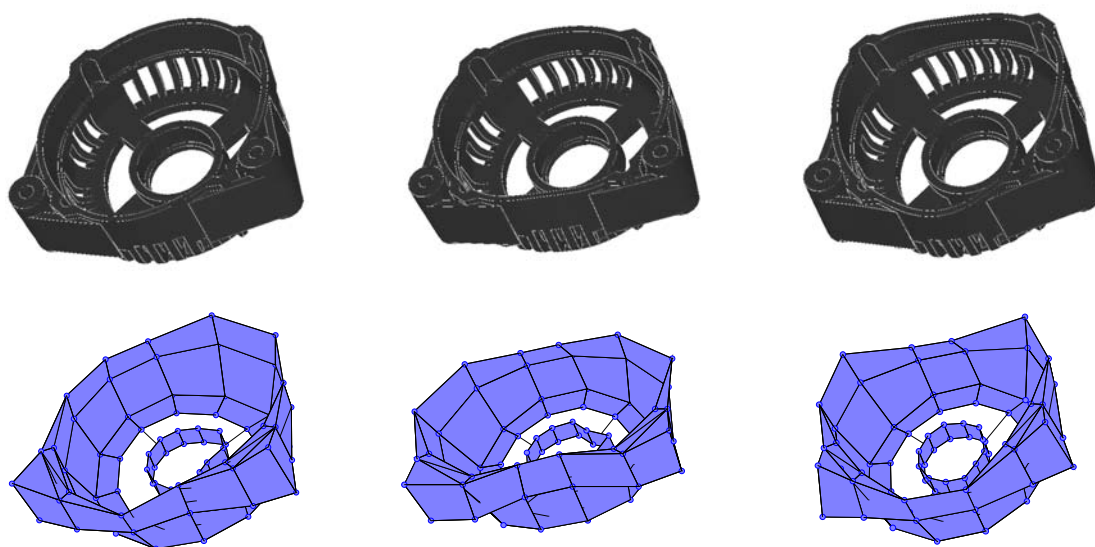
Fig. 5. Alternator subparts; drive-end bracket (upper row), stator (middle row) and rear-end bracket (lower row); and belonging real structure (left column), structural FEM model (middle column) and EMA model (right column)

mehanskimi povezavami. Najprej smo opredelili povezavo, ki jo predstavljata ležaja in se pojavlja v stiku med rotorjem in PLP ter ZLP. V našem primeru smo togosti ležajev izračunali ([1] in [2]) ter njune lastnosti uporabili v strukturnem modelu po MKE. Drugo obliko mehanske povezave, ki povezuje PLP, ZLP in stator, ter daje alternatorju značaj celote, predstavljajo štiri vijajčne zveze. Glede na to, da obravnavani spoj združuje okrov in prednji pokrov s silo in obliko, smo ga v strukturnem modelu po MKE izvedli z združitvijo vseh prostostnih stopenj v vozliščih, ki se pojavljajo na mestu vijajčne zveze. Tretja oblika mehanske povezave je stik, ki nastaja pri naleganju med statorjem in PLP ter ZLP. Ker smo se odločili, da mehansko strukturo opišemo z linearnim modelom, stika nismo mogli modelirati v pravem pomenu. Zato da smo ohranili linearnost strukturnega modela po MKE, smo ga modelirali tako, da smo spojili pomike na stičnih površinah.

mechanical connections. First of all we defined the connection between the rotor and both end brackets – the DEB and the REB. In our case we calculated the stiffness matrix of the bearings ([1] and [2]) and used them in the structural FEM model. The next type of coupling was used to connect the alternator as an integrity and represents four screws between the DEB and the REB. Taking into account that the mentioned connections couple subparts with shape and force, we modelled them by coupling all the degrees of freedom (DOFs) of the nodes situated in the proximity of the screw joint. A third different kind of connections was used to model the contact conditions between the stator and the DEB or REB. As we have decided to describe the mechanical structure with a linear model, we did not have the option to model the contact conditions as they should be. To ensure the structural FEM model's linearity, we used just connections that couple the nodal DOFs on the contact surfaces.

Ovrednotenje strukturnega modela po MKE smo izvajali na podlagi primerjave modalnih parametrov (lastnih frekvenc in vektorjev). Kot dodatna kriterija smo uporabili kriterij modalnega zaupanja (KMZ - MAC) ter vidno primerjavo modalnih oblik, ki nam jo omogoča EMA. Nenazadnje tudi masa strukturnega modela po MKE govori o resničnosti, zato smo jo vseskozi primerjali z maso dejanske strukture. Če so izpolnjeni vsi navedeni kriteriji, imamo zagotovilo, da model dobro opisuje masne in togostne lastnosti dejanske strukture. Vprašanje dušenja smo rešili tako, da smo v modelu po MKE uporabili nespremenljivi razmernik strukturnega dušenja en odstotek. Ker vemo, da ima gostota diskretizacije strukturnega modela po MKE vpliv na natančnost izračuna, smo njen vpliv omejili takole. Vsaka podvojitev števila elementov v modelu, bodisi celotnega alternatorja, sklopa ali podsestava, vodi do razlik v izračunanih vrednostih lastnih frekvenc v območju do 4 kHz, ki pa so manjše od enega odstotka. V nadaljevanju je kot primer prikazano ovrednotenje strukturnega modela po MKE za PLP (pregl. 1 in sl. 6) ter za celotni strukturni model alternatorja (pregl. 2 in sl. 7).

The validation of the structural FEM model was done by comparing the modal parameters to real subparts (natural frequencies and mode shapes). As additional criteria, we used the modal assurance criterion (MAC) and a visual comparison of the modal shapes, which was done by using means of the EMA. As a frequently used comparison criterion during model validation, we must also mention the mass of the structural FEM model. If we fulfil all the mentioned criteria we can be sure that our model properly describes the mass and stiffness properties of the real structure. The issue of damping the structural FEM model was solved by using a 1% constant-damping ratio. As we know, the FEM model mesh density has an influence on the accuracy of the calculation. It turns out that every doubling of the elements, irrespective of whether this is performed on just one subpart or on the whole alternator, leads to differences between the natural frequencies and the measured ones. This discrepancy is less than 1% in the range 0–4 kHz. The structural FEM model of the DEB (Figure 6, Table 1) and the whole alternator (Figure 7, Table 2) are shown as examples.

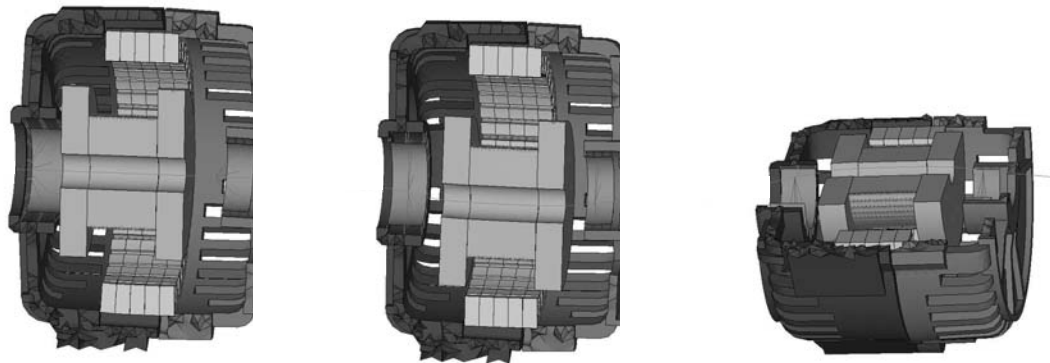


Sl. 6. Primerjava lastnih oblik PLP, strukturni model po MKE (zgoraj), model EMA (spodaj); prva (na levi), druga (na sredini) in tretja (na desni)
 Fig. 6. Comparison of the DEB mode shapes, the structural FEM model (above), the EMA model (below); first mode shape (left), second (middle), third (right)

Preglednica 1. Izračunane in izmerjene lastne frekvence za PLP
 Table 1. Calculated and measured natural frequencies of DBE

MKE		EMA			Δ_f
n	f [Hz]	n	f [Hz]	δ [%]	[%]
1	913	1	969	0,06	-5,8
2	1367	2	1457	0,04	-6,2
3	2547	3	2742	0,37	-7,1
4	2760	4	3062	0,17	-9,9
5	3107	5	3348	0,06	-7,2
6	3252	6	3693	0,07	-11,9
7	4062	7	3922	0,10	3,6

m_{MKE} [kg]	m_{EMA} [kg]	Δ_m [%]
0,829	0,844	-1,8



Sl. 7. Oblike strukturnega modela po MKE alternatorja; prva (levo), druga (sredina) in tretja (desno)
 Fig. 7. Alternator structural FEM model mode shapes; first mode shape (left), second (middle), third (right)

Preglednica 2. Izračunane in izmerjene lastne frekvence za alternator kot celoto
 Table 2. Calculated and measured natural frequencies of the alternator

MKE		EMA			Δ_f
n	f [Hz]	n	f [Hz]	δ [%]	[%]
1	412	1	587	2,02	-29,8
2	889	2	908	0,44	-2,1
3	900	3	951	0,69	-5,4
4	1726	4	1272	1,29	35,7

3.2 Prenos magnetnih sil v strukturni model ter odziv

V nadaljevanju je opisano ovrednotenje strukturnega odziva alternatorja na podlagi predhodno zgrajenega strukturnega modela po MKE, pri čemer je alternator vpet na motor z notranjim zgorevanjem. Pri določitvi narave vzbujevalnih sil smo izhajali iz rezultatov, dobljenih pri ovrednotenju magnetnih sil z MKE. Zato da bi lahko izvedli

3.2 Transfer of magnetic forces to a structural model and to the response

Work proceeds with the evaluation of the structural response of the alternator based on the previously built structural FEM model, while the alternator is mounted on the internal combustion engine. The nature of the excitation forces was determined from the results of the magnetic forces verification using the FEM. In order to compare measured and calculated data, the

primerjavo med meritvami in izračunom, je bilo treba določiti jakost magnetnih sil in njihovo osnovno frekvenco vzbujanja. Pri tem smo se oprli na izmerjene vrednosti toka, ki so določale moč magnetnih sil, ter na izmerjene vrednosti vrtilnih frekvenc, ki so določale osnovne frekvence vzbujanja.

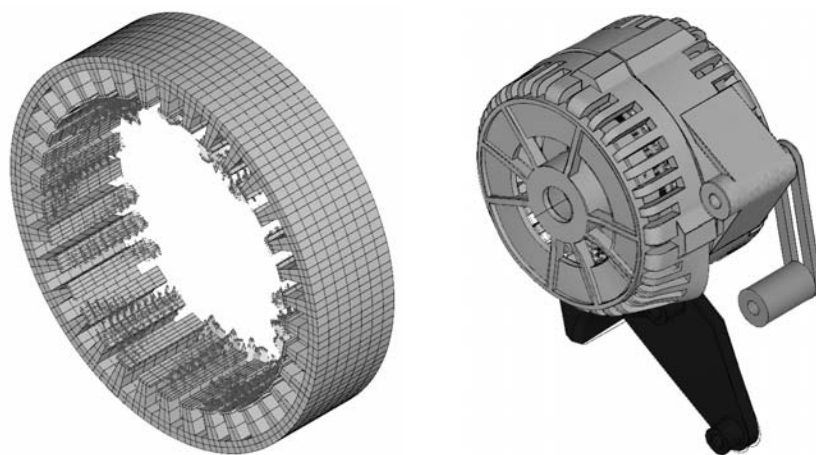
Ker je odziv strukture alternatorja močno odvisen od frekvence vzbujanja in zaradi tega od vrtilne frekvence alternatorja, smo osnovno frekvenco vzbujanja za harmonske komponente magnetnih sil vzeli iz meritev vrtilne frekvence. Le-ta se giblje med 3000 min^{-1} in 7500 min^{-1} . Tako je frekvenca osnovne harmonske komponente magnetnih sil (šest polovih parov na rotorju) v različnih razmerah obratovanja nahaja v območju od 300 Hz do 750 Hz.

Ker med posameznimi harmonskimi komponentami enakega reda, vendar za različne smeri rezultirajočih magnetnih sil, obstajajo fazni odmiki, je bilo pri prenosu magnetnih sil na strukturni model treba upoštevati tudi to. Fazno usklajenost smo ohranili tako, da smo harmonske komponente magnetnih sil v strukturni model po MKE vnesli v kompleksni obliki. Slika 8, na levi, prikazuje strukturni model po MKE statorja alternatorja s prirejenimi trenutnimi vrednostmi magnetnih sil, medtem ko slika 8, na desni, prikazuje strukturni odziv kot posledico obratovanja neobremenjenega alternatorja zaradi delovanja pete harmonske komponente magnetnih sil, katere frekvenca pri vrtilni frekvenci 3000 min^{-1} ustreza 1500 Hz.

intensity and the fundamental excitation frequency of the magnetic forces must be determined. This was done using the measured values of current, which determine the intensity of the magnetic forces, and the measured values of the rotational velocity, which determine the fundamental excitation frequencies.

The structural response of the alternator is strongly dependent on the excitation frequency and, consequently, on the rotational velocity of the alternator. For this reason, the fundamental excitation frequency for the harmonic components of the magnetic forces was adopted from the measurement of the rotational velocity. The latter varies from 3000 min^{-1} to 7500 min^{-1} . So, the frequency of the fundamental harmonic component of magnetic forces (six pole pairs on the rotor), on various working conditions, occurs in the range between 300 Hz and 750 Hz.

Between some particular harmonic components of the same order, but for different directions of the resulting magnetic forces, a phase shift occurs. During the transfer of magnetic forces to structural model this also had to be considered. The harmonic components of the magnetic forces were entered into the structural FEM model in a complex form, and a phase adjustment was preserved. Figure 8, on the left, shows the structural FEM model of the stator (of the alternator) with arranged instantaneous values of the magnetic forces, while Figure 8, on the right, depicts the structural response as a consequence of the operation of the unloaded alternator due to the effect of the 5th harmonic component of the magnetic forces. The frequency of the 5th harmonic component at rotational velocity of 3000 min^{-1} corresponds to 1500 Hz.



Sl. 8. Magnetne sile na statorju (na levi) ter strukturni odziv modela po MKE alternatorja kot posledice 5-te harmonske komponente magnetnih sil (na desni)
 Fig. 8. Magnetic forces on the stator (left) and structural response of the FEM model of the alternator as a consequence of the 5th harmonic component of the magnetic forces (right)

4 AKUSTIČNI ODZIV ALTERNATORJA

Zadnja faza vibroakustičnega modeliranja alternatorja je bila določitev zvočnega polja v njegovi okolici na podlagi predhodnega poznavanja strukturnega odziva modela MKE alternatorja. Pri numeričnem ovrednotenju, pri katerem z metodo robnih elementov (MRE) na podlagi znanega strukturnega odziva, izračunamo zvočno polje.

Pri ovrednotenju zvočnega polja smo se držali enakih omejitev, kakor smo jih navedli pri ovrednotenju strukturnega odziva. Bistvena je zahteva po ustaljenem obratovanju alternatorja. Strukturni odziv oz. vibracije, ki se pri takem obratovanju pojavijo na zunanjih površinah alternatorja, povzročajo zvočno valovanje ali ti. magnetni hrup. Ob predpostavki, da mehansko strukturo alternatorja in pojav zvočnega polja v njegovi okolici opišemo z linearnim modelom, lahko reševanje obravnavanega sklopljenega problema prevedemo na problem vsiljenega nihanja oz. na reševanje za posamezne harmonske komponente. Tako vsaka obratovalna oblika oz. strukturni odziv posamezne harmonske komponente povzroča pripadajočo harmonsko komponento zvočnega polja. Poznavanje zvočnega polja za vse harmonske komponente v končni fazi omogoča rekonstrukcijo celotnega zvočnega polja kot posledico strukturnega odziva alternatorja zaradi vzbujanja z magnetnimi silami.

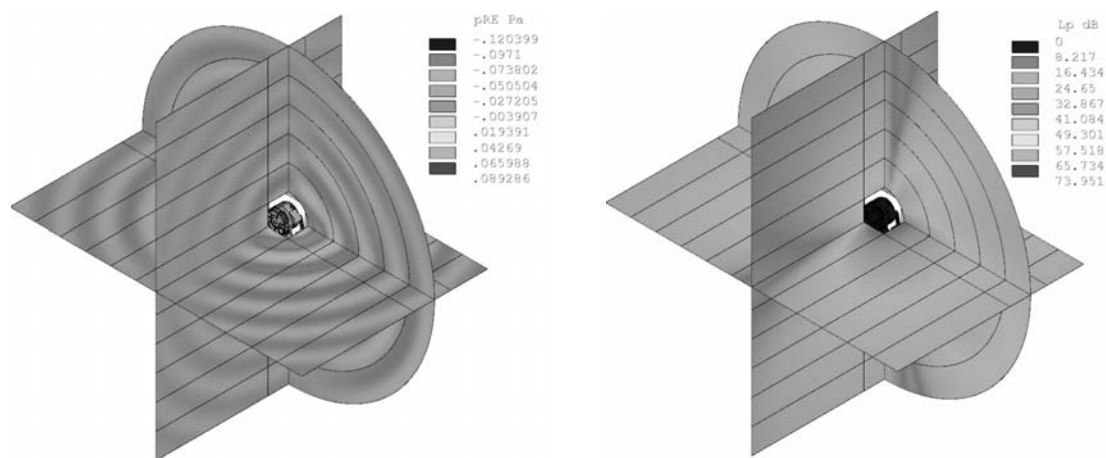
Pri gradnji akustičnega modela MRE smo izhajali iz strukturnega modela po MKE. Celotno zunanjo površino alternatorja, ki jo v strukturnem modelu po MKE sestavljata mreži PLP in ZLP, smo prekrili z redkejšo mrežo trikotnih robnih elementov. Pri tem je mreža robnih elementov zgrajena tako, da si robni elementi delijo vozlišča strukturnega modela po MKE, kar omogoča preprost prenos robnih pogojev iz strukturnega modela po MKE na akustični model MRE. V našem primeru akustičnega modela MRE je največja dolžina robnega elementa manjša od 9 mm, kar zagotavlja dovolj natančno reševanje v frekvenčnem območju do 6,4 kHz. Za opis akustičnega medija smo vzeli lastnosti zraka v normalnih okoliščinah. Z namenom, da bi se seznanili z zvočnim poljem v okolici alternatorja, smo zvočno polje okolice ovrednotili le za nekaj izbranih primerov obratovanja. Slika 9 prikazuje zvočno polje v okolici alternatorja pete harmonske komponente magnetnega hrupa neobremenjenega alternatorja pri obratovanju s 3000 min^{-1} .

4 ACOUSTIC RESPONSE OF THE ALTERNATOR

In the final step of the vibro-acoustic modelling of the alternator, a sound field in its surroundings was determined. This was obtained from the known structural response of the alternator FEM model. The numerical verification of the sound field is basically just an upgrade in the solving of the structural problem, where, on the basis of known structural response and by means of the boundary-element method (BEM), the sound field is calculated.

During the verification of the sound field the same restriction as at the verification of the structural response was used. The demand to have a stationary operation of the alternator is essential. The structural response during such an operation on the external surfaces of the alternator causes a sound radiation or the so-called magnetic noise. Suppose that the mechanical structure of the alternator and the phenomenon of the sound field in its surrounding can be described using a linear model, the solving of the discussed combined problem can then be transformed to a forced vibration problem or to solve a particular harmonic component. Thus, each operational shape, or the structural response at a particular harmonic component, contributes a belonging component to the sound field. Knowing the sound field for each harmonic component makes it possible to reconstruct the entire sound field as a consequence of the structural response of the alternator due to the magnetic force excitations.

The basis for the acoustic BEM model was the structural FEM model. The entire external surface of the alternator, which had been formed in the structural FEM model from the DEB and REB meshes, was covered with a less dense mesh consisting of triangular boundary elements. The mesh of the boundary elements was formed in such a way that its nodes coincided with the nodes of the structural FEM model. This enables an easy transfer of the boundary conditions from the structural FEM model to the acoustic BEM model. In our case of an acoustic BEM model, the maximum length of the boundary element was smaller than 9 mm, so an accurate solving in the region of 6.4 kHz was ensured. For the description of the acoustic medium, the air properties under regular conditions were adopted. In order to get to know the sound field in the surroundings of the alternator, the sound field was evaluated for just a few selected cases of the operation. Figure 9 shows the sound field in the surroundings of the unloaded alternator at 3000 min^{-1} as a consequence of the 5th harmonic component of the magnetic noise.



Sl. 9. Zvočno polje v okolici alternatorja kot posledica 5-te harmonske komponente magnetnih sil; trenutna vrednost zvočnega tlaka (na levi) in raven zvočnega tlaka (na desni)

Fig. 9. The sound field in the surroundings of the alternator as a consequence of the 5th harmonic component of the magnetic forces; the instantaneous value of sound pressure (left) and the level of sound pressure (right)

5 SKLEP

Prispevek predstavlja postopek izdelave in deloma tudi ovrednotenja sklopljenega vibroakustičnega modela alternatorja, ki združuje tri fizikalne probleme, tj. magnetni, strukturno-dinamični ter akustični problem. Predhodno je ovrednoten vibroakustični odziv alternatorja kot posledica vzbujanja z magnetnimi silami. S tem je postavljen postopek, ki omogoča preprosto in hitro posodabljanje parametrov modela ter razpoznavanje in raziskavo vpliva ključnih parametrov konstrukcije alternatorja na njegove tehnične značilnosti. Glede na dejstvo, da je izdelava vibroakustičnega modela v začetni fazi, je treba izvesti dodatno preverjanje in posodobitve modela predvsem v smislu izboljšanja modela mehanske strukture alternatorja.

5 CONCLUSION

This paper presents the process of building, and partly also of verifying, a coupled vibro-acoustic model of an alternator that unites three physical problems, i.e., the magnetic, the structural dynamic and the acoustic. The vibro-acoustic response as a result of the magnetic excitation is evaluated and it shows a preliminary study of the magnetic noise of the alternator. This means that we have successfully established the process where it is easily possible to change almost any parameters of the model and update the response results. In addition, this makes it possible to identify and to analyse the important design parameters of the alternator and find their influence on the technical characteristic of the alternator. Due to the fact that the vibro-acoustic model of the alternator is in its early stages, it needs additional verification and updating, especially the structural FEM model.

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